

FOOD PROCESSING TECHNOLOGY

Principles and Practice

Second Edition

P. Fellows

Director, Midway Technology and
Visiting Fellow in Food Technology at Oxford Brookes University



CRC Press

Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED

Cambridge England

Published by Woodhead Publishing Limited
Abington Hall, Abington
Cambridge CB1 6AH, England

Published in North and South America by CRC Press LLC
2000 Corporate Blvd, NW
Boca Raton FL 33431
USA

First edition 1988, Ellis Horwood Ltd
Second edition 2000, Woodhead Publishing Limited and CRC Press LLC

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British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library.

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress.

Woodhead Publishing Limited ISBN 1 85573 533 4
CRC Press ISBN 0 8493 0887 9
CRC Press order number: WP0887

Cover design by The ColourStudio

Project managed by Macfarlane Production Services, Markyate, Hertfordshire
Typeset by MHL Typesetting Ltd, Coventry, Warwickshire
Printed by TJ International, Cornwall, England

For Wen

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Acknowledgements

I am indebted to the large number of people who have given freely of their time and experience, provided me with information, checked the text and gave support during this revision of *Food Processing Technology*. My particular thanks to Dr Mike Lewis of Reading University for his support and technical editing skills; to Dr Mike Dillon of MD Associates for his assistance with Section 1.8 (Quality Assurance); to Francis Dodds of Woodhead Publishing for ideas, suggestions and references to new information; to staff and colleagues at Oxford Brookes University, particularly Professor Jeya Henry and Dr Neil Heppell for their advice and ideas; and to Dr Jeremy Selman at Campden Food RA. for his information. My thanks also to the many companies that responded positively to my requests for information about their equipment, machinery and products. They are listed individually at the end of each chapter. I should also not forget my parents, Jack and Gwen, who have always given unquestioning support to my efforts, and finally, but not least, my special thanks to my partner, Wen, for her constructive thoughts, encouragement and forbearance at my long hours in front of the computer screen over the best part of a year.

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Glossary

Absorption	Uptake of moisture by dry foods.
Acid food	A food with a pH of less than 4.6 and a water activity (a_w) equal to or greater than 0.85.
Additives	Chemicals added to food to improve their eating quality or shelf life.
Adiabatic	Changes to the humidity and temperature of air without loss or gain of heat (in drying).
Adiabatic process	Processing in which no heat is added or removed from a system.
Adulterants	Chemicals that are intentionally added to food which are forbidden by law.
Agglomeration	The production of granules from powder particles.
Algorithms	Software building blocks used to construct control sequences in computerised process control.
Alkaline phosphatase	An enzyme in raw milk having a similar <i>D</i> -value to heat-resistant pathogens, used to test for effectiveness of pasteurisation.
Annealing	Heating to control the ductility of a material.
Aseptic processing	Heat sterilisation of foods before filling into pre-sterilised (aseptic) containers.
Atomiser	A device to form fine droplets of food (e.g. in a spray drier).
Bacteriocins	Naturally produced peptides that inhibit other micro-organisms, similar in effect to antibiotics.
Baroresistance	Resistance to high pressure.
Barosensitivity	Sensitivity to high pressure.
Biological oxidation demand (BOD)	A measure of the oxygen requirement by micro-organisms when breaking down organic matter, used as a measure of the polluting potential of materials in water.
Black body	A theoretical concept for a material that can either absorb all the heat that lands on it or radiate all of the heat that it contains.
Blancher	Equipment used to blanch foods.
Blanching	Heating foods, especially vegetables, to below 100°C for a short time, to both inactivate enzymes which would cause a loss of quality during storage and to remove air and soften the food.
Blinding	Blocking of a sieve by food particles.

xx Glossary

Bloom	A thin layer of unstable forms of cocoa fat that crystallise at the surface of a coating to produce dullness or white specks.
Botulin	An exotoxin produced by <i>Cl. Botulinum</i> , able to cause fatal food poisoning.
Bound moisture	Liquid physically or chemically bound to a solid food matrix which exerts a lower vapour pressure than pure liquid at the same temperature.
Boundary film (or surface film)	Film of fluid next to the surface over which a fluid flows that causes a resistance to heat transfer.
Breading	The application of pre-prepared breadcrumbs to the surface of a food.
Calandria	Heat exchanger used in an evaporator.
Carborundum	An abrasive material made from silicon and carbon.
Case hardening	Formation of a hard impermeable skin on some foods during drying, which reduces the rate of drying and produces a food with a dry surface and a moist interior.
Cashflow	The balance of money at a given time entering and leaving a business.
Cavitation	Production of bubbles in foods by ultrasound and their rapid expansion/contraction.
Centrifugation	The separation of immiscible liquids or solids from liquids by the application of centrifugal force.
Chelating agents	Chemicals which sequester trace metals.
Chemical oxidation demand (COD)	A chemical method used to measure the polluting potential of materials in water.
Chilling	Reduction in the temperature of a food to between -1°C and 8°C .
Chilling injury	Physiological changes to some types of fruits and vegetables caused by low temperatures which result in loss of eating quality.
Choke	Restriction of the outlet to a mill to retain particles until sufficiently small (or restriction of the outlet in an extruder).
Climacteric	Abrupt increase in respiration rate in some fruits during ripening.
Clinching	Partial sealing of can lids.
Coating	A generic term to describe the application of a viscous covering (such as batter, chocolate, starch/sugar mixtures) to the surface of a food.
Co-extrusion	The simultaneous extrusion of two or more films to make a co-extruded film or the extrusion of two foods in which a filling is continuously injected into an outer casing in an extruder.
Cold shortening	Undesirable changes to meat caused by cooling before rigor mortis has occurred.
Collapse temperature	The maximum temperature of a frozen food before solute movement causes a collapse of the food structure and prevents movement of water vapour during freeze drying.
Commercial sterility	A term used in heat sterilisation to indicate that processing inactivates substantially all micro-organisms and spores which, if present, would be capable of growing in the food under defined storage conditions.
Common Object Resource Based Architecture (CORBA)	Computer software that acts as an information broker to link process control systems with other computerised company information.
Compound coating	A coating material in which cocoa solids and hardened vegetable oils are used to replace cocoa butter.
Conduction	The movement of heat by direct transfer of molecular energy within solids.
Constant-rate drying	The drying period in which the rate of moisture loss is constant when surface moisture is removed.
Continuous phase	The medium that contains the dispersed phase in an emulsion.

Convection	The transfer of heat in fluids by groups of molecules that move as a result of differences in density or as a result of agitation.
Critical control point (CCP)	A processing factor of which a loss of control would result in an unacceptable food safety or quality risk.
Critical moisture content	The amount of moisture in a food at the end of the constant-rate period of drying.
Crumb	Pre-prepared breadcrumbs used to cover food pieces, or the porous inner part of baked foods.
Crust	Hard surface layer on baked foods.
Cryogen	A refrigerant that absorbs latent heat and changes phase from solid or liquid to a gas, e.g. subliming or evaporating carbon dioxide or liquid nitrogen.
Cryogenic freezers	Equipment that uses subliming or evaporating carbon dioxide or liquid nitrogen directly in contact with food to freeze it.
Cryogenic grinding	Mixing liquid nitrogen or solid carbon dioxide with food to cool it during grinding.
Dead-folding	A crease or fold made in a material that will stay in place.
Decimal reduction time	The time needed to destroy 90% of micro-organisms (to reduce their numbers by a factor of 10).
Depositor	Machine for placing an accurate amount of food onto a conveyor or into a mould.
Desorption	Removal of moisture from a food.
Detergents	Chemicals that reduce the surface tension of water and hence assist in the release of soils from equipment or foods.
Dew point	Temperature at which an air–water vapour mixture becomes saturated with moisture, marking the onset of condensation.
Diafiltration	A process to improve the recovery of solutes by diluting the concentrate during reverse osmosis or ultrafiltration.
Die	A restricted opening at the discharge end of an extruder barrel.
Dielectric constant	The ratio of the capacitance of a food to the capacitance of air or vacuum under the same conditions.
Dielectric heating	A generic term that includes heating by both microwave and radio frequency energy.
Dilatant material	Food in which the consistency increases with shear rate.
Direct heating ovens	Ovens in which products of combustion are in contact with the food.
Dispersed phase	Droplets in an emulsion.
Dosimeter	A device that qualitatively or quantitatively measures the dose of irradiation received by a food.
Dry bulb temperature	Temperature measured by a dry thermometer in an air–water vapour mixture.
Effective freezing time	The time required to lower the temperature of a food from an initial value to a pre-determined final temperature at the thermal centre.
Electrical conductivity	The capacity of a material to conduct electricity.
Electrodialysis	The separation of electrolytes into anions and cations by the application of a direct electrical current and the use of ion-selective membranes.
Emulsification	Creation of an emulsion by the dispersion of one immiscible liquid (dispersed phase) in the form of small droplets in a second immiscible liquid (continuous phase).
Emulsifying agent	Chemical that forms micelles around each droplet in the dispersed phase of an emulsion to reduce interfacial tension and prevent droplets from coalescing.
Enrobing	The unit operation in which food pieces are coated with chocolate or other materials.

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Entrainment	Oil droplets that are carried over in steam produced by vigorously frying foods, leading to loss of oil, or loss of concentrated droplets of product with vapour during evaporation by boiling.
Equilibrium moisture content	The moisture content of a food at which it neither gains nor loses moisture to its surroundings (at a given temperature and pressure, the food is in equilibrium with the air vapour mixture surrounding it).
Equilibrium relative humidity	Relative humidity of the storage atmosphere in equilibrium with the moisture content of food.
Eutectic temperature (in freezing)	The temperature at which a crystal of an individual solute exists in equilibrium with the unfrozen liquor and ice.
Exhausting	Removal of air from a container before heat processing.
Expeller	A horizontal barrel, containing a helical screw, used to extract oil from seeds or nuts.
Expression	The separation of liquids from solids by applied pressure.
Extractors	Equipment used to extract food components using solvents.
Extruder	One or more screws rotating in a barrel with restricted apertures at the discharge end, used for producing extruded foods.
Extrusion	A process that involves the combination of several unit operations including mixing, cooking, kneading, shearing, shaping and forming to produce extruded foods.
<i>F</i> -value	The time required to destroy a given percentage of micro-organisms at a specified reference temperature and <i>z</i> value.
Falling-rate drying	The drying period in which the rate of moisture loss declines.
Feedback control	Automatic control of a process using information from sensors to adjust processing conditions.
Feed-forward control	Comparison of processing conditions with a model system, used in automatic process control.
Field heat	Heat within crops when they are harvested.
Filter cake	Solids removed by filtration.
Filter medium	Porous material through which food is filtered.
Filtrate	The liquor remaining after solids are removed by filtration.
Filtration	The separation of solids from liquids by passing the mixture through a bed of porous material.
Final eutectic temperature (in freezing)	The lowest eutectic temperature of solutes in equilibrium with unfrozen liquor and ice.
Flash pasteurisation	Heat treatment involving temperature greater than 72°C for 15 s for milk. (Also known as higher-heat shorter-time processing.)
Flash-over	Arcing of electricity between electrodes without heating taking place.
Fluence	Energy imparted by light to the surface of a material.
Flux	Flow of liquid through reverse osmosis or ultrafiltration membranes.
Foam	A colloidal system with a liquid or solid continuous phase and a gaseous dispersed phase.
Forming	Moulding of doughs and other materials into different shapes.
Fouling	Deposits of food or limescale on surfaces of heat exchangers.
Free moisture	Moisture in excess of the equilibrium moisture content at a particular temperature and humidity, and so free to be removed.
Freeze concentration	Concentration of liquid foods by freezing water to ice and removal of ice crystals.
Freeze drying	Dehydration of food by freezing water to form ice, followed by removal of ice by sublimation.
Freezing plateau	The period during freezing when the temperature of a food remains almost constant as latent heat of crystallisation is removed and ice is formed.

Friability	The hardness of a food and its tendency to crack.
Grading	The assessment of a number of attributes to obtain an indication of overall quality of a food.
Grey body	A concept used to take account of the fact that materials are not perfect absorbers or radiators of heat.
Half-life	The time taken for an isotope to lose half of its radioactivity.
Hazard analysis	The identification of potentially hazardous ingredients, storage conditions, packaging, critical process points and relevant human factors which may affect product safety or quality.
Headspace	The space in a container between the surface of a food and the underside of the lid.
Heat sterilisation	Destruction of the majority of micro-organisms in a food by heating.
Hermetically-sealed container	A package that is designed to be secure against entry of micro-organisms and maintain the commercial sterility of its contents after processing.
Heterofermentative micro-organisms	Micro-organisms that produce more than one main metabolic product.
Homofermentative micro-organisms	Micro-organisms that produce a single main byproduct.
Homogenisation	The reduction in size and increase in number of solid or liquid particles in the dispersed phase.
Humectants	Chemicals (e.g. salt, sugar, glycerol) that are able to lower the water activity in a food by depressing the vapour pressure.
Hydrocooling	Immersion of fruits and vegetables in chilled water.
Hydrophile-lipophile balance (HLB value)	The ratio of hydrophilic to hydrophobic groups on the molecules of an emulsifier.
Hygroscopic foods	Foods in which the partial pressure of water vapour varies with the moisture content.
Hydrostatic head	The pressure resulting from the weight of a column of liquid.
Hyperfiltration	Reverse osmosis.
Impact strength	The force required to penetrate a material.
Indirect heating ovens	Ovens in which heat from combustion is passed through a heat exchanger to heat air which is then in contact with the food.
Inventory	The stored accumulation of materials in an operation.
Ion exchange	The selective removal of charged molecules from a liquid by electrostatic adsorption, followed by their transfer to a second liquid using an ion-exchange material.
Ionisation	Breakage of chemical bonds (e.g. during irradiation).
Irradiation	The use of γ -rays to preserve foods by destruction of micro-organisms or inhibition of biochemical changes.
Isostatic	Uniform pressure throughout a food.
Isotope	A source of γ -rays from a radioactive material such as cobalt-60 or caesium-137.
Just-in-time	Management system in which goods are ordered as they are required and stocks are not held in warehouses.
Kinetic energy	Energy due to motion.
Lamination	Bonding together of two or more packaging films, papers or foods.
Latent heat	Heat taken up or released when a material undergoes a change of state.
Leaching	Washing out of soluble components from the food.
Lethality	Integrated effect of heating temperature and time on micro-organisms.
Loss factor	A measure of the amount of energy that a material will dissipate when subjected to an alternating electric field (in microwave and dielectric heating). (Also termed the 'dielectric loss' or 'loss tangent'.)

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Low acid food	A food with a pH greater than 4.6 and a water activity (a_w) equal to or greater than 0.85.
Manufacturing resource planning	Computer-based systems used to control distribution networks by using forecasted demand for and actual orders to assist management decisions.
Material requirement planning	A single integrated computer system, containing a database that can be accessed by all parts of the company for management planning.
Mechanical refrigerators	Equipment which evaporates and compresses a refrigerant in a continuous cycle, using cooled air, cooled liquid or cooled surfaces to freeze foods.
Metallisation	A thin coating of aluminium on plastic packaging.
Microfiltration	A pressure-driven membrane process using membranes with a pore size of 0.2–2 μm at lower pressures than ultrafiltration.
Microwaves	Energy produced commercially at frequencies of 2450 MHz for domestic ovens, 896 MHz for industrial heating in Europe and 915 MHz for industrial heating in the USA.
Mimetics	Low calorie fat substitutes.
Mimic panel	A graphical display of a process.
Moulders	Machines that form dough or confectionery into different shapes.
Multiple effect	The re-use of vapour from boiling liquor in one evaporator as the heating medium in another evaporator operating at a lower pressure.
Nanofiltration	A membrane process to separate particles with molecular weights from 300–1000 Da, using lower pressures than reverse osmosis.
Neural networks	Computer systems that are able to analyse complex relationships in a process and 'learn' from experience.
Nip	The gap between rollers in a mill or a moulding/forming machine.
Nominal freezing time	The time between the surface of the food reaching 0°C and the thermal centre reaching 10°C below the temperature of the first ice formation.
Non-hygroscopic foods	Foods that have a constant water vapour pressure at different moisture contents.
Non-Newtonian liquid	Food in which the viscosity changes with rate of shear.
Nucleation	The formation of a nucleus of water molecules that is required for ice crystal formation.
Ohmic heating	Direct electrical heating of foods.
Overall heat transfer coefficient (OHTC)	The sum of the resistances to heat flow due to conduction and convection.
Panning	The process of building up thin layers of sugar, sweetener or other coatings in a controlled way onto solid cores of nuts, fruit, etc.
Pasteurisation	A relatively mild heat treatment in which food is heated to below 100°C to preserve it without substantial changes to sensory characteristics or nutritional value. In low acid foods, the main reason for pasteurisation is destruction of pathogens.
Pinholes	Small holes in can seams or flexible packaging.
Plasticiser	Chemicals added to plastic films to make them more flexible.
Polymorphic fat	A fat that can crystallise into more than one form.
Potential energy	Energy due to position of an object.
Preforms	Small dense pellets made in an extruder from pre-gelatinised cereal dough, which are suitable for extended storage until they are converted to snackfoods by frying, toasting or puffing. (Also known as 'half-products'.)
Press cake	Solid residue remaining after extraction of liquid component from foods.
Process inter-locking	Linking different parts of a process so that one cannot operate until a

	second is correctly set up.
Programmable logic controllers (PLCs)	A microcomputer that is used in process control to replace electrical relays and to collect and store process data.
Pseudoplastic material	Food in which the viscosity decreases with increasing shear rate.
Psychrometrics	The study of inter-related properties of air–water vapour systems.
Radiation	The transfer of heat by electromagnetic waves.
Radio frequency energy	Energy produced commercially at frequencies of 13.56 MHz, 27.12 MHz or 40.68 MHz for industrial heating.
Radiolysis	Changes to a food material caused by ionising radiation to produce chemicals that destroy micro-organisms, etc.
Recrystallisation	Physical changes to ice crystals (changes in shape, size or orientation) which are an important cause of quality loss in some frozen foods.
Redox potential	Oxidation/reduction potential of a food or microbial substrate.
Refrigerant	A liquid that has a low boiling point and high latent heat of vaporisation so that it can change phase and absorb or lose heat in a refrigerator.
Refrigerators	Equipment that evaporates and compresses a refrigerant in a continuous cycle, using cooled air, cooled liquid or cooled surfaces to freeze foods.
Relative humidity	The ratio of the partial pressure of water vapour in air to the pressure of saturated water vapour at the same temperature, multiplied by 100.
Respiration	Metabolic activity of living animal or plant tissues.
Retort	A pressurised vessel used to heat foods above 100°C during canning.
Reverse osmosis	Unit operation in which small molecular weight solutes (with molecular weights of approx. 100 DA) are selectively removed by a semi-permeable membrane under high pressure.
Screen	A sieve.
Sensible heat	Heat used to raise the temperature of a food or removed during cooling, without a change in phase.
Sequence control	A type of process control in which the completion of one operation signals the start of the next.
Soils	A generic term used for all types of contaminating materials on foods or equipment.
Sorption isotherm	A curve produced from different values of relative humidity plotted against equilibrium moisture content.
Sorting	The separation of foods into categories on the basis of a measurable physical property.
Specific electrical resistance	Electrical resistance of a food between two 1 cm ² electrodes that are located 1 cm apart (i.e. the resistance of 1 cm ³ of product), having units of ohms cm ⁻² cm ⁻¹ .
Specific growth rate	The slope of the curve when the natural logarithm of microbial cell concentration is plotted against time.
Specific heat	The amount of heat that accompanies a unit change in temperature by a unit mass of material.
Stabilisers	Hydrocolloids that dissolve in water to form viscous solutions or gels.
Steady-state heat transfer	Heating or cooling when there is no change in temperature at any specific location.
Sterilants	Chemicals that inactivate micro-organisms.
Streamline (or laminar) flow	Flow of liquids in layers without significant mixing between layers.
Sublimation	A change in state of water directly from ice to water vapour without melting.
Substrate	A growth medium for micro-organisms.

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Supercooling	A phenomenon in which water remains liquid although the temperature is below its freezing point.
Supercritical carbon dioxide	Liquid CO ₂ used to extract food components.
Supervisory Control and Data Acquisition (SCADA)	A type of computer software that collects data from programmable logic controllers and displays it as graphics to operators in real-time.
Surface heat transfer coefficient	A measure of the resistance to heat flow caused by a boundary film of liquid.
Susceptor	A packaging material that is used to create a localised high temperature in microwave ovens; usually made from lightly metallised polyethylene terephthalate.
Tempering	Cooling food to close to its freezing point, or a process of re-heating, stirring and cooling chocolate to remove unstable forms of polymorphic fats.
Tensile elongation	A measure of the ability to stretch.
Tensile strength	The force needed to stretch a material.
Thermal centre	The point in a food that heats or cools most slowly.
Thermal conductivity	A measure of the heat transfer properties of solid materials.
Thermal death time (TDT) or <i>F</i> -value	The time required to achieve a specified reduction in microbial numbers at a given temperature.
Thermal diffusivity	The ratio of thermal conductivity of a product to specific heat, multiplied by the density.
Thermal shock	Heating: fracture to a glass container caused by rapid changes in temperature; freezing: a rapid reduction in temperature that causes foods to fracture.
Ultra high temperature (UHT)	Processing heat sterilisation at above 135°C for a few seconds.
Ultrafiltration	Unit operation in which solutes having molecular weights in the range of 1–200 kDA are selectively removed using a semi-permeable membrane operating at lower pressure than reverse osmosis.
Ultrasonication	Treatment of foods using ultrasound.
Unitised loads	Grouping of packages into larger loads.
Usage value	The rate of usage of individual materials in an inventory multiplied by their individual value.
Unsteady-state heat transfer	Heating or cooling where the temperature of the food and/or the heating or cooling medium are constantly changing.
Venting	Removal of air from a retort before heat processing.
Viscoelastic material	Food materials which exhibit viscous and elastic properties including stress relaxation, creep and recoil.
Voidage	The fraction of the total volume occupied by air (the degree of openness) of a bed of material in fluidised-bed drying.
Water activity	The ratio of vapour pressure of water in a solid to that of pure water at the same temperature.
Web	A packaging film.
Wet bulb temperature	Temperature measured by a wet thermometer in an air–water vapour mixture.
Yield	Weight of food after processing compared to weight before processing.
Young's modulus	(also modulus of elasticity) = stress/strain and is a measure of the hardness of a material.

Symbols

<i>A</i>	Area
<i>a</i>	Thermal diffusivity
<i>a</i>	Throttling factor (extrusion)
<i>a_w</i>	Water activity
<i>B</i>	Time of heating (canning)
<i>Bi</i>	Biot number
<i>b</i>	Permeability
<i>b</i>	Slope of sorption isotherm
<i>C_d</i>	Drag coefficient (fluid dynamics)
<i>c</i>	Concentration
<i>c</i>	Internal seam length (canning)
<i>c</i>	Specific heat capacity
<i>c_p</i>	Specific heat at constant pressure
<i>D</i>	Diameter (pipe, vessel)
<i>D</i>	Dilution rate (fermentation)
<i>D</i>	Decimal reduction time
<i>D</i>	Diffusion coefficient
<i>d</i>	Diameter (sphere, size of sieve aperture)
<i>d</i>	Differential operator
<i>E</i>	Electrical field strength
<i>E</i>	Energy (size reduction, radio frequency heating)
<i>F</i>	Feed flow rate (sorting, fermentation)
<i>F</i>	<i>F</i> -value (canning)
<i>F</i>	Shape factors (extruders)
<i>Fr</i>	Froude number
<i>f</i>	Slope of heat penetration curve (canning)
<i>f</i>	Frequency (microwaves)
<i>G</i>	Geometric constants (extruders)
<i>G</i>	Air mass flowrate (dehydration)
<i>g</i>	Acceleration due to gravity (9.81 m s ⁻²)
<i>g</i>	Retort temperature minus product temperature (canning)
<i>H</i>	Humidity

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h	Heat transfer coefficient
h_c	Convective heat transfer coefficient
h_s	Surface heat transfer coefficient
I	Light intensity
I	Electrical current
I_h	Retort temperature minus product temperature (canning)
J	Flux (membrane concentration)
j	Heating/cooling factor (canning)
K	Mass transfer coefficient (dehydration, membrane concentration)
K	Constant
K_k	Kick's constant (size reduction)
K_R	Ritinger's constant (size reduction)
K_s	Substrate utilisation constant (fermentation)
k	Thermal conductivity
L	Length
L	Equivalent thickness of filter cake
l	Come-up time (canning)
M	Moisture content, dry-weight basis
M	Molar concentration
m	Mass
m	Mass flow rate
m	Moisture content (wet-weight basis)
N	Speed
N	Rate of diffusion
Nu	Nusselt number
n	Number
P	Pressure
P	Product Row rate (sorting)
P	Power
P	Productivity (fermentation)
Po	Power number (mixing)
Po	Vapour pressure of pure water
Q	Rate of heat transfer
Q	Volumetric flowrate
q_p	Specific rate of product formation (fermentation)
R	Universal gas constant
R	Reject flowrate (sorting)
R	Resistance to flow through a filter
R	Fraction of reflected light (packaging)
R	Electrical resistance
Re	Reynolds number
r	Radius
r	Specific resistance to flow through a filter
S	Substrate concentration (fermentation)
s	Compressibility of filter cake
T	Absolute temperature
T	Fractional transmission of light (packaging)
t	Time
t	Metal thickness (canning)
U	Overall heat transfer coefficient
U	Thermal death time at retort temperature (canning)
V	Volume
V	Voltage

V_c	Fractional volume of filter cake
v	Velocity
v_e	Air velocity needed to convey particles
v_f	Air velocity needed for fluidisation
W	Work index (size reduction)
x	Thickness, depth
x	Direction of heat flow
\bar{x}	Mass fraction
\bar{x}	Average
y	Cover hook length (canning)
Y	Yield or yield factor (fermentation)
z	Height
z	z -value (canning)
α	Absorbance, absorptivity
β	Coefficient of thermal expansion
Δ	Difference, change
δ	Half dimension
$\tan\delta$	Loss tangent (microwaves)
ϵ	Porosity
ϵ	Voidage of fluidised bed
ϵ	Emmissivity (infrared radiation)
ϵ'	Dielectric constant (microwaves)
ϵ''	Loss factor (microwaves)
θ	Temperature
λ	Latent heat
λ	Wavelength
μ	Viscosity
μ	Specific growth rate (fermentation)
Π	Osmotic pressure
π	Constant = 3.142
ρ	Density
Σ	Sum
σ	Standard deviation
σ	Electrical conductivity
σ	Stefan-Boltzmann constant (infrared radiation)
ω	Angular velocity

Acronyms

AGV	Automatically guided vehicle
AQL	Acceptable quality limit
CAP	Controlled atmosphere packaging
CAS	Controlled atmosphere storage
CBE	Cocoa butter equivalent
CIP	Cleaning in place
CCP	Critical control point
CFC	Chlorofluorocarbon
CORBA	Common Object Resource Based Architecture
DCS	Distributed control systems
DDE	Dynamic data exchange
EDI	Electronic data interchange
EMA	Equilibrium modified atmosphere
EPSL	Edible protective superficial coating
ESR	Electron spin resonance
GEP	Gas exchange preservation
GMP	Good manufacturing practice
HACCP	Hazard analysis critical control point
HLB	Hydrophile-lipophile balance
HTST	High-temperature short-time
IBC	Intermediate bulk container
IQF	Individual quick frozen/freezing
JIT	Just in time
MAP	Modified atmosphere packaging
MAS	Modified atmosphere storage
MRP	Material resource planning
NMR	Nuclear magnetic resonance
NVDP	Non-volatile decomposition products
OLE	Object linking and embedding
ODBC	Open data base connectivity
OPC	Object linking and embedding for process control
PAM	Passive atmosphere modification

PCS	Process control system
PLC	Programmable logic controller
PPP	Product processing packaging
PSL	Photostimulated luminescence
PSL	Practical storage life
PVdC	Poly vinylidene chloride
RDA	Recommended daily allowance
REFPED	Ready-to-eat-products-for-extended-durability (also refrigerated-pasteurised-foods-for-extended-durability)
SCADA	Supervisory control and data acquisition
TDT	Thermal death time
TQM	Total quality management
TTT	Time temperature tolerance
UHT	Ultra high temperature
VDP	Volatile decomposition products
VOC	Volatile organic compounds
VP	Vacuum packaging
VSP	Vacuum skin packaging
WHO	World Health Organisation
WOF	Warmed over flavour
WTO	World Trade Organisation

Introduction

The food industry today

The aims of the food industry today, as in the past, are fourfold:

1. To extend the period during which a food remains wholesome (the shelf life) by preservation techniques which inhibit microbiological or biochemical changes and thus allow time for distribution, sales and home storage.
2. To increase variety in the diet by providing a range of attractive flavours, colours, aromas and textures in food (collectively known as *eating quality*, *sensory characteristics* or *organoleptic quality*); a related aim is to change the form of the food to allow further processing (for example the milling of grains to flour).
3. To provide the nutrients required for health (termed *nutritional quality* of a food).
4. To generate income for the manufacturing company.

Each of these aims exists to a greater or lesser extent in all food production, but the processing of a given product may emphasise some more than others. For example, frozen vegetables are intended to have sensory and nutritional qualities that are as close as possible to the fresh product, but with a shelf life of several months instead of a few days or weeks. The main purpose of freezing is therefore to preserve the food. In contrast, sugar confectionery and snackfoods are intended to provide variety in the diet, and a large number of shapes, flavours, colours and textures are produced from basic raw materials.

All food processing involves a combination of procedures to achieve the intended changes to the raw materials. These are conveniently categorised as *unit operations*, each of which has a specific, identifiable and predictable effect on a food. Unit operations are grouped together to form a process. The combination and sequence of operations determines the nature of the final product.

In industrialised countries the market for processed foods is changing, and in contrast to earlier years, consumers no longer require a shelf life of several months at ambient temperature for the majority of their foods. Changes in family lifestyle, and increased ownership of freezers and microwave ovens, are reflected in demands for foods that are convenient to prepare, are suitable for frozen or chilled storage, or have a moderate shelf

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life at ambient temperatures. There is now an increasing demand by consumers for foods that have fewer synthetic additives, or have undergone fewer changes during processing. These foods more closely resemble the original raw materials and have a 'healthy' or 'natural' image. Correspondingly, growth in demand for organic foods has significantly increased in Europe during the 1990s. These pressures are an important influence on changes that are taking place in the food processing industry, and manufacturers have responded by reducing or eliminating synthetic additives from products (particularly colourants and flavours) and substituting them with natural or 'nature-equivalent' alternatives. They have also introduced new ranges of low-fat, sugar-free or low-salt products in nearly all sub-sectors (Anon., 1999). New products that are supplemented with vitamins, minerals and probiotic cultures (or 'functional' foods) have appeared in recent years, and products containing organic ingredients are now widely available. At the time of writing (2000), a debate over the safety of genetically modified (GM) food ingredients is unresolved. Consumer pressure for more 'natural' products has also stimulated development of novel 'minimal' processes that reduce the changes to sensory characteristics or nutritional value of foods.

Improvements to food quality during the last 10–15 years have also been achieved through changes in legislation, including legal requirements on manufacturers and retailers to display 'due diligence' in protecting consumers from potentially hazardous foods. This has in part arisen from a series of highly publicised cases of food poisoning and food adulteration in Europe during the 1980s and 1990s, and the outbreak of Bovine Spongiform Encephalitis (BSE) in British cattle, which led to public pressure for improved food safety and quality. Legislation is now increasingly international in its focus and application, and international standards for both specific products and also for methods of achieving quality assurance are in force.

Trends that started during the 1960s and 1970s, and accelerated during the last 10–15 years, have caused food processors to change their operations in four key respects. First, there is increasing investment in capital intensive, automated processes to reduce labour and energy costs. Second, there has been a change in philosophy from quality control, achieved by testing final products, to a more sophisticated approach to quality assurance, which involves all aspects of management. Third, high levels of competition and slowing of the growth in the food market in Europe and USA during the 1970s, has caused manufacturers to adopt a more proactive approach to creating demand, using sophisticated marketing techniques and large advertising budgets. Mergers or take-overs of competitors have resulted from the increased competition. Fourth, there has been a shift in power and control of food markets from manufacturers to large retail companies.

The changes in technology have been influenced by a variety of factors: substantial increases in the costs of both energy and labour, by public pressure and legislation to reduce negative environmental effects of processing, particularly air or water pollution and energy consumption. Food processing equipment now has increasingly sophisticated levels of control to reduce processing costs, enable rapid change-overs between shorter production runs, to improve product quality and to provide improved records for management decisions. Microprocessors are now almost universally used to control food processing equipment. The automation of entire processes, from reception of materials, through processing and packaging to warehousing, has become a reality. This requires a higher capital investment by manufacturers but, together with improved quality assurance, reduces production costs and wastage. It increases production efficiency, uses less energy and often fewer operators, and generates increased revenue and market share from products that have higher quality.

The food industry has now become a global industry, dominated by a relatively few multinational conglomerates. Many of the mergers and take-overs that created these companies took place in the 1980s and early 1990s when large companies bought their competitors in order to acquire brand names and increase their market share. In 1988 for example, a total of \$42.5 billion was spent on the purchase of just three companies (Rowntree, Kraft and Nabisco) (Giles, 1993). Multinational companies are now focusing on development of new markets and are either buying up or forming alliances with local competitors in South East Asia, India, Eastern Europe and Latin America.

Global sourcing of raw materials and ingredients has been a feature of some industries from their inception (spices, coffee, cocoa are a few examples), but this has now expanded to many more sectors, to reduce costs and ensure continuity of supply. These developments have in turn prompted increased consumer awareness of both ethical purchasing issues, such as employment and working conditions in suppliers' factories, and also environmental issues, such as safeguards in countries which have less developed legislative controls, and the environmental impact of international transportation of foods by air. There has also been a resurgence of consumer interest in locally distinctive foods and 'Fair-Traded' foods in some European countries, but at the time of writing this is confined to higher value niche products.

During the last decade or so, there has been a substantial increase in the power and influence of large retailing companies, especially in the USA and Europe. Much of the change in food quality and choice that has been witnessed during this time has arisen from competition between these retail companies and the pressures that they have exerted on manufacturers. Manufacturers are now responding to the shift in power to supermarkets by forming international strategic alliances with other large manufacturers. This enables them to develop pan-regional economies of scale and to focus on their own core products while sharing the benefits of joint marketing or research and development. They are also promoting 'tele-shopping', especially using the Internet, and developing other types of sales outlets (e.g. at sports or cultural venues) that by-pass existing retailers.

About this book

Heat has important influences on food processing in a number of respects: it is the most convenient way of extending the shelf life of foods by destroying enzymic and microbiological activity, or by removing water to inhibit deterioration; it changes the nutritional and sensory qualities of foods; and generation of heat is a major processing cost. The unit operations described in this book are therefore grouped according to the nature of heat transfer that takes place.

After Part I, which describes some important basic concepts, Part II describes unit operations that take place at ambient temperature and involve minimum heating of foods; Part III includes those operations that heat foods to extend the shelf life or to alter the eating quality; Part IV describes operations that remove heat from foods to extend the shelf life with minimal changes in nutritional qualities and sensory characteristics; the final part, Part V, is concerned with operations that are integral to a food process but are supplementary to the main method of processing.

In each chapter, the theoretical basis of the unit operation is first described. Formulae required for calculation of processing parameters and sample problems are

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given where appropriate, and sources of more detailed information are indicated. Details of the equipment used for practical implementation of theoretical concepts are then described, and developments in technology that relate to savings in energy or labour, or to improvement in product quality are noted. Finally the effect of the unit operation on sensory characteristics and nutritional properties of selected foods is described.

This book therefore aims to show how a knowledge of the properties of foods is used to design processing equipment and to control processing conditions on an industrial scale, to achieve the desired aims of altering the eating quality or extending the shelf life, with minimal changes to sensory characteristics and nutritional qualities. The book aims to introduce students of food science and technology, or biotechnology to the wide range of processing techniques that are used in food processing. It attempts to describe each topic at a level that is accessible without an advanced mathematical background, while providing reference to more detailed or more advanced texts. The book is therefore also suitable for students studying nutrition, catering or agriculture as an additional perspective on their subject areas.

Note on the second edition

There have been major developments in technology during the last decade which have justified new chapters on:

- computer control of processing (Chapter 2)
- novel food processes that have a minimal effect on food quality (Chapter 9 and ohmic heating in Chapter 18)
- modified atmosphere packaging (Chapter 20).

Nearly all of the unit operations described in the first edition have undergone significant developments and these are reflected in additional material in each chapter. This is especially so for:

- sorting foods (Chapter 3)
- membrane separation technologies (Chapter 6)
- bacteriocins (Chapter 7)
- detection of irradiated foods (Chapter 8)
- UHT/Aseptic processing (Chapter 12)
- chilling (Chapter 19)
- packaging (Chapters 24 and 25)
- materials handling (Chapter 26).

Additional material has also been included in Chapter 1 to both make the text more comprehensive and to include an outline of quality assurance and Hurdle Technology, and in Chapter 13 to include an outline of distillation.

Where appropriate, the original text has been clarified and edited, and new photographs, illustrations and tables have been included to provide additional information and updated descriptions of technologies. All new developments have been fully referenced in each chapter, and a new glossary of technical terms and list of acronyms has been included.

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Part I

Basic principles

1

Properties of foods and processing theory

1.1 Properties of liquids, solids and gases

Liquids, gases and some solids (for example powders and particulate materials) are termed 'fluids' and can flow without disintegration when a pressure is applied to them. In contrast, solids deform when pressure is applied to them (Section 1.1.4). In this section, the properties of fluids and solids that are relevant to both the design of food processes and the quality of processed food are described. More detailed mathematical treatments and derivations of formulae used in food engineering calculations are given in a number of texts including Toledo (1999), Lewis (1990), Brennan *et al.* (1990) and Earle (1983).

The transition from solid to fluid and back is known as a *phase transition* and this is important in many types of food processing (e.g. water to water vapour in evaporation and distillation (Chapter 13) and dehydration (Chapter 15); water to ice in freezing (Chapter 21) and freeze drying or freeze concentration (Chapter 22) or crystallisation of fats (Chapter 23)). Phase transition takes place isothermally at the phase transition temperature by release or absorption of latent heat, and can be represented by a *phase diagram* (for example Chapter 22, Fig. 22.1).

A second type of transition, known as *glass transition*, takes place without the release or absorption of latent heat and involves the transition of a food to an amorphous glass state at its glass transition temperature. The transition is dependent on the temperature of the food, time, and the moisture content of the food. Examples of glass transition temperatures are given in Chapter 21 (Table 21.2). When materials change to glasses, they do not become crystalline, but retain the disorder of the liquid state. However, their physical, mechanical, electrical and thermal properties change as they undergo the transition. In their glassy state, foods become very stable because compounds that are involved in chemical reactions that lead to deterioration are immobilised and take long periods of time to diffuse through the material to react together. Details of nine key concepts underlying the relationship between molecular mobility and food stability are given by Fennema (1996). Processes that are significantly influenced by transition to a glassy state include aroma retention, crystallisation, enzyme activity, microbial activity, non-enzymic browning, oxidation, agglomeration and caking. The relationship between

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glass transition and water activity (Section 1.5) and factors that affect glass transition are described in detail by Rahman (1999), Blanshard (1995) and Fennema (1996).

1.1.1 Density and specific gravity

A knowledge of the density of foods is important in separation processes (Chapter 6), and differences in density can have important effects on the operation of size reduction and mixing equipment (Chapters 4 and 5). The density of a material is equal to its mass divided by its volume and has units of kg m^{-3} . Examples of the density of solid foods and other materials used in food processing are shown in Table 1.1 (see also Chapter 15, Table 15.7) and examples of densities of liquids are shown in Table 1.2. The density of materials is not constant and changes with temperature (higher temperatures reduce the density of materials) and pressure. This is particularly important in fluids where differences in density cause convection currents to be established (Section 1.4.3).

Table 1.1 Densities of foods and other materials

Material	Density (kg m^{-3})	Bulk density (kg m^{-3})	Temperature (°C)
<i>Solids</i>			
Aluminium	2640	–	0
Copper	8900	–	0
Stainless steel	7950	–	20
Concrete	2000	–	20
Grapes	1067	368	–
Tomatoes	–	672	–
Lemons/oranges	–	768	–
Fresh fruit	865–1067	–	–
Frozen fruit	625–801	–	–
Fresh fish	967	–	–
Frozen fish	1056	–	–
Water (0°C)	1000	–	0
Ice (0°C)	916	–	0
Ice (–10°C)	933	–	–10
Ice (–20°C)	948	–	–20
Fat	900–950	–	20
Salt	2160	960	–
Sugar (granulated)	1590	800	–
Sugar (powdered)	–	480	–
Starch	1500	–	–
Wheat	1409–1430	790–819	–
Wheat flour	–	480	–
Barley	1374–1415	564–650	–
Oats	1350–1378	358–511	–
Rice	1358–1386	561–591	–
<i>Gases</i>			
Air	1.29	–	0
Air	0.94	–	100
Carbon dioxide	1.98	–	0
Carbon dioxide	1.46	–	100
Nitrogen	1.30	–	0

Adapted from data of Earle (1983), Lewis (1990), Milson and Kirk (1980), Peleg (1983) and Mohsenin (1970).

Table 1.2 Properties of fluids

	Thermal conductivity ($\text{W m}^{-1}\text{°K}^{-1}$)	Specific heat ($\text{kJ kg}^{-1}\text{°K}^{-1}$)	Density (kg m^{-3})	Dynamic viscosity (N s m^{-2})	Temperature (°C)
Air	0.024	1.005	1.29	1.73×10^{-5}	0
	0.031	1.005	0.94	2.21×10^{-5}	100
Carbon dioxide	0.015	0.80	1.98		0
Oxygen		0.92		1.48×10^{-3}	20
Nitrogen	0.024	1.05	1.30		0
Refrigerant 12	0.0083	0.92			
Water	0.57	4.21	1000	1.79×10^{-3}	0
	0.68	4.21	958	0.28×10^{-3}	100
Sucrose solution (60%)				6.02×10^{-2}	20
Sucrose solution (20%)	0.54	3.8	1070	1.92×10^{-3}	20
Sodium chloride solution (22%)	0.54	3.4	1240	2.7×10^{-3}	2
Acetic acid	0.17	2.2	1050	1.2×10^{-3}	20
Ethanol	0.18	2.3	790	1.2×10^{-3}	20
Rape-seed oil			900	1.18×10^{-1}	20
Maize oil		1.73			20
Olive oil	0.168			8.4×10^{-2}	29
Sunflower oil		1.93			20
Whole milk	0.56	3.9	1030	2.12×10^{-3}	20
				2.8×10^{-3}	10
Skim milk			1040	1.4×10^{-3}	25
Cream (20% fat)			1010	6.2×10^{-3}	3
Locust bean gum (1% solution)				1.5×10^{-2}	
Xanthan gum (1% solution)			1000		

From Earle (1983), Lewis (1987) and Peleg and Bagley (1983).

The density of liquids is a straightforward measure of mass/volume at a particular temperature, but for particulate solids and powders there are two forms of density: the density of the individual pieces and the density of the bulk of material, which also includes the air spaces between the pieces. This latter measure is termed the *bulk density* and is ‘the mass of solids divided by the bulk volume’. The fraction of the volume that is taken up by air is termed the *porosity* (ϵ) and is calculated by:

$$\epsilon = V_a/V_b \quad \boxed{1.1}$$

where V_a = volume of air (m^3) and V_b = volume of bulk sample (m^3).

The bulk density of a material depends on the solids density and the geometry, size and surface properties of the individual particles. Examples of bulk densities of foods are shown in Table 1.1 and bulk density is discussed in relation to spray dried powders in Chapter 15.

The density of liquids can be expressed as *specific gravity* (SG), a dimensionless number (Appendix D), which is found by dividing the mass (or density) of a liquid by the mass (or density) of an equal volume of pure water at the same temperature:

$$\text{SG} = \text{mass of liquid/mass water} \quad \boxed{1.2}$$

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SG = density of liquid/density water

1.3

If the specific gravity of a liquid is known at a particular temperature, its density can be found using:

$$\rho_L = (SG)_T \cdot \rho_w$$

1.4

where ρ_L = liquid density (kg m^{-3}) and ρ_w = density of water, each at temperature T ($^{\circ}\text{C}$).

Specific gravity is widely used instead of density in brewing and other alcoholic fermentations (Chapter 7), where the term 'original gravity (OG)' is used to indicate the specific gravity of the liquor before fermentation (for example '1072' or '72' refers to a specific gravity of 1.072).

The density of gases depends on their pressure and temperature (Table 1.1). Pressure is often expressed as 'gauge pressure' when it is above atmospheric pressure, or as 'gauge vacuum' when it is below atmospheric pressure. Pressure is calculated using the *Ideal Gas Equation* as follows:

$$PV = nRT$$

1.5

where P = absolute pressure (Pa), V = volume (m^3), n = number of moles of gas (kmole), R = the gas constant ($8314 \text{ N(m)/(kmole K)}$) and T = temperature (K).

This equation is useful for calculation of gas transfer in applications such as modified atmosphere storage or packaging (Chapter 20), cryogenic freezing (Chapter 21) and the permeability of packaging materials (Chapter 24).

Sample problem 1.1

Calculate the amount of oxygen that enters through a polyethylene packaging material in 24 h if the pack has a surface area of 750 cm^2 and an oxygen permeability of 120 ml m^{-2} per 24 h at $23 \text{ }^{\circ}\text{C}$ and 85% relative humidity (see Chapter 24, Table 24.2).

Solution to Sample problem 1.1

The volume of oxygen entering through the polyethylene:

$$V = 120 \times \frac{750}{100^2}$$

$$= 9.0 \text{ cm}^3$$

using equation 1.5,

$$n = 9.0 \times 1000 / (8314 \times 273)$$

$$= 0.00396 \text{ kmole}$$

The density of gases and vapours is also referred to as *specific volume* which is 'the volume occupied by unit mass of gas or vapour' and is the inverse of density. This is used for example in the calculation of the amount of vapour that must be handled by fans during dehydration (Chapter 15) or by vacuum pumps in freeze drying (Chapter 22) or vacuum evaporation (Chapter 13). Further details are given by Lewis (1990) and Toledo (1999).

When air is incorporated into liquids (for example cake batters, ice cream, whipped cream) it creates a foam and the density is reduced. The amount of air that is incorporated

is referred to as the *over-run* and is described in Chapter 4 (Section 4.2.3)

$$\text{over-run} = \frac{\text{volume of foam} - \text{volume of liquid}}{\text{volume of liquid}} \times 100$$

Typical over-run values are 60–100% for ice cream and 100–120% for whipped cream.

1.1.2 Viscosity

Viscosity is an important characteristic of liquid foods in many areas of food processing. For example the characteristic mouth feel of food products such as tomato ketchup, cream, syrup and yoghurt is dependent on their consistency or viscosity.¹ The viscosity of many liquids changes during heating, cooling, concentration, etc. and this has important effects on, for example, the power needed to pump these products. Viscosities of some common fluids in food processing are shown in Table 1.2.

Viscosity may be thought of as a liquid's internal resistance to flow. A liquid can be envisaged as having a series of layers and when it flows over a surface, the uppermost layer flows fastest and drags the next layer along at a slightly lower velocity, and so on through the layers until the one next to the surface is stationary. The force that moves the liquid is known as the *shearing force* or *shear stress* and the velocity gradient is known as the *shear rate*. If shear stress is plotted against shear rate, most simple liquids and gases show a linear relationship (line A in Fig. 1.1) and these are termed *Newtonian* fluids. Examples include water, most oils, gases, and simple solutions of sugars and salts. Where the relationship is non-linear (lines B–E in Fig. 1.1), the fluids are termed 'non-Newtonian'. Further details are given by Nedderman (1997). For all liquids, viscosity decreases with an increase in temperature but for most gases it increases with temperature (Lewis, 1990).

Many liquid foods are non-Newtonian, including emulsions and suspensions, and concentrated solutions that contain starches, pectins, gums and proteins. These liquids often display Newtonian properties at low concentrations but as the concentration of the solution is increased, the viscosity increases rapidly and there is a transition to non-Newtonian properties (Rielly, 1997). Non-Newtonian fluids can be classified broadly into the following types:

- pseudoplastic fluid (line B in Fig. 1.1) – viscosity decreases as the shear rate increases (e.g. emulsions, and suspensions such as concentrated fruit juices and purées)
- dilatant fluid (line C in Fig. 1.1) – viscosity increases as the shear rate increases. (This behaviour is less common but is found with liquid chocolate and cornflour suspension.)
- Bingham or Casson plastic fluids (lines D and E in Fig. 1.1) – there is no flow until a critical shear stress is reached and then shear rate is either linear (Bingham type) or non-linear (Casson type) (e.g. tomato ketchup)
- thixotropic fluid – the structure breaks down and viscosity decreases with continued shear stress (most creams)
- rheopectic fluid – the structure builds up and viscosity increases with continued shear stress (e.g. whipping cream)

1. Although these two terms are often used inter-changeably, strictly 'viscosity' is only applied to Newtonian fluids – see below.

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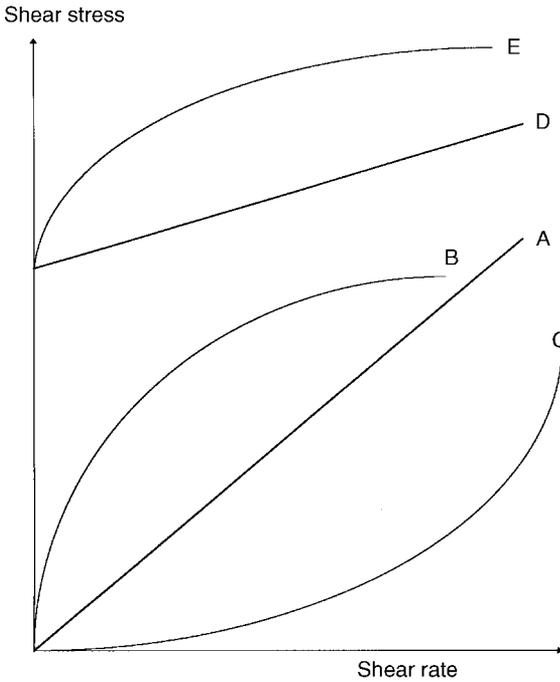


Fig. 1.1 Changes in viscosity of Newtonian fluid (A) and different types of non-Newtonian fluids; (B) pseudoplastic fluid; (C) dilatant fluid; (D) Bingham plastic fluid and (E) Casson plastic fluid. (After Lewis (1990).)

- viscoelastic material – has viscous and elastic properties exhibited at the same time. When a shear stress is removed the material never fully returns to its original shape and there is a permanent deformation (e.g. dough, cheese, gelled foods).

The measurement of viscosity is complicated by the range of terms used to describe it. The simplest is the ratio of shear stress to shear rate, which is termed the *dynamic viscosity* ($\text{kg m}^{-1} \text{s}^{-1}$). This is related to another term, *kinematic viscosity* ($\text{m}^2 \text{s}^{-1}$), as follows:

$$\text{kinematic viscosity} = \frac{\text{dynamic viscosity}}{\text{density}} \quad \boxed{1.6}$$

Other terms, including ‘relative viscosity’, ‘specific viscosity’ and ‘apparent viscosity’, together with descriptions of methods of measuring viscosity, are given by Lewis (1990) and Toledo (1999).

1.1.3 Surface activity

A large number of foods comprise two or more immiscible components, which have a boundary between the phases (Table 1.3). The phases are known as the *dispersed phase* (the one containing small droplets or particles) and the *continuous phase* (the phase in which the droplets or particles are distributed). Details of the preparation of emulsions are given in Chapter 4.

One characteristic of these systems is the very large surface area of the dispersed phase that is in contact with the continuous phase. In order to create the increased surface

Table 1.3 Examples of colloidal food systems

Dispersed phase	Continuous phase	Name	Example
Liquid	Gas	Fog, mist, aerosol	Sprays (e.g. spray drying)
Solid	Gas	Smoke, aerosol	Carbon dioxide fog, smoke
Gas	Liquid	Foam	Whipped cream, aeration of fermentation media, hydrogenation of oils (hydrogen in oil)
Liquid	Liquid	Emulsion	Cream, mayonnaise, margarine and low-fat spreads, salad cream, sausagemeat and cakes
Solid	Liquid	Sol, colloidal solution, gel suspension	Chocolate drinks, fruit juice
Gas	Solid	Solid foam	Meringue, ice cream

From Lewis (1990).

area, a considerable amount of energy needs to be put into the system using for example a high-speed mixer or an homogeniser. Droplets are formed when new surfaces are created. To understand the reason for this it is necessary to know the forces acting in liquids: within the bulk of a liquid the forces acting on each individual molecule are equal in all directions and they cancel each other out. However, at the surface the net attraction is towards the bulk of the liquid and as a result, the surface molecules are 'pulled inwards' and are therefore in a state of tension (produced by surface tension forces). This causes liquid droplets to form into spheres because this shape has the minimum surface area for the particular volume of liquid.

Emulsions

Chemicals that reduce the surface tension in the surface of a liquid are termed *surface active* and are known as 'surfactants', 'emulsifying agents' or 'detergents'. By reducing the surface tension, they permit new surfaces to be produced more easily when energy is put into the system (for example by homogenisers) and thus enable larger numbers of droplets to be formed. There are naturally occurring surfactants in foods, including alcohols, phospholipids and proteins and these are sometimes used to create food emulsions (for example using egg in cake batters). However, synthetic chemicals have more powerful surface activity and are used in very small amounts to create emulsions. Others are used in detergents for cleaning operations (Chapter 26). Details of synthetic emulsifying agents are given in Chapter 4 and Appendix C.

Surface active agents contain molecules which are polar (or 'hydrophilic') at one end and non-polar (or 'lipophilic') at the other end. In emulsions, the molecules of emulsifying agents become oriented at the surfaces of droplets, with the polar end in the aqueous phase and the non-polar end in the oil phase.

Detergents are surface active agents that reduce the surface tension of liquids to both promote wetting (spreading of the liquid) and to act as emulsifying agents to dissolve fats. The detergent molecules have a lipophilic region of long chain fatty acids and a hydrophilic region of either a sodium salt of carboxylic acid (soapy detergents) or the sodium salt of an alkyl or aryl sulphonate (anionic detergents). Anionic detergents are not affected by hard water, whereas soapy detergents form a scum in hard water. Non-ionic detergents, which have alcohols, esters or ethers as the hydrophilic component, produce little foam and are easily rinsed off. Enzymes may also be added to detergents to remove proteins, and other ingredients may include polyphosphates (to soften water and keep dirt

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in suspension), sodium sulphate or sodium silicate (to make detergent powder free-flowing) and sodium perborate (bleaching agent).

Foams

Foams are two-phase systems which have gas bubbles dispersed in a liquid or a solid, separated from each other by a thin film. In addition to food foams (Table 1.3), foams are widely used for cleaning equipment. The main factors needed to produce a stable foam are:

- a low surface tension to allow the bubbles to contain more air and prevent them contracting
- gelation or insolubilisation of the bubble film to minimise loss of the trapped gas and to increase the rigidity of the foam and
- a low vapour pressure in the bubbles to reduce evaporation and rupturing of the film.

In food foams, the structure of the foam may be stabilised by freezing (ice cream), by gelation (setting gelatin in marshmallow), by heating (cakes, meringues) or by the addition of stabilisers such as proteins or gums (Appendix C).

1.1.4 Rheology and texture

The texture of foods has a substantial influence on consumers' perception of 'quality' and during chewing (or 'mastication'), information on the changes in texture of a food is transmitted to the brain from sensors in the mouth, from the sense of hearing and from memory, to build up an image of the textural properties of the food. This may be seen as taking place in a number of stages:

1. an initial assessment of hardness, ability to fracture and consistency during the first bite
2. a perception of chewiness, adhesiveness and gumminess during chewing, the moistness and greasiness of the food, together with an assessment of the size and geometry of individual pieces of food
3. a perception of the rate at which the food breaks down while chewing, the types of pieces formed, the release or absorption of moisture and any coating of the mouth or tongue with food.

These various characteristics have been categorised (Table 1.4) and used to assess and monitor the changes in texture that affect the quality of foods.

Rheology is the science of deformation of objects under the influence of applied forces. When a material is stressed it deforms, and the rate and type of deformation characterise its rheological properties. (The rheological properties of solid foods are described in more detail in Chapter 4.) A large number of different methods have been used to assess the texture of food, including texture profiling by sensory methods using taste panels (e.g. Bourne, 1982), Quantitative Descriptive Analysis (QDA) (Fig. 1.2), described by Clark (1990), and empirical methods in which measurements of the forces needed to shear, penetrate, extrude, compress or cut a food are related to a textural characteristic. These methods are reviewed by Kilcast (1999), Rosenthal (1999), Lawless and Heyman (1998) and Brennan (1984).

Examples of these instrumental methods include the Brabender system to measure dough texture or the viscosity of starch pastes, cone or rod penetrometers to measure the yield stress of margarine and spreads or the hardness of fruits, the General Foods Texturometer which simulates mastication by compressing foods using a plunger, and the

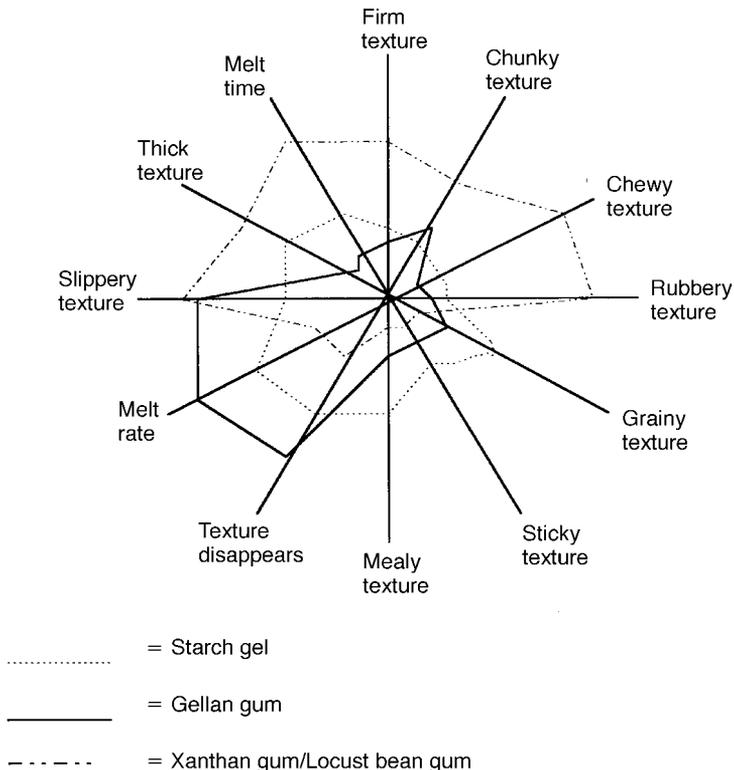


Fig. 1.2 Example of texture assessment using quantitative descriptive analysis. (Adapted from Clark (1990).)

Table 1.4 Textural characteristics of foods

Primary characteristic	Secondary characteristic	Popular terms
<i>Mechanical characteristics</i>		
Hardness		Soft→firm→hard
Cohesiveness	Brittleness Chewiness Gumminess	Crumbly, crunchy, brittle Tender, chewy, tough
Viscosity		Short, mealy, pasty, gummy
Elasticity		Thin, viscous
Adhesiveness		Plastic, elastic Sticky, tacky, gooey
<i>Geometrical characteristics</i>		
Particle size and shape		Gritty, grainy, coarse
Particle shape and orientation		Fibrous, cellular, crystalline
<i>Other characteristics</i>		
Moisture content		Dry→moist→wet→watery
Fat content	Oiliness Greasiness	Oily Greasy

Adapted from Szczesniak (1963).

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Instron Universal Testing machine, which measures stress and strain forces by compression or extension. Chemical methods include measurement of starch or pectin content, and microscopic methods include electron microscopy of emulsions or the flesh structure of meat and fish. These methods are described in detail by Sherman (1979), Prentice (1984), Bourne (1978), Brennan (1984), Kramer and Szczesniak (1973), Lewis (1990) and Bourne (1982).

1.2 Material transfer

The transfer of matter is an important aspect of a large number of food processing operations: it is a key factor in solvent extraction, distillation (Chapter 13) and membrane processing (Chapter 6) and it is an important factor in loss of nutrients during blanching (Chapter 10). Mass transfer of gases and vapours is a primary factor in evaporation (Chapter 13), dehydration (Chapter 15), baking and roasting (Chapter 16), frying (Chapter 17), freeze drying (Chapter 22), the cause of freezer burn during freezing (Chapter 21) and a cause of loss in food quality in chilled, MAP and packaged foods (Chapters 19, 20 and 24, respectively).

In an analogous way to heat transfer (Section 1.4), the two factors that influence the rate of mass transfer are a driving force to move materials and a resistance to their flow. When considering dissolved solids in liquids, the driving force is a difference in the solids concentration, whereas for gases and vapours, it is a difference in partial pressure or vapour pressure. The resistance arises from the medium through which the liquid, gas or vapour moves and any interactions between the medium and the material.

An example of materials transfer is diffusion of water vapour through a boundary layer of air in operations such as dehydration, baking, etc. Packaging also creates additional boundary layers which act as barriers to movement of moisture and to heat transfer (Fig. 1.3).

The rate of diffusion is found using:

$$N_A = D_w / RT_x \cdot P_T / P_{Am} \cdot (P_{w1} - P_{w2}) \quad \boxed{1.7}$$

where N_A (kg s^{-1}) or (kmols s^{-1}) = rate of diffusion, D_w = diffusion coefficient of water vapour in air, R = the Gas Constant ($= 8.314 \text{ kJ kmol}^{-1} \text{ K}^{-1}$), T (K) = temperature, x (m) = distance across stationary layer, P_T (kNm^{-2}) = total pressure, P_{Am} (kNm^{-2}) = mean pressure of non-diffusing gas across the stationary layer and $P_{w1} - P_{w2}$ (kNm^{-2}) = water vapour pressure driving force.

Formulae for diffusion of solutes through liquids and for gases dissolving in liquids are given by Lewis (1990) and Toledo (1999).

Mass balances

The law of conservation of mass states that 'the mass of material entering a process equals the mass of material leaving'. This has applications in, for example, mixing (Chapter 5), fermentation (Chapter 7), and evaporation (Chapter 13).

In general a mass balance for a process takes the following form:

$$\text{mass of raw materials in} = \text{mass of products and wastes out} + \text{mass of stored materials} + \text{losses}$$

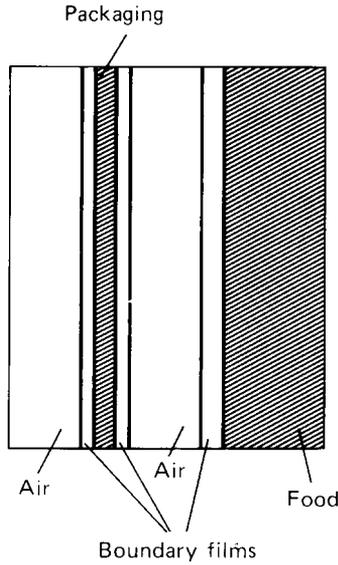


Fig. 1.3 Barriers to mass transfer and heat flow due to packaging.

Many mass balances are analysed under steady-state conditions where the mass of stored materials and losses are equal to zero. Mass balances are used to calculate the quantities of materials in different process streams, to design processes, to calculate recipe formulations, the composition after blending, process yields and separation efficiencies. A typical mass balance is shown in Fig. 1.4.

Here the total mass balance is

$$W + A = \text{moist air} + D$$

The mass balance for air is

$$A + \text{moisture} = \text{moist air}$$

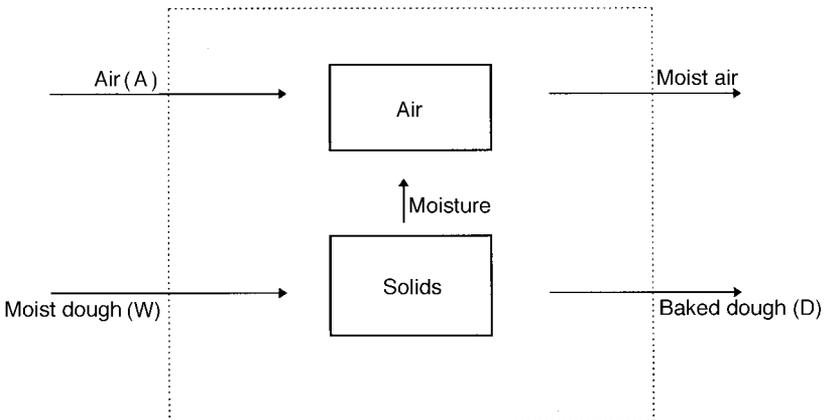


Fig. 1.4 Diagram of material flow during baking in an oven.

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The mass balance for solids is

$$W = \text{moist air} + D$$

Examples of mass balances calculations are shown in Chapter 13 (Sample problem 13.1) and Chapter 15 (Sample problem 15.2).

In applications involving concentration or dilution, the use of mass fraction or weight percentage is often used:

$$\text{Mass fraction A} = \frac{\text{mass of component A}}{\text{total mass of mixture}}$$

or

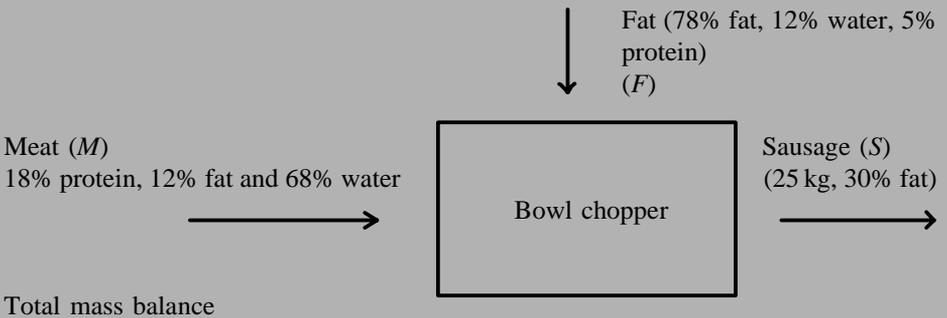
Sample problem 1.2

Calculate the total mass balance and component mass balance for mixing ingredients to make 25 kg of beef sausages having a fat content of 30%, using fresh beef meat and beef fat. Typically, beef meat contains 18% protein, 12% fat and 68% water and beef fat contains 78% fat, 12% water and 5% protein.

Solution to Sample problem 1.2

Let F = mass of beef fat (kg)

Let M = mass of beef meat (kg)



$$M + F = 25$$

Fat balance

$$0.12M + 0.78F = 0.3(25)$$

Substitute $M = 25 - F$ into the fat balance

$$0.12(25 - F) + 0.78F = 7.5$$

$$\begin{aligned} 3.0 - 0.12F + 0.78F &= 7.5 \\ &= 6.82 \text{ kg} \end{aligned}$$

and

$$\begin{aligned} M &= 25 - 6.82 \\ &= 18.18 \text{ kg} \end{aligned}$$

$$\text{Total mass of mixture} = \frac{\text{mass of component A}}{\text{mass fraction of A}}$$

If the weight of the component and its mass fraction are known, the total mass of the mixture can be calculated. Computerised recipe calculations are described in Chapter 2 (Section 2.2.1).

A simple method to calculate the relative masses of two materials that are required to form a mixture of known composition is the *Pearson Square* (Anon., 1996). If, for example, homogenised milk (3.5% fat) is to be mixed with cream (20% fat) to produce a light cream containing 10% fat, the Pearson Square (Fig. 1.5) is constructed with the fat composition of ingredients on the left side, the fat content of the product in the centre. By subtracting diagonally across the square, the resulting proportions of milk and cream can be found (i.e. 10 parts milk and 6.5 parts cream in Fig 1.5). An alternative method is to use a total balance and a fat balance (see Sample problem 1.2). Toledo (1999) describes the application of mass balances to multi-stage processing and includes a computer programme for the use of mass balances in recipe formulations. Another example of the use of a Pearson Square is shown in Sample problem 1.3.

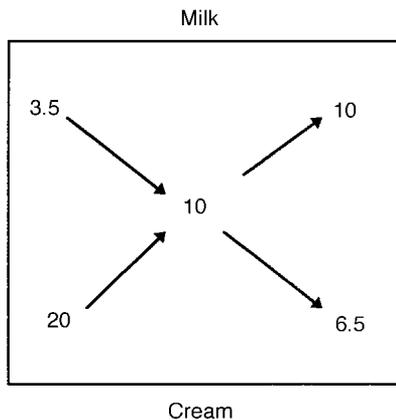


Fig. 1.5 Pearson Square.
(From Anon. (1996).)

1.3 Fluid flow

Many types of liquid food are transported through pipes during processing, and powders and small-particulate foods are more easily handled as fluids (by fluidisation). Gases obey the same laws as liquids and, for the purposes of calculations, gases are treated as compressible fluids. Properties of selected fluids are shown in Table 1.2. The study of fluids is therefore of great importance in food processing. It is divided into fluid statics (stationary fluids) and fluid dynamics (moving fluids).

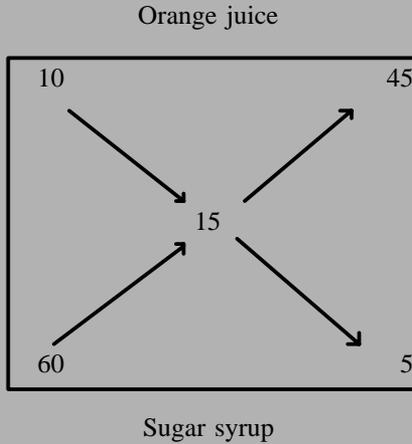
A property of static liquids is the pressure that they exert on the containing vessel. The pressure is related to the density of the liquid and the depth or the mass of liquid in the vessel. Liquids at the base of a vessel are at a higher pressure than at the surface, owing to the weight of liquid above (the *hydrostatic head*). This is important in the design of holding tanks and processing vessel, to ensure that the vessel is constructed using materials of

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Sample problem 1.3

Use a Pearson Square to calculate the amounts of orange juice (10% sugar content) and sugar syrup (60% sugar content) needed to produce 50 kg of fruit squash containing 15% sugar.

Solution to Sample problem 1.3



The result indicates that 45 kg of orange juice should be mixed with 5 kg of sugar syrup.

adequate strength. A large hydrostatic head also affects the boiling point of liquids, which is important in the design of some types of evaporation equipment (Chapter 13).

When a fluid flows through pipes or processing equipment (Fig. 1.6), there is a loss of energy and a drop in pressure which are due to frictional resistance to flow. These friction losses and changes in the potential energy, kinetic energy and pressure energy are described in detail in the food engineering texts referenced at the start of this chapter and by Loncin and Merson (1979). The loss of pressure in pipes is determined by a number of factors including the density and viscosity of the fluid, the length and diameter of the pipe and the number of bends, valves, etc., in the pipeline. To overcome this loss in energy, it is necessary to apply power using pumps to transport the fluid. The amount of power required is determined by the viscosity of the fluid (Section 1.1.2), the size of the pipework, the number of bends and fittings, and the height and distance that the fluid is to be moved.

To calculate the energy balance when a liquid flows through pipework, the effect of valves or bends on the flow rate, or the pressure developed by a pump, use is made of *Bernoulli's equation*, which is a statement of the conservation of energy.

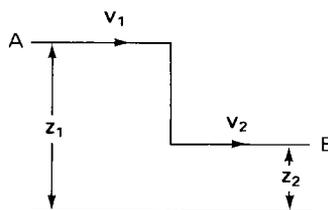


Fig 1.6 Application of Bernoulli's equation to frictionless fluid flow.

$$\frac{P_1}{\rho_1} + \frac{v_1^2}{2} = z_1 g = \frac{P_2}{\rho_2} + \frac{v_2^2}{2} + z_2 g \quad \boxed{1.8}$$

where P (Pa) = the pressure, ρ (kg m^{-3}) = the fluid density, g ($= 9.81 \text{ m s}^{-1}$) = acceleration due to gravity, v (m s^{-1}) = the velocity of the fluid and z (m) = the height. The subscript 1 indicates the first position in the pipework and the subscript 2 the second position in the pipework.

In any system in which fluids flow, there exists a *boundary film* (or surface film) of

Sample problem 1.4

A 20% sucrose solution flows from a mixing tank at 50 kPa through an horizontal pipe 5 cm in diameter at $25 \text{ m}^3 \text{ h}^{-1}$. If the pipe diameter reduces to 3 cm, calculate the new pressure in the pipe. (The density of sucrose solution is 1070 kg m^{-3} (Table 1.2).)

Solution to Sample problem 1.4

$$\begin{aligned} \text{Flow rate} &= \frac{25}{3600} \text{ m}^3 \text{ s}^{-1} \\ &= 6.94 \times 10^{-3} \text{ m}^3 \text{ s}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Area of pipe 5 cm in diameter} &= \frac{\pi}{4} D^2 \\ &= \frac{3.142}{4} (0.05)^2 \\ &= 1.96 \times 10^{-3} \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Velocity of Flow} &= \frac{6.94 \times 10^{-3}}{1.96 \times 10^{-3}} \\ &= 3.54 \text{ m s}^{-1} \end{aligned}$$

$$\text{Area of pipe 3 cm in diameter} = 7.07 \times 10^{-4} \text{ m}^2$$

$$\begin{aligned} \text{Velocity of Flow} &= \frac{6.94 \times 10^{-3}}{7.07 \times 10^{-4}} \\ &= 9.81 \text{ m s}^{-1} \end{aligned}$$

Using equation (1.8),

$$\frac{P_1}{\rho_1} + \frac{v_1^2}{2} + z_1 g = \frac{P_2}{\rho_2} + \frac{v_2^2}{2} + z_2 g$$

$$\frac{3.54^2}{2} + \frac{50 \times 10^3}{1070} + 0 = \frac{P_2}{1070} + \frac{9.81^2}{2} + 0$$

Therefore,

$$\begin{aligned} P_2 &= 56\,656 \text{ Pa} \\ &= 56.7 \text{ kPa} \end{aligned}$$

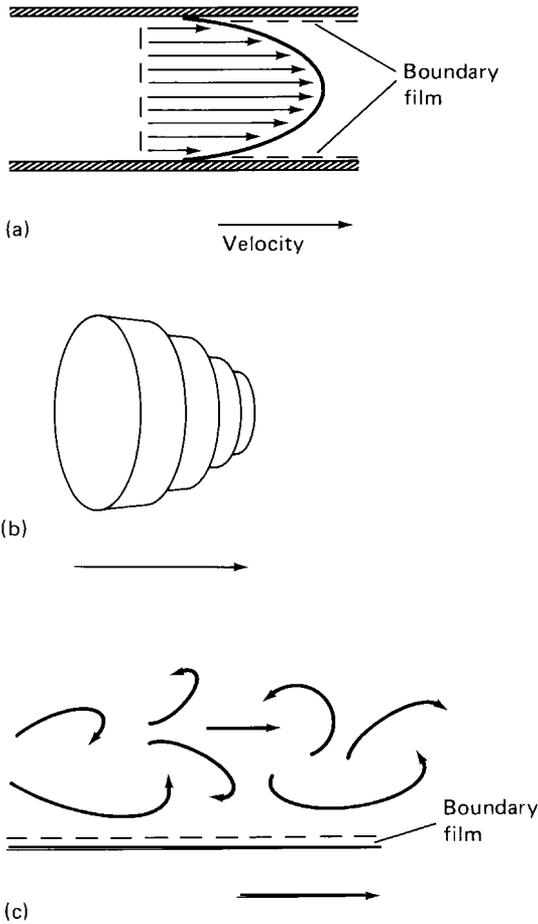


Fig. 1.7 Fluid flow: (a) velocity distribution and boundary layer; (b) streamline flow; (c) turbulent flow.

fluid next to the surface over which the fluid flows (Fig. 1.7(a)). The thickness of the boundary film is influenced by a number of factors, including the velocity, viscosity, density and temperature of the fluid. Fluids which have a low flow rate or high viscosity may be thought of as a series of layers which move over one another without mixing (Fig. 1.7(b)). This produces movement of the fluid, which is termed *streamline* (or laminar) flow. In a pipe, the velocity of the fluid is highest at the centre and zero at the pipe wall. Above a certain flow rate, which is determined by the nature of fluid and the pipe, the layers of liquid mix together and *turbulent* flow is established (Fig. 1.7 (c)) in the bulk of the fluid, although the flow remains streamline in the boundary film. Higher flowrates produce more turbulent flow and hence thinner boundary films.

Fluid flow is characterised by a dimensionless group (Appendix D) named the *Reynolds number* (Re). This is calculated using

$$\text{Re} = \frac{Dv\rho}{\mu}$$

1.9

where D (m) = the diameter of the pipe, v (m s^{-1}) = average velocity, ρ (kg m^{-3}) = fluid density and μ (N s m^{-2}) = fluid viscosity.

A Reynolds number of less than 2100 describes streamline flow and a Reynolds number of more than 4000 describes turbulent flow. For Reynolds numbers between 2100 and 4000, *transitional* flow is present, which can be either laminar or turbulent at different times. These different flow characteristics have important implications for heat transfer and mixing operations; turbulent flow produces thinner boundary layers, which in turn permit higher rates of heat transfer. The implications of this for the design and performance of equipment are discussed in Chapters 11–13 and 17 (for liquids through pipes or over metal plates) and Chapters 15, 16 and 21 (for air moving over the surface of food or metal). The Reynolds number can also be used to determine the power requirements for pumps and mixers used for blending and mixing operations (Chapter 5).

In turbulent flow, particles of fluid move in all directions and solids are retained in suspension more readily. This reduces the formation of deposits on heat exchangers and prevents solids from settling out in pipework. Streamline flow produces a larger range of residence times for individual particles flowing in a tube. This is especially important when calculating the residence time required for heat treatment of liquid foods, as it is necessary to ensure that all parts of the food receive the required amount of heat. This aspect is discussed in more detail in relation to ohmic heating (Chapter 18). Turbulent flow causes higher friction losses than streamline flow does and therefore requires higher energy inputs from pumps.

Sample problem 1.5

Two fluids, milk and rape-seed oil, are flowing along pipes of the same diameter (5 cm) at 20°C and at the same flow velocity of 3 m s⁻¹. Determine whether the flow is streamline or turbulent in each fluid. (Physical properties of milk and rape-seed oil are shown in Table 1.2.)

Solution to Sample problem 1.5

For milk from Table 1.2, $\mu = 2.10 \times 10^{-3} \text{ N s m}^{-2}$ and $\rho = 1030 \text{ kg m}^{-3}$. From equation (1.9),

$$\text{Re} = \frac{Dv\rho}{\mu}$$

Therefore,

$$\begin{aligned} \text{Re} &= \frac{0.05 \times 3 \times 1030}{2.1 \times 10^{-3}} \\ &= 73\,571 \end{aligned}$$

Thus the flow is turbulent (because Re is greater than 4000).

For rape-seed oil, from Table 1.2, $\mu = 118 \times 10^{-3} \text{ N s m}^{-2}$ and $\rho = 900 \text{ kg m}^{-3}$. Therefore

$$\begin{aligned} \text{Re} &= \frac{0.05 \times 3 \times 900}{118 \times 10^{-3}} \\ &= 1144 \end{aligned}$$

Thus the flow is streamline (because Re is less than 2100).

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1.3.1 Fluid flow through fluidised beds

When air passes upwards through a bed of food, the particles create a resistance to the flow of air and reduce the area available for it to flow through the bed. As the air velocity is increased, a point is reached where the weight of the food is just balanced by the force of the air, and the bed becomes fluidised (for example fluidised-bed drying (Chapter 15)). If the velocity is increased further, the bed becomes more open (the *voidage* is increased), until eventually the particles are conveyed in the fluid stream (for example pneumatic separation (Chapter 3), pneumatic drying (Chapter 15), or pneumatic conveying (Chapter 26)). The velocity of the air needed to achieve fluidisation of spherical particles is calculated using

$$v_f = \frac{(\rho_s - \rho)g}{\mu} \frac{d^2 \epsilon^3}{180(1 - \epsilon)} \quad (1.10)$$

where v_f (m s^{-1}) = fluidisation velocity, ρ_s (kg m^{-3}) = density of the solid particles, ρ (kg m^{-3}) = density of the fluid, g (m s^{-2}) = acceleration due to gravity, μ (N s m^{-2}) = viscosity of the fluid, d (m) = diameter of the particles, ϵ = the voidage of the bed.

Formulae for foods of other shapes are described by Kunii and Levenspiel (1969). The minimum air velocity needed to convey particles is found using

$$v_e = \sqrt{\left[\frac{4d(\rho_s - \rho)}{3C_d \rho} \right]} \quad (1.11)$$

where v_e (m s^{-1}) = minimum air velocity and C_d ($= 0.44$ for $\text{Re} = 500\text{--}200\,000$) = the drag coefficient.

Sample problem 1.6

Peas which have an average diameter of 6 mm and a density of 880 kg m^{-3} are dried in a fluidised-bed drier (Chapter 15). The minimum voidage is 0.4 and the cross-sectional area of the bed is 0.25 m^2 . Calculate the minimum air velocity needed to fluidise the bed if the air density is 0.96 kg m^{-3} and the air viscosity is $2.15 \times 10^{-5} \text{ N s m}^{-2}$.

Solution to Sample problem 1.6

From equation (1.10),

$$\begin{aligned} v_f &= \frac{(880 - 0.96)9.81 (0.006)^2 (0.4)^3}{2.15 \times 10^{-5} 180(1 - 0.4)} \\ &= 8.5 \text{ m s}^{-1} \end{aligned}$$

1.4 Heat transfer

Most unit operations in food processing involve the transfer of heat into or out of a food. There are three ways in which heat may be transferred: by radiation, by conduction and by convection. *Radiation*, which is described in detail in Chapter 18, is the transfer of heat by electromagnetic waves (see Chapter 18, Fig. 18.1), for example in an electric grill. *Conduction* is the movement of heat by direct transfer of molecular energy within solids (for example through metal containers or solid foods). *Convection* is the transfer of heat by groups of molecules that move as a result of differences in density (for example in heated

air) or as a result of agitation (for example in stirred liquids). In the majority of applications all three types of heat transfer occur simultaneously but one type may be more important than others in particular applications. Further details are given by Hayhurst (1997).

1.4.1 Energy balances

An energy balance states that 'the amount of heat or mechanical energy entering a process = the total energy leaving with the products and wastes + stored energy + energy lost to the surroundings'. If heat losses are minimised, energy losses to the surroundings may be ignored for approximate solutions to calculation of, for example, the quantity of steam, hot air or refrigerant required. For more accurate solutions, compensation should be made for heat losses.

1.4.2 Mechanisms of heat transfer

Steady-state heat transfer takes place when there is a constant temperature difference between two materials. The amount of heat entering a material equals the amount of heat leaving, and there is no change in temperature of the material. This occurs for example when heat is transferred through the wall of a cold store if the store temperature and ambient temperature are constant (Chapter 19), and in continuous processes once operating conditions have stabilised. However, in the majority of food-processing applications the temperature of the food and/or the heating or cooling medium are constantly changing, and *unsteady-state* heat transfer is more commonly found. Calculations of heat transfer under these conditions are extremely complicated but are simplified by making a number of assumptions and using prepared charts and computer models to give approximate solutions (Toledo, 1999).

Steady-state conduction

The rate at which heat is transferred by conduction is determined by the temperature difference between the food and the heating or cooling medium, and the total resistance to heat transfer. The resistance to heat transfer is expressed as the conductance of a material, or more usefully as the reciprocal which is termed the *thermal conductivity*. Thermal conductivities of some materials found in food processing are shown in Tables 1.2 and 1.5.

Under steady-state conditions the rate of heat transfer is calculated using

$$Q = \frac{kA(\theta_1 - \theta_2)}{x} \quad \boxed{1.12}$$

where Q (J s^{-1}) = rate of heat transfer, k ($\text{J m}^{-1} \text{s}^{-1} \text{K}^{-1}$ or $\text{W m}^{-1} \text{K}^{-1}$) = thermal conductivity, A (m^2) = surface area, $\theta_1 - \theta_2$ ($^{\circ}\text{C}$ or K) = temperature difference and x (m) = thickness of the material. $(\theta_1 - \theta_2)/x$ is also known as the temperature gradient.

Although, for example, stainless steel conducts heat ten times less well than aluminium (Table 1.5), the difference is small compared to the low thermal conductivity of foods (twenty to thirty times smaller than steel) and does not limit the rate of heat transfer. Stainless steel is much less reactive than other metals, particularly with acidic foods, and is therefore used in most food-processing equipment that comes into contact with foods.

The thermal conductivity of foods is influenced by a number of factors concerned with the nature of the food (for example cell structure, the amount of air trapped between the

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Table 1.5 Thermal conductivity of selected foods and other materials

Type of material	Thermal conductivity (W m ⁻¹ K ⁻¹)	Temperature of measurement (°C)
<i>Construction materials</i>		
Aluminium	220	0
Copper	388	0
Stainless steel	21	20
Other metals	45–400	0
Brick	0.69	20
Concrete	0.87	20
<i>Foods</i>		
Olive oil ^a	0.17	20
Whole milk ^a	0.56	20
Freeze-dried foods	0.01–0.04	0
Frozen beef ^b	1.30	–10
Pork (lean) ^b	0.48	3.8
Frozen cod	1.66	–10
Apple juice	0.56	20
Orange	0.41	0–15
Green beans	0.80	–12.1
Cauliflower	0.80	–6.6
Egg	0.96	–8
Ice	2.25	0
Water ^a	0.57	0
<i>Packaging materials</i>		
Cardboard	0.07	20
Glass, soda	0.52	20
Polyethylene	0.55	20
Poly(vinyl chloride)	0.29	20
<i>Insulating materials</i>		
Polystyrene foam	0.036	0
Polyurethane foam	0.026	0
Other types	0.026–0.052	30

^a Assuming convection currents are absent.

^b Heat flow parallel to fibres.

From Earle (1983), Lewis (1987) and Woodams and Nowrey (1968).

cells, and the moisture content), and the temperature and pressure of the surroundings. A reduction in moisture content causes a substantial reduction in thermal conductivity. This has important implications in unit operations which involve conduction of heat through food to remove water (for example drying (Chapter 15), frying (Chapter 17) and freeze drying (Chapter 22)). In freeze drying the reduction in atmospheric pressure also influences the thermal conductivity of the food. Ice has a higher thermal conductivity than water and this is important in determining the rate of freezing and thawing (Chapter 21). (A sample problem indicating the importance of thermal conductivity is shown in Chapter 17.)

Unsteady-state conduction

During processing, the temperature at a given point within a food depends on the rate of heating or cooling and the position in the food. The temperature therefore changes continuously. The factors that influence the temperature change are:

- the temperature of the heating medium

Table 1.6 Specific heat of selected foods and other materials

Food/material	Specific heat (kJ kg ⁻¹ K ⁻¹)	Temperature (°C)
Aluminium	0.89	20
Apples	3.59	ambient
Apples	1.88	frozen
Cod	3.76	ambient
Cod	2.05	frozen
Copper	0.38	20
Ice	2.04	0
Lamb	2.80	ambient
Lamb	1.25	frozen
Potatoes	3.43	ambient
Potatoes	1.80	frozen
Stainless steel	0.46	20
Water	4.18	15
Water vapour	2.05	100

Adapted from data of Peleg and Bagley (1983), Jowitt *et al.* (1983) and Polley *et al.* (1980).

- the thermal conductivity of the food
- the specific heat of the food.

Examples of the specific heat of foods are given in Tables 1.2 and 1.6. Thermal diffusivity is related to the thermal conductivity, specific heat and density of a food by

$$a = \frac{k}{\rho c} \tag{1.13}$$

where a (m² s⁻¹) = the thermal diffusivity, ρ (kg m⁻³) = density, c (J kg⁻¹ K⁻¹) = specific heat capacity and k (W m⁻¹ K⁻¹) = thermal conductivity.

The basic equation for unsteady-state heat transfer in a single direction (x) is

$$\frac{d\theta}{dt} = \frac{k}{\rho c} \frac{d^2\theta}{dx^2} \tag{1.14}$$

where $d\theta/dt$ = change in temperature with time.

Examples of solutions to this equation for simple shapes (for example a slab, cylinder or sphere) are described by Earle (1983), Jackson and Lamb (1981) and Loncin and Merson (1979).

Convection

When a fluid changes temperature, the resulting changes in density establish natural-convection currents. Examples include natural-circulation evaporators (Chapter 13), air movement in chest freezers (Chapter 21), and movement of liquids inside cans during sterilisation (Chapter 12). Forced convection takes place when a stirrer or fan is used to agitate the fluid. This reduces the boundary film thickness to produce higher rates of heat transfer and a more rapid temperature redistribution. Consequently, forced convection is more commonly used than natural convection in food processing. Examples of forced convection include mixers (Chapter 5), fluidised-bed driers (Chapter 15), air blast freezers (Chapter 21) and liquids pumped through heat exchangers (Chapters 11–13).

When liquids or gases are used as heating or cooling media, the rate of heat transfer from the fluid to the surface of a food is found using

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$$Q = h_s A (\theta_b - \theta_s) \quad \boxed{1.15}$$

where Q (J s^{-1}) = rate of heat transfer, A (m^2) = surface area, θ_s (K) = surface temperature, θ_b (K) = bulk fluid temperature and h_s ($\text{W m}^{-2} \text{K}^{-1}$) = surface (or film) heat transfer coefficient.

The *surface heat transfer coefficient* is a measure of the resistance to heat flow, caused by the boundary film, and is therefore equivalent to the term k/x in the conduction equation (equation 1.12) (Polley *et al.*, 1980). It is higher in turbulent flow than in streamline flow. Typical values of h_s are given in Table 1.7.

These data indicate that heat transfer through air is lower than through liquids and higher rates of heat transfer are obtained by moving air than still air. Larger heat exchangers are therefore necessary when air is used for heating (Chapters 15 and 16) or cooling (Chapters 19 and 21) compared to those needed for liquids. Condensing steam produces higher rates of heat transfer than hot water at the same temperature and the presence of air in steam reduces the rate of heat transfer. This has important implications for canning (Chapter 12) as any air in the steam lowers the temperature and hence lowers that amount of heat received by the food. Both thermometers and pressure gauges are therefore needed to assess whether steam is saturated.

The surface heat transfer coefficient is related to the physical properties of a fluid (for example density, viscosity, specific heat), gravity (which causes circulation due to changes in density), temperature difference and the length or diameter of the container under investigation. The formulae which relate these factors are expressed as dimensionless numbers (Appendix D) as follows:

$$\text{Nusselt number } \text{Nu} = \frac{h_c D}{k} \quad \boxed{1.16}$$

$$\text{Prandtl number } \text{Pr} = \frac{c_p \mu}{k} \quad \boxed{1.17}$$

$$\text{Grashof number } \text{Gr} = \frac{D^3 \rho^2 g \beta \Delta \theta}{\mu^2} \quad \boxed{1.18}$$

where h_c ($\text{W m}^{-2} \text{K}^{-1}$) = convection heat transfer coefficient at the solid-liquid interface, D (m) = the characteristic dimension (length or diameter), k ($\text{W m}^{-1} \text{K}^{-1}$) = thermal con-

Table 1.7 Values of surface heat transfer coefficients

	Surface heat transfer coefficient h_s ($\text{W m}^{-2} \text{K}^{-1}$)	Typical applications
Boiling liquids	2400–60 000	Evaporation
Condensing saturated steam	12 000	Canning, evaporation
Condensing steam		
With 3% air	3500	Canning
With 6% air	1200	
Condensing ammonia	6000	Freezing, chilling
Liquid flowing through pipes		
low viscosity	1200–6000	Pasteurisation
high viscosity	120–1200	Evaporation
Moving air (3 m s^{-1})	30	Freezing, baking
Still air	6	Cold stores

Adapted from Loncin and Merson (1979) and Earle (1983).

ductivity of the fluid, c_p ($\text{J kg}^{-1} \text{K}^{-1}$) = specific heat at constant pressure, ρ (kg m^{-3}) = density, μ (N s m^{-2}) = viscosity, g (m s^{-2}) = acceleration due to gravity, β ($\text{m m}^{-1} \text{K}^{-1}$) = coefficient of thermal expansion, $\Delta\theta$ (K) = temperature difference and v (m s^{-1}) = velocity.

For streamline flow through pipes,

$$\text{Nu} = 1.62(\text{Re Pr} \frac{D}{L})^{0.33} \quad \boxed{1.19}$$

where L (m) = length of pipe, when $\text{Re Pr } D/L > 120$ and all physical properties are measured at the mean bulk temperature of the fluid.

For turbulent flow through pipes,

$$\text{Nu} = 0.023(\text{Re})^{0.8}(\text{Pr})^n \quad \boxed{1.20}$$

where $n = 0.4$ for heating or $n = 0.3$ for cooling, when $\text{Re} > 10\,000$, viscosity is measured at the mean *film* temperature and other physical properties are measured at the mean bulk temperature of the fluid.

The Grashof number is used for natural convection when there is no turbulence in the fluid. Formulae for other types of flow conditions and different vessels are described by Loncin and Merson (1979), Jackson and Lamb (1981) and Earle (1983).

Sample problem 1.7

Whole milk is cooled in the pipes of a tubular heat exchanger from 30°C to 10°C , by water at 1°C . The pipe diameter is 5 cm and the milk flow velocity is 1.0 m s^{-1} . Calculate the heat transfer coefficient for the milk using physical properties described in Table 1.2.

Solution to Sample problem 1.7

$$\begin{aligned} \text{Mean bulk temperature} &= \frac{30 + 10}{2} \\ &= 20^\circ\text{C} \end{aligned}$$

From Table 1.2, $\rho = 1030 \text{ kg m}^{-3}$, $c = 3.9 \text{ kJ kg}^{-1} \text{K}^{-1}$ and

$$k = 0.56 \text{ W m}^{-2} \text{K}^{-1}.$$

If $\text{Re} > 10\,000$ viscosity should be measured at the mean temperature.

$$\begin{aligned} \text{Mean film temperature} &= \frac{1 + \frac{1}{2}(30 + 10)}{2} \\ &= 10.5^\circ\text{C} \end{aligned}$$

For milk at 10.5°C , $\mu = 2.8 \times 10^{-3} \text{ N s m}^{-2}$. From equation (1.9),

$$\begin{aligned} \text{Re} &= \frac{Dv\rho}{\mu} \\ &= \frac{0.05 \times 1.0 \times 1030}{2.8 \times 10^{-3}} \\ &= 18\,393 \end{aligned}$$

From equation (1.17)

$$\begin{aligned} \text{Pr} &= \frac{c_p \mu}{k} \\ &= \frac{(3.9 \times 10^3)(2.8 \times 10^{-3})}{0.56} \\ &= 19.5 \end{aligned}$$

From equations (1.16) and (1.20)

$$\begin{aligned} \text{Nu} &= \frac{h_c D}{k} \\ &= 0.023(\text{Re})^{0.8}(\text{Pr})^{0.33} \end{aligned}$$

Therefore,

$$\begin{aligned} h_c &= 0.023 \frac{k}{D} (\text{Re})^{0.8} (\text{Pr})^{0.33} \\ &= 0.023 \frac{0.56}{0.05} (18\,393)^{0.8} (19.5)^{0.33} \\ &= 1768 \text{ W m}^{-2} \text{ }^\circ\text{K}^{-1} \end{aligned}$$

Most cases of heat transfer in food processing involve heat transfer through a number of different materials. For example heat transfer in a heat exchanger from a hot fluid, through the wall of a vessel to a second fluid is shown in Fig. 1.8.

The overall temperature difference is found using

$$\theta_a - \theta_b = \frac{Q}{A} \left(\frac{1}{h_a} + \frac{x}{k} + \frac{1}{h_b} \right) \quad (1.21)$$

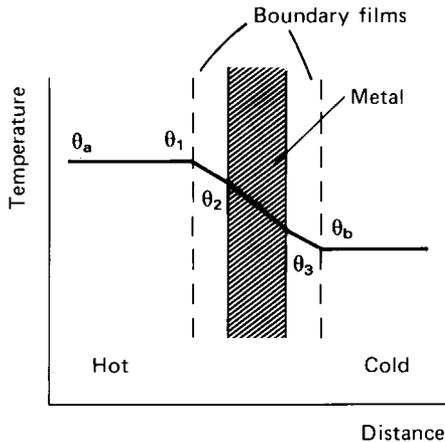


Fig. 1.8 Temperature changes from a hot liquid through a vessel wall to a cold liquid.

Table 1.8 OHTCs in food processing

Heat transfer fluids	Example	OHTC ($\text{W m}^{-2} \text{K}^{-1}$)
Hot water–air	Air heater	10–50
Viscous liquid–hot water	Jacketed vessel	100
Viscous liquid–hot water	Agitated jacketed vessel	500
Viscous liquid–steam	Evaporator	500
Non-viscous liquid–steam	Evaporator	1000–3000
Flue gas–water	Boiler	5–50
Evaporating ammonia–water	Chilled water plant	500

Adapted from Lewis (1990).

The unknown wall temperatures θ_2 and θ_3 are therefore not required and all factors to solve the equation can be measured.

The sum of the resistances to heat flow is termed the *overall heat transfer coefficient* (OHTC) U and the rate of heat transfer may then be expressed as

$$Q = UA(\theta_a - \theta_b) \tag{1.22}$$

The OHTC is an important term which is used, for example, to indicate the effectiveness of heating or cooling in different types of processing equipment. Examples are shown in Table 1.8.

Liquids can be made to flow in either the same direction or in opposite directions in a heat exchanger. Counter-current flow of fluids (Fig. 1.9) has a higher heat transfer efficiency than co-current (or ‘parallel’) flow and is therefore widely used in heat exchangers (for example Chapters 10–21). However, the temperature difference varies at different points in the heat exchanger and it is necessary to use a logarithmic mean temperature difference in calculations (equation 1.23):

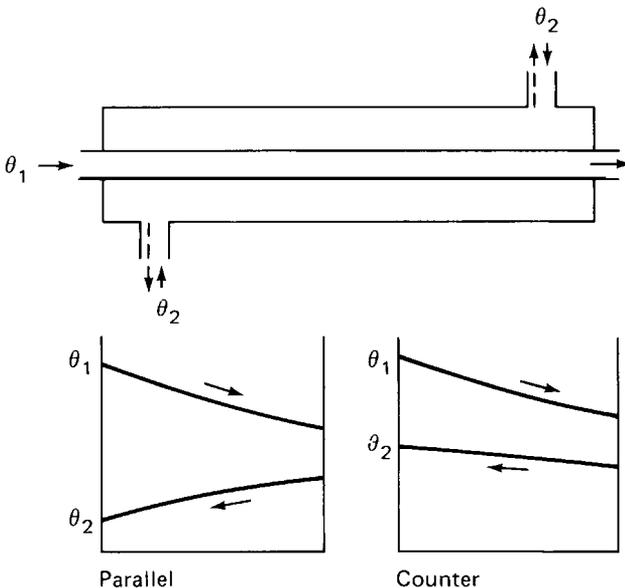


Fig. 1.9 Parallel and counter-current flow through a heat exchanger.

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$$\Delta\theta_m = \frac{\Delta\theta_1 - \Delta\theta_2}{\ln(\Delta\theta_1/\Delta\theta_2)} \quad \boxed{1.23}$$

where θ_1 is higher than θ_2 .

Related sample problems are shown in Chapters 11, 13 and 15.

The heating time in batch processing is found using

$$t = \frac{mc}{UA} \ln\left(\frac{\theta_h - \theta_i}{\theta_h - \theta_f}\right) \quad \boxed{1.24}$$

where m (kg) = the mass, c ($\text{J kg}^{-1} \text{ }^\circ\text{K}^{-1}$) = specific heat capacity, θ_h ($^\circ\text{C}$) = temperature of the heating medium, θ_i ($^\circ\text{C}$) = initial temperature, θ_f ($^\circ\text{C}$) = final temperature, A (m^2) = surface area and U ($\text{W m}^{-2} \text{ K}^{-1}$) = OHTC.

Sample problem 1.8

In the counter-current heat exchanger shown in Fig. 1.9, milk is cooled from 73°C to 38°C at the rate of 2500 kg h^{-1} , using water at 15°C which leaves the heat exchanger at 40°C . The pipework 2.5 cm in diameter is constructed from stainless steel 3 mm thick; the surface film heat transfer coefficients are $1200 \text{ W m}^{-2} \text{ K}^{-1}$ on the milk side and $3000 \text{ W m}^{-2} \text{ K}^{-1}$ on the water side of the pipe. Calculate the OHTC and the length of pipe required.

Solution to Sample problem 1.8

To find the OHTC, from equations (1.21) and (1.22),

$$\begin{aligned} \frac{1}{U} &= \frac{1}{h_a} + \frac{x}{k} + \frac{1}{h_b} \\ &= \frac{1}{1200} + \frac{3 \times 10^{-3}}{21} + \frac{1}{3000} \\ &= 1.3 \times 10^{-3} \end{aligned}$$

Therefore the OHTC is

$$U = 769.2 \text{ W m}^{-2} \text{ }^\circ\text{K}^{-1}$$

To find the length of pipe required, we proceed as follows.

From equations (1.22) and (1.23),

$$Q = UA\Delta\theta_m$$

and

$$\begin{aligned} \Delta\theta_m &= \frac{\Delta\theta_1 - \Delta\theta_2}{\ln(\Delta\theta_1/\Delta\theta_2)} \\ &= \frac{(73 - 40)/(38 - 15)}{\ln[(73 - 40)/(38 - 15)]} \\ &= 27.8^\circ\text{C} \end{aligned}$$

Now Q is the heat removed from the milk which equals $mc_p(\theta_a - \theta_b)$. From Table 1.2, $c_p = 3.9 \text{ kJ kg}^{-1} \text{ }^\circ\text{K}^{-1}$. Therefore,

$$Q = \frac{2500}{3600} (3.9 \times 10^3)(73 - 38)$$

$$= 9.48 \times 10^4 \text{ J}$$

Now the area is

$$A = \frac{Q}{U \Delta \theta_m}$$

$$= \frac{9.48 \times 10^4}{769.2 \times 27.8}$$

$$= 4.4 \text{ m}^2$$

Also

$$A = \pi DL$$

Therefore the length of pipe is

$$L = \frac{A}{\pi D}$$

$$= \frac{4.4}{3.142 \times 0.025} = 56 \text{ m}$$

Unsteady-state heat transfer by conduction and convection

When a solid piece of food is heated or cooled by a fluid, the resistances to heat transfer are the surface heat transfer coefficient and the thermal conductivity of the food. These two factors are related by the *Biot Number* Bi:

$$\text{Bi} = \frac{h\delta}{k} \quad \boxed{1.25}$$

where h ($\text{W m}^{-2} \text{K}^{-1}$) = heat transfer coefficient, δ = the characteristic 'half dimension' (e.g. radius of a sphere or cylinder, half thickness of a slab) and k ($\text{W m}^{-1} \text{K}^{-1}$) = thermal conductivity.

At small Bi values (less than 0.2) the surface film is the main resistance to heat flow and the time required to heat the solid food is found using equation (1.24), using the film heat transfer coefficient h_s instead of U . However, in most applications the thermal conductivity of the food limits the rate of heat transfer ($\text{Bi} > 0.2$). These calculations are complex, and a series of charts is available to solve the unsteady-state equations for simple shaped foods (Fig. 1.10). The charts relate the Biot number (Bi) (equation 1.25), the *temperature factor* (the fraction of the temperature change that remains to be accomplished (equation (1.26))) and the *Fourier number* Fo (a dimensionless number which relates the thermal diffusivity, the size of the piece and the time of heating or cooling (equation (1.27))).

$$\frac{\theta_h - \theta_f}{\theta_h - \theta_i} \quad \boxed{1.26}$$

where the subscript h indicates the heating medium, the subscript f the final value and the subscript i the initial value.

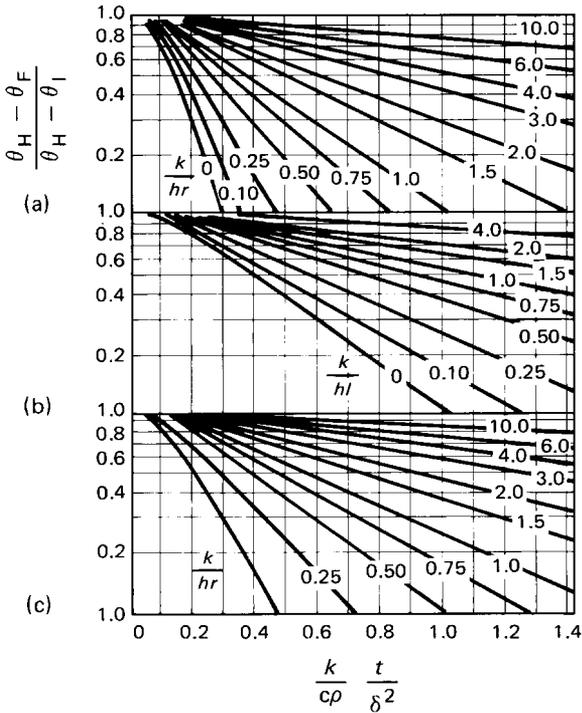


Fig. 1.10 Chart for unsteady-state heat transfer: (a) sphere; (b) slab; (c) cylinder.
(After Henderson and Perry (1955).)

$$Fo = \frac{k}{c\rho} \frac{t}{\delta^2}$$

1.27

Examples of unsteady-state calculations are shown below and in Chapter 19. More complex calculations are described by Lewis (1990), Earle (1983) and Jackson and Lamb (1981).

Sample problem 1.9

Peas which have an average diameter of 6 mm are blanched to give a temperature of 85°C at the centre. The initial temperature of the peas is 15°C and the temperature of the blancher water is 95°C. Calculate the time required, assuming that the heat transfer coefficient is 1200 W m⁻² K⁻¹ and, for peas, the thermal conductivity is 0.35 W m⁻¹ K⁻¹, the specific heat is 3.3 KJ kg⁻¹ K⁻¹, and the density is 980 kg m⁻³.

Solution to Sample problem 1.9

From equation (1.25),

$$\begin{aligned} Bi &= \frac{h\delta}{k} \\ &= \frac{1200(3 \times 10^{-3})}{0.35} \\ &= 10.3 \end{aligned}$$

Therefore,

$$\frac{k}{h\delta} = 0.097$$

From equation (1.26),

$$\begin{aligned}\frac{\theta_h - \theta_f}{\theta_h - \theta_i} &= \frac{95 - 85}{95 - 15} \\ &= 0.125\end{aligned}$$

From the chart for a sphere (Fig. 1.10), $Fo = 0.32$. From equation (1.27),

$$\begin{aligned}Fo &= \frac{k t}{c\rho\delta^2} \\ &= 0.32\end{aligned}$$

Therefore,

$$\begin{aligned}\text{time } t &= 0.32 \frac{c\rho\delta^2}{k} \\ &= \frac{0.32(3.3 \times 10^3)980(3 \times 10^{-3})^2}{0.35} \\ &= 26.6 \text{ s}\end{aligned}$$

1.4.3 Sources of heat and methods of application to foods

The cost of energy for heating has become one of the major considerations in the selection of processing methods and ultimately in the cost of the processed food and the profitability of the operation. Different fuels have specific advantages and limitations in terms of cost, safety, risk of contamination of the food, flexibility of use, and capital and operating costs for heat transfer equipment. The following sources of energy are used in food processing:

- electricity
- gas (natural and liquid petroleum gas)
- liquid fuel oil.

Solid fuels (anthracite, coal, wood and charcoal) are only used to a small extent. The advantages and limitations of each type of energy source are shown in Table 1.9.

Direct heating methods

In direct methods the heat and products of combustion from the burning fuel come directly into contact with the food. There is an obvious risk of contamination of the food by odours or incompletely burned fuel and, for this reason, only gas and, to a lesser extent, liquid fuels are used. Applications include kiln driers (Chapter 15) and baking ovens (Chapter 16). These direct methods should not be confused with 'direct' steam injection where the steam is produced in a separate location from the processing plant. Electricity is not a fuel in the same sense as the other types described above. It is generated by steam turbines heated by a primary fuel (for example coal or fuel oil) or by hydro-power or nuclear fission. However, electrical energy is also said to be used directly in dielectric heating or microwave heating (Chapter 18).

Table 1.9 Advantages and limitations of different energy sources for food processing

	Electricity	Gas	Liquid fuel	Solid fuel
Energy per unit mass or volume	Not applicable	Low ^a	High ^b	Moderate to high ^c
Cost per kilojoule of energy	High	Low	Low	Low
Heat transfer equipment cost	Low	Low	High	High
Efficiency of heating ^d	High	Moderate to high	Moderate to low	Low
Flexibility of use	High	High	Low	Low
Fire or explosion hazard	Low	High	Low	Low
Risk of food contamination	Low	Low	High	High
Labour and handling costs	Low	Low	Low	High

^a Heating value for gas is $1.17 \times 10^3 - 4.78 \times 10^3$ kJ kg⁻¹.

^b Heating value for oil is $8.6 \times 10^3 - 9.3 \times 10^3$ kJ kg⁻¹.

^c Heating value for coal is $5.26 \times 10^3 - 6.7 \times 10^3$ kJ kg⁻¹ and for wood is $3.8 \times 10^3 - 5.26 \times 10^3$ kJ kg⁻¹.

^d Efficiency defined as the amount of energy used to heat the product divided by the amount of energy supplied. Data compiled from Farrall (1979) and Whitman *et al.* (1981).

Indirect methods

Indirect cooling of foods is described in Chapters 19 and 21. Indirect heating methods employ a heat exchanger to separate the food from the products of combustion. At its simplest an indirect system consists of burning fuel beneath a metal plate and heating by energy radiated from the plate. The most common type of indirect-heating system used in food processing is steam or hot water generated by a heat exchanger (a boiler) located away from the processing area. A second heat exchanger transfers the heat from the steam to the food under controlled conditions or the steam is injected into the food. A variation on this system involves an additional heat exchanger which transfers heat from the steam to air in order to dry foods or to heat them under dry conditions. The advantages of steam for process heating, and a description of equipment for producing and handling different types of steam, are given by Farrall (1979). Properties of steam are discussed by Brennan *et al.* (1990) and Toledo (1999) and the temperatures of saturated steam are shown in Chapter 12 (Table 12.6).

Indirect electrical heating uses resistance heaters or infrared heaters. Resistance heaters are nickel-chromium wires contained in solid plates or coils, which are attached to the walls of vessels, in flexible jackets which wrap around vessels, or in immersion heaters which are submerged in the food. These types of heater are used for localised or intermittent heating. Infrared heaters are described in Chapter 18.

1.4.4 Energy conservation

A survey of food industries within the European Union found large variations in energy consumption in different types of processing; flour milling has the lowest energy input (586 MJ per tonne of product) and cocoa and chocolate processing the highest (8335 MJ per tonne of product) (Whitman *et al.*, 1981). A comparison of energy inputs in different types of potato processing is shown in Table 1.10.

In all types of food processing, most of the energy (58%; range, 40–80%) is used for actual processing, but significant amounts are also used for packaging (11%; range, 15–40%), transport (12%; range, 0.56–30%), cleaning water (15%) and storage (up to 85% of total energy input for deep-frozen foods). Boiler fuel accounts for 8.6–97.2% of the total

Table 1.10 Comparative energy inputs in potato processing

	Energy input (MJ t ⁻¹)				
	Hot air dried	Freeze dried	Canned	Retort pouched	Frozen
Processing	8	42	6	4	5
Packaging	1	2	14	7	7
Storage	0.1	0.1	0.1	0.1	32
(Home)	0	0	0	0	(24)
Transport	2	2	8	8	8
Total	11	46	28	19	52

Reported in Kelford (1982).

energy input to a factory, but boiler utilisation averages only 45%, owing to the practice of keeping the boiler on low heat during periods of low production rates (for example evening and night shifts). In addition an average of only half of the condensate is returned to the boiler and the heat contained in the condensate is therefore wasted. On average 40% of the heat lost from factories is contained in vapours and steam and a further 10–20% is lost in hot water (Whitman *et al.*, 1981).

It is clear from this and other data (for example Kefford, 1982), that potentially the main energy savings in food processing are associated with boiler operation, the supply of steam or hot air, and re-use of waste heat. An *energy audit* is used to identify specific areas and equipment within a factory where energy savings can be made (Boardman, 1986). In summary, boiler operation is improved by:

- returning condensate as feed water
- pre-heating air for combustion of fuel
- insulating the boiler
- recovering heat from the flue.

Computer control of boiler operation is described by Wells and Swientek (1983). Energy savings in steam supply to processing areas are achieved by:

- proper insulation of steam and hot-water pipes
- minimising steam leaks
- fitting steam traps.

Individual processing equipment is designed for energy saving. Examples include regeneration of heat in heat exchangers (Delashmit *et al.*, 1983) (examples in Chapters 10, 11, 16 and 17), multiple-effect or vapour recompression systems (Chapter 13) and automatic defrosting and correct insulation of freezing equipment (Chapters 19–21). Microprocessor control of processing equipment (Chapter 2) is widely used to reduce energy consumption. Recovery of heat from drying air is more difficult than from steam or vapours because air is not recompressible. However, a number of heat exchanger designs are used to recover waste heat from air or gases (for example the ‘thermal wheel’ in Fig. 1.11).

Commercial applications of this equipment are described in Chapter 15 (baking ovens) and Chapter 16 (deep-fat fryers). If the humidity of air is reduced, it is reheated more economically. The ‘rotaire wheel’ (Fig. 1.12) and heat pump are examples of dehumidifying equipment. Heat pumps are similar to refrigeration plant (see Chapter 19, Fig. 19.1) but operate by removing heat from a low-temperature source and using it to heat air or water. The application of heat pumps to low-temperature drying of

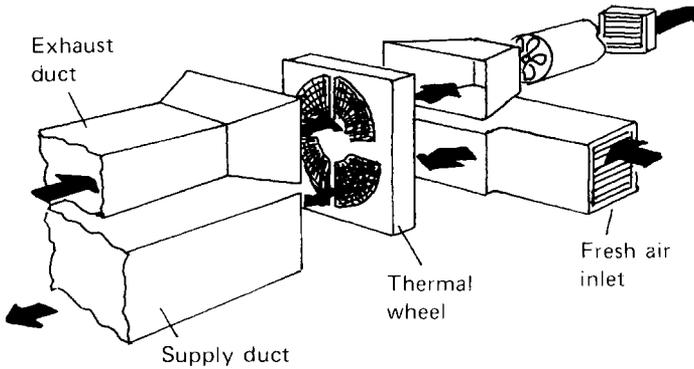


Fig. 1.11 Thermal wheel (Courtesy of the Electricity Council.)

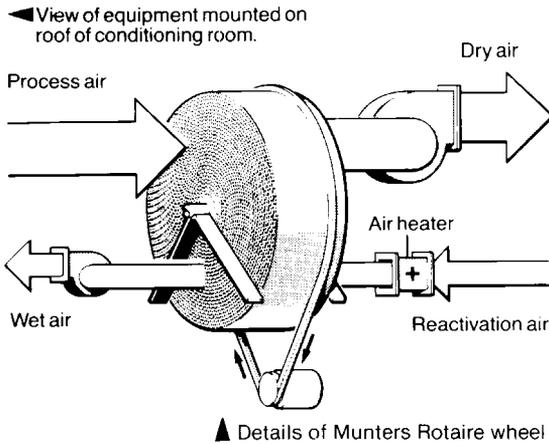


Fig 1.12 Rotaire wheel (Courtesy of the Electricity Council.)

confectionery is described by Anon. (1983a, b, c). The use of air knives for package drying is described by Anon. (1983d) and Beevers (1985). Other energy-saving techniques during dehydration are described by Senhaji and Bimbenet (1984), Flink (1977) and Green (1982).

1.4.5 Effect of heat on micro-organisms

The preservative effect of heat processing is due to the denaturation of proteins, which destroys enzyme activity and enzyme-controlled metabolism in micro-organisms. The rate of destruction is a first-order reaction; that is when food is heated to a temperature that is high enough to destroy contaminating micro-organisms, the same percentage die in a given time interval regardless of the numbers present initially. This is known as the *logarithmic order of death* and is described by a *death rate curve* (Fig. 1.13).

The time needed to destroy 90% of the micro-organisms (to reduce their numbers by a factor of 10) is referred to as the *decimal reduction time* or *D value* (5 min in Fig. 1.13). *D* values differ for different microbial species (Table 1.11), and a higher *D* value indicates greater heat resistance.

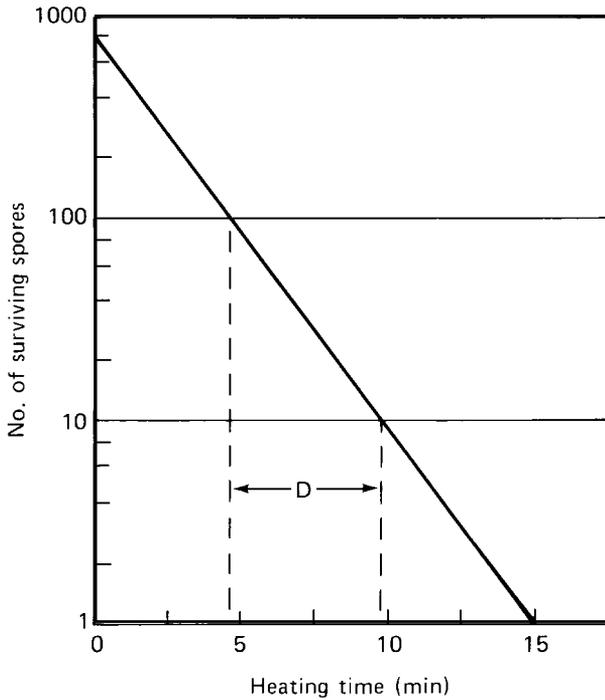


Fig. 1.13 Death rate curve.

Table 1.11 Thermal properties of selected nutritional and sensory components of foods in relation to heat-resistant enzymes and bacteria

Component	Source	pH	z (°C)	D_{121} (min)	Temperature range (°C)
Thiamin	Carrot purée	5.9	25	158	109–149
Thiamin	Pea purée	Natural	27	247	121–138
Thiamin	Lamb purée	6.2	25	120	109–149
Lysine	Soya bean meal	–	21	786	100–127
Chlorophyll a	Spinach	6.5	51	13.0	127–149
Chlorophyll a	Spinach	Natural	45	34.1	100–130
Chlorophyll b	Spinach	5.5	79	14.7	127–149
Chlorophyll b	Spinach	Natural	59	48	100–130
Anthocyanin	Grape juice	Natural	23.2	17.8*	20–121
Betanin	Beetroot juice	5.0	58.9	46.6*	50–100
Carotenoids	Paprika	Natural	18.9	0.038*	52–65
Peroxidase	Peas	Natural	37.2	3.0	110–138
Peroxidase	Various	–	28–44	–	–
<i>Clostridium botulinum</i> spores type A + B	Various	>4.5	5.5–10	0.1–0.3*	104
<i>Bacillus stercorophilus</i>	Various	>4.5	7–12	4.0–5.0	110+

* D values at temperatures other than 121°C.

Adapted from Felliciotti and Esselen (1957), Taira *et al.* (1966), Gupta *et al.* (1964), Ponting *et al.* (1960), von Elbe *et al.* (1974), Adams and Yawger (1961), Esselen and Anderson (1956) and Stumbo (1973).

There are two important implications arising from the decimal reduction time: first, the higher the number of micro-organisms present in a raw material, the longer it takes to reduce the numbers to a specified level. In commercial operation the number of micro-organisms varies in each batch of raw material, but it is difficult to recalculate process times for each batch of food. A specific temperature–time combination is therefore used to process every batch of a particular product, and adequate preparation procedures (Chapter 3) are used to ensure that the raw material has a satisfactory and uniform microbiological quality. Second, because microbial destruction takes place logarithmically, it is theoretically possible to destroy all cells only after heating for an infinite time. Processing therefore aims to reduce the number of surviving micro-organisms by a pre-determined amount. This gives rise to the concept of *commercial sterility*, which is discussed further in Chapters 10–12.

The destruction of micro-organisms is temperature dependent; cells die more rapidly at higher temperatures. By collating D values at different temperatures, a *thermal death time* (TDT) curve is constructed (Fig. 1.14). The slope of the TDT curve is termed the z value and is defined as the number of degrees Celsius required to bring about a ten-fold change in decimal reduction time (10.5°C in Fig. 1.14). The D value and z value are used to characterise the heat resistance of a micro-organism and its temperature dependence respectively.

There are a large number of factors which determine the heat resistance of micro-organisms, but general statements of the effect of a given variable on heat resistance are not always possible. The following factors are known to be important.

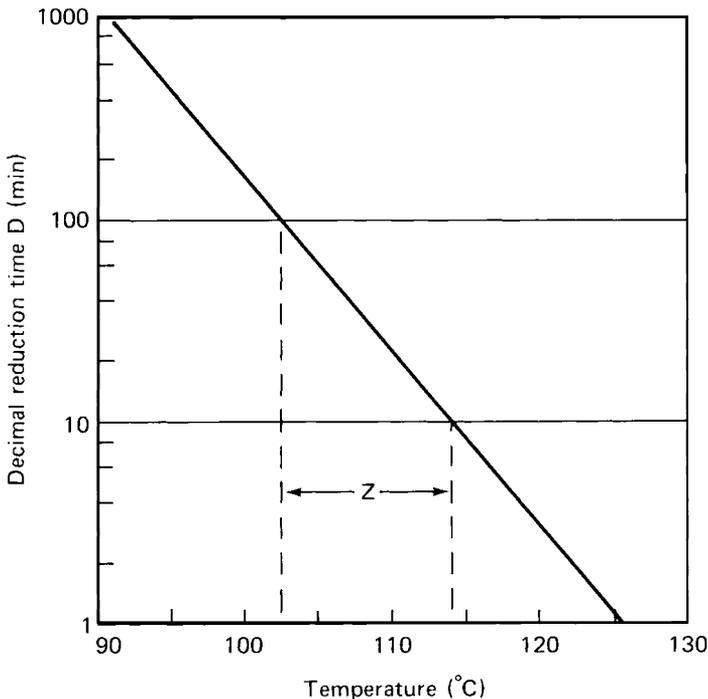


Fig. 1.14 TDT curve. Microbial destruction is faster at higher temperatures (for example 100 min at 102.5°C has the same lethal effect as 10 min at 113°C).

1. *Type of micro-organism.* Different species and strains show wide variation in their heat resistance (Table 1.11). Spores are much more heat resistant than vegetative cells.
2. *Incubation conditions* during cell growth or spore formation. These include:
 - (a) temperature (spores produced at higher temperatures are more resistant than those produced at lower temperatures)
 - (b) age of the culture (the stage of growth of vegetative cells affects their heat resistance)
 - (c) culture medium used (for example mineral salts and fatty acids influence the heat resistance of spores).
3. *Conditions during heat treatment.* The important conditions are:
 - (a) pH of the food (pathogenic and spoilage bacteria are more heat resistant near to neutrality; yeasts and fungi are able to tolerate more acidic conditions but are less heat resistant than bacterial spores)
 - (b) water activity of the food (section 1.5) influences the heat resistance of vegetative cells; in addition moist heat is more effective than dry heat for spore destruction
 - (c) composition of the food (proteins, fats and high concentration of sucrose increase the heat resistance of micro-organisms; the low concentration of sodium chloride used in most foods does not have a significant effect; the physical state of the food, particularly the presence of colloids, affects the heat resistance of vegetative cells)
 - (d) the growth media and incubation conditions, used to assess recovery of micro-organisms in heat resistance studies, affect the number of survivors observed.

Most enzymes have D and z values within a similar range to micro-organisms, and are therefore inactivated during normal heat processing. However, some enzymes are very heat resistant. These are particularly important in acidic foods, where they may not be completely denatured by the relatively short heat treatments and lower temperatures required for microbial destruction. The factors which influence heat resistance of enzymes are similar to those described for micro-organisms and are discussed in detail by Whitaker (1972).

A knowledge of the heat resistance of the enzymes and/or micro-organisms found in a specific food is used to calculate the heating conditions needed for their destruction. In practice the most heat resistant enzyme or micro-organism likely to be present in a given food is used as a basis for calculating process conditions. It is assumed that other less heat-resistant species are also destroyed. Methods for the calculation of processing time are described in Chapter 12.

1.4.6 Effect of heat on nutritional and sensory characteristics

The destruction of many vitamins, aroma compounds and pigments by heat follows a similar first-order reaction to microbial destruction. Examples of D and z values of selected vitamins and pigments are shown in Table 1.11. In general both values are higher than those of micro-organisms and enzymes. As a result, nutritional and sensory properties are better retained by the use of higher temperatures and shorter times during heat processing. It is therefore possible to select particular time-temperature combinations from a TDT curve (all of which achieve the same degree of enzyme or microbial destruction), to optimise a process for nutrient retention or preservation of desirable sensory qualities. This

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concept forms the basis of individual quick blanching (Chapter 10), high-temperature short-time (HTST) pasteurisation (Chapter 11), ultrahigh-temperature sterilisation (Chapter 12) and HTST extrusion (Chapter 14). The loss of nutrients and changes to sensory quality during heat processing are reported in Chapters 10–18.

1.5 Water activity

Deterioration of foods by micro-organisms can take place rapidly, whereas enzymic and chemical reactions take place more slowly during storage. In either case the water content is a very important factor controlling the rate of deterioration. The moisture content of foods can be expressed either on a wet-weight basis:

$$m = \frac{\text{mass of water}}{\text{mass of sample}} \times 100 \quad \boxed{1.28}$$

$$m = \frac{\text{mass of water}}{\text{mass of water} + \text{solids}} \times 100 \quad \boxed{1.29}$$

or on a dry-weight basis

$$m = \frac{\text{mass of water}}{\text{mass of solids}} \quad \boxed{1.30}$$

(Lewis, 1990).

The dry-weight basis is more commonly used for processing calculations, whereas the wet-weight basis is frequently quoted in food composition tables. It is important, however, to note which system is used when expressing a result. Wet-weight basis is used throughout this text unless otherwise stated.

A knowledge of the moisture content alone is not sufficient to predict the stability of foods. Some foods are unstable at a low moisture content (for example peanut oil deteriorates if the moisture content exceeds 0.6%), whereas other foods are stable at relatively high moisture contents (for example potato starch is stable at 20% moisture) (van den Berg, 1986). It is the *availability* of water for microbial, enzymic or chemical activity that determines the shelf life of a food, and this is measured by the water activity (a_w) of a food, also known as the Relative Vapour Pressure (RVP).

Examples of unit operations that reduce the availability of water in foods include those that physically remove water (dehydration (Chapter 15), evaporation (Chapter 13) and freeze drying or freeze concentration (Chapter 22)) and those that immobilise water in the food (for example by the use of humectants in ‘intermediate-moisture’ foods and by formation of ice crystals in freezing (Chapter 21)). Examples of the moisture content and a_w of foods are shown in Table 1.12 and the effect of reduced a_w on food stability is shown in Table 1.13.

Water in food exerts a vapour pressure. The size of the vapour pressure depends on:

- the amount of water present
- the temperature
- the concentration of dissolved solutes (particularly salts and sugars) in the water.

Water activity is defined as ‘the ratio of the vapour pressure of water in a food to the saturated vapour pressure of water at the same temperature’ (equation 1.31):

Table 1.12 Moisture content and water activity of foods

Food	Moisture content (%)	Water activity	Degree of protection required
Ice (0°C)	100	1.00 ^a	
Fresh meat	70	0.985	
Bread	40	0.96	Package to prevent moisture loss
Ice (-10°C)	100	0.91 ^a	
Marmalade	35	0.86	
Ice (-20°C)	100	0.82 ^a	
Wheat flour	14.5	0.72	
Ice (-50°C)	100	0.62 ^a	Minimum protection or no packaging required
Raisins	27	0.60	
Macaroni	10	0.45	
Cocoa powder		0.40	
Boiled sweets	3.0	0.30	
Biscuits	5.0	0.20	Package to prevent moisture uptake
Dried milk	3.5	0.11	
Potato crisps	1.5	0.08	

^a Vapour pressure of ice divided by vapour pressure of water.

Adapted from Troller and Christian (1978), van den Berg (1986) and Brenndorfer *et al.* (1985).

Table 1.13 The importance of water activity in foods

a_w	Phenomenon	Examples
1.00		Highly perishable fresh foods
0.95	<i>Pseudomonas</i> , <i>Bacillus</i> , <i>Clostridium perfringens</i> and some yeasts inhibited	Foods with 40% sucrose or 7% salt, cooked sausages, bread
0.90	Lower limit for bacterial growth (general), <i>Salmonella</i> , <i>Vibrio parahaemolyticus</i> , <i>Clostridium botulinum</i> , <i>Lactobacillus</i> , and some yeasts and fungi inhibited	Foods with 55% sucrose, 12% salt, cured ham, medium-age chesse. Intermediate-moisture foods ($a_w = 0.90 - 0.55$)
0.85	Many yeasts inhibited	Foods with 65% sucrose, 15% salt, salami, mature cheese, margarine
0.80	Lower limit for most enzyme activity and growth of most fungi; <i>Staphylococcus aureus</i> inhibited	Flour, rice (15–17% water) fruit cake, sweetened condensed milk, fruit syrups, fondant
0.75	Lower limit for halophilic bacteria	Marzipan (15–17% water), jams
0.70	Lower limit for growth of most xerophilic fungi	
0.65	Maximum velocity of Maillard reactions	Rolled oats (10% water), fudge, molasses, nuts
0.60	Lower limit for growth of osmophilic or xerophilic yeasts and fungi	Dried fruits (15–20% water), toffees, caramels (8% water), honey
0.55	Deoxyribonucleic acid becomes disordered (lower limit for life to continue)	
0.50		Dried foods ($a_w = 0-0.55$), spices, noodles
0.40	Minimum oxidation velocity	Whole egg powder (5% water)
0.30		Crackers, bread crusts (3–5% water)
0.25	Maximum heat resistance of bacterial spores	
0.20		Whole milk powder (2–3% water), dried vegetables (5% water), cornflakes (5% water)

$$a_w = \frac{P}{P_0} \quad (1.31)$$

where P (Pa) = vapour pressure of the food, P_0 (Pa) = vapour pressure of pure water at the same temperature. a_w is related to the moisture content by a number of equations, including the following:

$$\frac{a_w}{M(1 - a_w)} = \frac{1}{M_1 C} + \frac{C - 1}{M_1 C} a_w \quad (1.32)$$

where a_w = water activity, M = moisture as percentage dry weight, M_1 = moisture (dry-weight basis) of a monomolecular layer and C = a constant. A sample calculation is described by Karel (1975).

A proportion of the total water in a food is strongly bound to specific sites (for example hydroxyl groups of polysaccharides, carbonyl and amino groups of proteins, and hydrogen bonding). When all sites are (statistically) occupied by adsorbed water the moisture content is termed the *BET* (Brunauer–Emmett–Teller) *monolayer* value (Fennema, 1996). Typical examples include gelatin (11%), starch (11%), amorphous lactose (6%) and whole spray-dried milk (3%). The BET monolayer value therefore represents the moisture content at which the food is most stable. At moisture contents below this level, there is a higher rate of lipid oxidation and, at higher moisture contents, Maillard browning and then enzymic and microbiological activities are promoted (Fig. 1.15).

The movement of water vapour from a food to the surrounding air depends upon both the food (moisture content and composition) and the condition of the air (temperature and humidity). At a constant temperature, the moisture content of food changes until it comes into equilibrium with water vapour in the surrounding air. The food then neither gains nor loses weight on storage under those conditions. This is called the *equilibrium moisture content* of the food and the relative humidity of the storage atmosphere is known as the *equilibrium relative humidity*. When different values of relative humidity versus equilibrium moisture content are plotted, a curve known as a *water sorption isotherm* is obtained (Fig. 1.16).

Each food has a unique set of sorption isotherms at different temperatures. The precise shape of the sorption isotherm is caused by differences in the physical structure, chemical composition and extent of water binding within the food, but all sorption isotherms have a characteristic shape, similar to that shown in Fig. 1.16. The first part of the curve, to point A, represents monolayer water, which is very stable, unfreezable and not removed by drying. The second, relatively straight part of the curve (AB) represents water adsorbed in multilayers within the food and solutions of soluble components. The third portion, (above point B) is 'free' water condensed within the capillary structure or in the cells of a food. It is mechanically trapped within the food and held by only weak forces. It is easily removed by drying and easily frozen, as indicated by the steepness of the curve. Free water is available for microbial growth and enzyme activity, and a food which has a moisture content above point B on the curve is likely to be susceptible to spoilage.

The sorption isotherm indicates the a_w at which a food is stable and allows predictions of the effect of changes in moisture content on a_w and hence on storage stability. It is used to determine the rate and extent of drying (Chapter 15), the optimum frozen storage temperatures (Chapter 21) and the moisture barrier properties required in packaging materials (Chapter 24).

The rate of change in a_w on a sorption isotherm differs according to whether moisture is removed from a food (*desorption*) or whether it is added to dry food (*absorption*) (Fig. 1.16). This is termed a *hysteresis loop*. The difference is large in some foods (for example

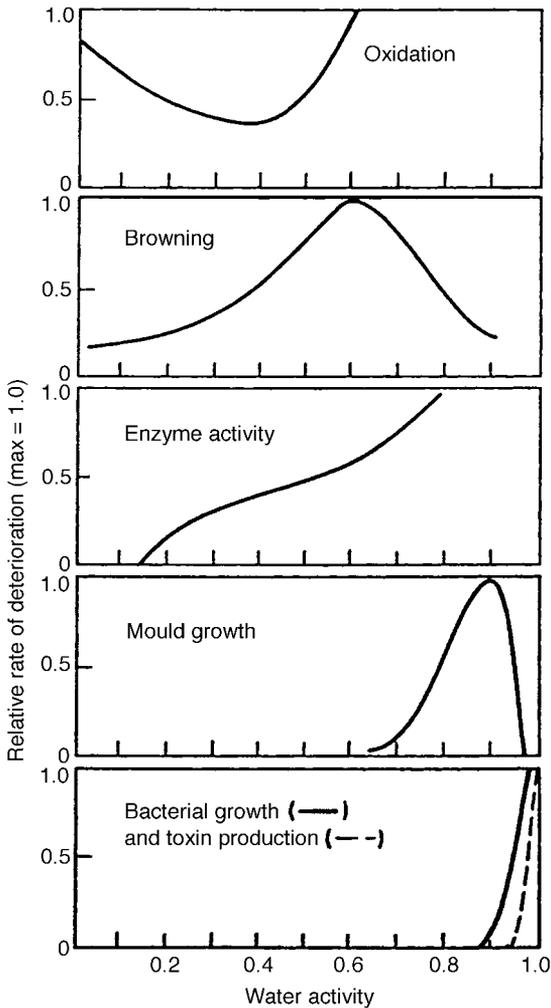


Fig. 1.15 Effect of water activity on microbial, enzymic and chemical changes to foods. (After Karel (1975).)

rice) and is important for example in determining the protection required against moisture uptake.

1.5.1 Effect of a_w on foods

The effect of a_w on microbiological and selected biochemical reactions is shown in Fig. 1.15 and Table 1.13. Almost all microbial activity is inhibited below $a_w = 0.6$, most fungi are inhibited below $a_w = 0.7$, most yeasts are inhibited below $a_w = 0.8$ and most bacteria below $a_w = 0.9$. The interaction of a_w with temperature, pH, oxygen and carbon dioxide, or chemical preservatives has an important effect on the inhibition of microbial growth. When any one of the other environmental conditions is sub-optimal for a given micro-organism, the effect of reduced a_w is enhanced. This permits the combination of several mild control mechanisms which result in the preservation of food without substantial loss of nutritional value or sensory characteristics (Table 1.14) (see also the 'Hurdle effect' in Section 1.8.2).

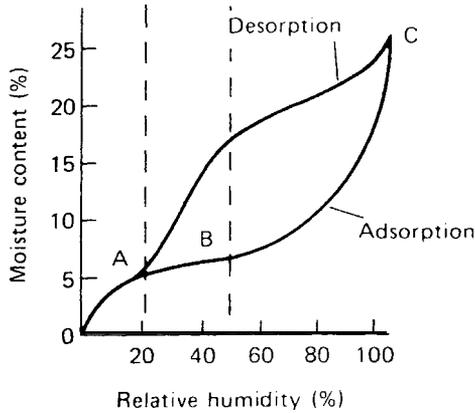


Fig. 1.16 Water sorption isotherm.

Table 1.14 Interaction of a_w , pH and temperature in selected foods

Food	pH	a_w	Shelf life	Notes
Fresh meat	>4.5	>0.95	days	Preserve by chilling
Cooked meat	>4.5	0.95	weeks	Ambient storage when packaged
Dry sausage	>4.5	<0.90	months	Preserved by salt and low a_w
Fresh vegetables	>4.5	>0.95	weeks	'Stable' while respiring
Pickles	<4.5	0.90	months	Low pH maintained by packaging
Bread	>4.5	>0.95	days	
Fruit cake	>4.5	<0.90	weeks	Preserved by heat and low a_w
Milk	>4.5	>0.95	days	Preserved by chilling
Yoghurt	<4.5	<0.95	weeks	Preserved by low pH and chilling
Dried milk	>4.5	<0.90	months	Preserved by low a_w

Enzymic activity virtually ceases at a_w values below the BET monolayer value. This is due to the low substrate mobility and its inability to diffuse to the reactive site on the enzyme. Chemical changes are more complex. The two most important that occur in foods which have a low a_w are Maillard browning and oxidation of lipids. The a_w that causes the maximum rate of browning varies with different foods. However, in general, a low a_w restricts the mobility of the reactants and browning is reduced. At a higher a_w , browning reaches a maximum. Water is a product of the condensation reaction in browning and, at higher moisture levels, browning is slowed by 'end product inhibition'. At high moisture contents, water dilutes the reactants and the rate of browning falls.

Oxidation of lipids occurs at low a_w values owing to the action of free radicals. Above the BET monolayer value, anti-oxidants and chelating agents (which sequester trace metal catalysts) become soluble and reduce the rate of oxidation. At higher a_w values the catalytic activity of metals is reduced by hydration and the formation of insoluble hydroxides but, at high a_w values, metal catalysts become soluble, and the structure of the food swells to expose more reactive sites (Fig. 1.15).

1.6 Effects of processing on the sensory characteristics of foods

There are a number of definitions of 'quality' of foods, which are discussed by Cardello (1998). To the consumer, the most important quality attributes of a food are its sensory

characteristics (texture, flavour, aroma, shape and colour). These determine an individual's preference for specific products, and small differences between brands of similar products can have a substantial influence on acceptability. A continuing aim of food manufacturers is to find improvements in processing technology which retain or create desirable sensory qualities or reduce the damage to food caused by processing. Examples of such improvements are described in subsequent chapters.

1.6.1 Texture

The texture of foods is mostly determined by the moisture and fat contents, and the types and amounts of structural carbohydrates (cellulose, starches and pectic materials) and proteins that are present. Changes in texture are caused by loss of moisture or fat, formation or breakdown of emulsions and gels, hydrolysis of polymeric carbohydrates, and coagulation or hydrolysis of proteins. Detailed information on the textural characteristics of food is given by Mohsenin (1980), Lewis (1990) and Szczesniak (1983). The effect of food composition and structure on texture is described by Stanley and Tung (1976) and Sherman (1976).

1.6.2 Taste, flavour and aroma

Taste attributes consist of saltiness, sweetness, bitterness and acidity and some of these attributes can be detected in very low thresholds in foods (Table 1.15). The taste of foods is largely determined by the formulation used for a particular food and is mostly unaffected by processing. Exceptions to this include increased sweetness due to

Table 1.15 Detection thresholds for common food components

Compound	Taste or odour	Threshold
<i>Taste compounds</i>		
Hydrochloric acid	Sour	0.0009 N
Citric acid	Sour	0.0016 N
Lactic acid	Sour	0.0023 N
Sodium chloride	Salty	0.01 M
Potassium chloride	Bitter/salty	0.017 M
Sucrose	Sweet	0.01 M
Glucose	Sweet	0.08 M
Sodium saccharine	Sweet	0.000023 M
Quinine sulphate	Bitter	0.000008 M
Caffeine	Bitter	0.0007 M
<i>Odour compounds</i>		
Citral	Lemon	0.000003 mg/l
Limonene	Lemon	0.1 mg/l
Butyric acid	Rancid butter	0.009 mg/l
Benzaldehyde	Bitter almond	0.003 mg/l
Ethyl acetate	Fruity	0.0036 mg/l
Methyl salicylate	Wintergreen	0.1 mg/l
Hydrogen sulphide	Rotten eggs	0.00018 mg/l
Amyl acetate	Banana oil	0.039 mg/l
Safrol	Sassafras	0.005 mg/l
Ethyl mercaptan	Rotten cabbage	0.00000066 mg/l

From Cardello (1998).

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respiratory changes in fresh foods (Chapter 19) and changes in acidity or sweetness during food fermentations (Chapter 7). Fresh foods contain complex mixtures of volatile compounds, which give characteristic flavours and aromas, some of which are detectable at extremely low concentrations (Table 1.15). These compounds may be lost during processing, which reduces the intensity of flavour or reveals other flavour/aroma compounds. Volatile aroma compounds are also produced by the action of heat, ionising radiation, oxidation or enzyme activity on proteins, fats and carbohydrates. Examples include the Maillard reaction between amino acids and reducing sugars or carbonyl groups and the products of lipid degradation (Chapter 16), or hydrolysis of lipids to fatty acids and subsequent conversion to aldehydes, esters and alcohols. The perceived aroma of foods arises from complex combinations of many hundreds of compounds, some of which act synergistically (Maruniak and MacKay-Sim, 1984). In addition, the perceived flavour of foods is influenced by the rate at which flavour compounds are released during chewing, and hence is closely associated with the texture of foods and the rate of breakdown of food structure during mastication (Clark, 1990). Research into flavour release is described by Wyeth and Kilcast (1991) and Plattig (1984) and more detailed descriptions of the production of aroma compounds or loss of naturally occurring aroma compounds are given by Lindsay (1996) and in subsequent chapters.

1.6.3 Colour

Methods to assess the colour and appearance of foods are described by MacDougall (1984). Many naturally occurring pigments are destroyed by heat processing, chemically altered by changes in pH or oxidised during storage (Table 1.16). As a result the processed food may lose its characteristic colour and hence its value. Synthetic pigments (Appendix C) are more stable to heat, light and changes in pH, and they are therefore added to retain the colour of some processed foods. Details of changes to naturally occurring pigments are described in Chapters 10–17. Maillard browning is an important cause of both desirable changes in food colour (for example in baking or frying (Chapters 16 and 17), and in the development of off-colours (for example during canning and drying (Chapters 12 and 15)).

1.7 Effects of processing on nutritional properties

Many unit operations, especially those that do not involve heat, have little or no effect on the nutritional quality of foods. Examples include mixing, cleaning, sorting, freeze drying and pasteurisation. Unit operations that intentionally separate the components of foods (Chapters 3, 4 and 6) alter the nutritional quality of each fraction compared with the raw material. Unintentional separation of water-soluble nutrients (minerals, water-soluble vitamins and sugars) also occurs in some unit operations (for example blanching (Chapter 10), and in drip losses from roast or frozen foods (Chapters 16 and 21)).

Heat processing is a major cause of changes to nutritional properties of foods. For example gelatinisation of starches and coagulation of proteins improve their digestibility, and anti-nutritional compounds (for example a trypsin inhibitor in legumes) are destroyed. However, heat also destroys some types of heat-labile vitamin (Fig. 1.17), reduces the biological value of proteins (owing to destruction of amino acids or Maillard browning reactions) and promotes lipid oxidation. The effects of heat on proteins and lipids are described in detail by Mauron (1982) and Witting and Dimick (1982) respectively.

Table 1.16 Naturally occurring pigments in foods

Pigment	Typical source	Oil or water soluble	Stability to the following			
			Heat	Light	Oxygen	pH change
Anthocyanins	Fruits	Water soluble	High	High	High	Low
Betalaines	Beetroot	Water soluble	Moderate	High	High	High
Bixin	Seed coat of <i>Bixa orellana</i>	Oil soluble	Moderate to low	Low	High	–
Canxanthin		Oil soluble	Moderate	Moderate	Moderate	Moderate
Caramel	Heated sugar	Water soluble	High	High	High	High
Carotenes	Leaves	Oil soluble	Moderate to low	Low	Low	High
Chlorophylls	Leaves	Water soluble	High	High	High	Low
Cochineal ^a	Insect (<i>Dactylopius coccus</i>)	Water soluble	High	High	–	Moderate to high
Curcumin	Turmeric	Water soluble	Low	Low	Low	–
Norbixin	See Bixin	Water soluble	Moderate to low	Low	High	–
Oxymyoglobin	Animals	Water soluble	Low	–	High	Low
Polyphenols	Tea leaf	Water soluble	High	High	High	High
Quinones	Roots, bark	Water soluble	High	Moderate	–	Moderate
Xanthophylls	Fruits	Water soluble	Moderate	High	High	Low

^a As aluminium lake.

From the data of Zapsalis and Beck (1985) and Coultate (1984).

Oxidation is a second important cause of nutritional changes to foods. This occurs when food is exposed to air (for example in size reduction or hot-air drying (Chapters 4 and 15)) or as a result of the action of heat or oxidative enzymes (for example peroxidase or lipoxygenase). The main nutritional effects of oxidation are:

- the degeneration of lipids to hydroperoxides and subsequent reactions to form a wide variety of carbonyl compounds, hydroxy compounds and short chain fatty acids, and in frying oils to toxic compounds (Chapter 17)
- the destruction of oxygen-sensitive vitamins (Fig. 1.17 and Appendix A).

Changes to lipids are discussed by Zapsalis and Beck (1985) and a discussion of the properties of vitamins and losses during processing is given by Bender (1978), Harris and Karmas (1975) and De Ritter (1982). Examples of vitamin losses caused by individual unit operations are described in subsequent chapters.

The importance of nutrient losses during processing depends on the nutritional value of a particular food in the diet. Some foods (for example bread, potatoes and milk in Western countries and rice or maize in Eastern and developing countries) are an

A	D	E	K	C	B complex and pantothenic acid
Destroyed by ultraviolet and air	Increase in ultraviolet	Destroyed by rancid fat	Very stable	Destroyed by air, enzymes, ultraviolet, iron and copper	—
Stable to heat, not normally affected by heat processing				Unstable to heat	More heat stable
				Leached out, destroyed by alkalis, stable in acid	

Fig. 1.17 Stability of vitamins in foods.

important source of nutrients for large numbers of people. Vitamin losses are therefore more significant in these foods than in those which either are eaten in small quantities or have low concentrations of nutrients.

In industrialised countries, the majority of the population achieve an adequate supply of nutrients from the mixture of foods that is eaten. Losses due to processing of one component of the diet are therefore insignificant to the long-term health of an individual. In an example described by Bender (1987), complete meals which initially contained 16.5 µg of vitamin A lost 50% on canning and 100% after storage for 18 months. Although the losses appear to be significant, the original meal contained only 2% of the recommended daily intake (RDA), and the extent of loss is therefore of minor importance. The same meal contained 9 mg of thiamin and lost 75% after 18 months' storage. The thiamin content is ten times the RDA, and adequate quantities therefore remained. Possible exceptions are the special dietary needs of pre-term infants, pregnant women and the elderly. In these groups there may be either a special need for certain nutrients or a more restricted diet than normal. These special cases are discussed in detail by Watson (1986) and Francis (1986).

Reported vitamin losses during processing are included in subsequent chapters to give an indication of the severity of each unit operation. However, such data should be treated with caution. Variation in nutrient losses between cultivars or varieties can exceed differences caused by alternative methods of processing. Growth conditions, or handling and preparation procedures prior to processing, also cause substantial variation in nutrient loss. Data on nutritional changes cannot be directly applied to individual commercial operations, because of differences in ingredients, processing conditions and equipment used by different manufacturers.

1.8 Food safety, good manufacturing practice and quality assurance

Traditionally, quality control systems were based on the inspection of a product at various points within a process, and rejection of any product that did not meet agreed standards. This reactive approach to food quality focused mainly on end-product testing, which is now recognised to be a waste of resources (resources have already been spent on producing the food by the time it is tested and rejection means a financial loss). A more proactive preventative approach to food safety and quality management, termed 'Quality Assurance' was developed during the 1980s, based on the principles of Good Manufacturing Practice (GMP) (Anon., 1998). It aimed to ensure that quality and safety

are maintained throughout a process and thus prevent product rejection and financial losses.

The pressures for this development came from two sources: first, commercial pressures including:

- increasing competition between companies
- the need to access expanding national and international food markets
- product quality management systems required by major retailers.

These all required an effective food monitoring and control system to control resources and ensure that safe, high quality products were consistently manufactured, and led to the concept of Total Quality Management (TQM). Second, new legislation demanded systems that would both maintain quality and safety, and prove that a business is in control of these. The initial quality assurance legislation (BS 5750/BS EN ISO 9000 standards) has now been expanded to take all business operations into account. The aim of TQM is therefore for companies to define and understand *all* of their processes, to implement controls, monitor performance and measure improvements. The standard BS 7850 defines TQM as ‘management philosophy and company practices that aim to harness the human and material resources of an organisation in the most effective way to achieve the objectives of the organisation’. This concept takes into account separate standards for production operations and new product development (BS EN ISO 9001), production facilities (BS EN ISO 9002), environmental and waste management (ISO 14001, also Chapter 26), employment rights, health and safety (BS 8800), laboratory management (EN 45000) as well as food quality and safety.

As part of a TQM programme, food manufacturers must also take into account the requirements of a food safety management system termed ‘HACCP’ (Hazard Analysis Critical Control Point), which was developed by Codex Alimentarius. This provides the key control measures needed to understand the mechanisms for producing safe food and the basis to create production control systems to ensure product quality. A major shift in emphasis from national legislation to international legislation occurred in 1994, when a GATT² agreement recommended acceptance of HACCP as the required standard for free international movement of food. The WTO now evaluates both technical barriers to trade and sanitary controls with reference to Codex HACCP standards (Mitchell, 1996).

More recently in the UK, the British Retail Consortium has issued a ‘Technical Standard for Companies Supplying Retailer Branded Food Products’, which is being used by retailers as the definitive standard for suppliers, and forms the basis of their terms of business (Rose, 2000). It covers six key areas: HACCP systems, quality management systems, factory environmental standards, product control, process control and personnel, and is implemented through third-party inspection bodies (e.g. the European Food Safety Inspection Service (EFSIS)).

TQM is therefore broader than quality control, and is a management philosophy that seeks to continually improve the effectiveness and competitiveness of the business as a whole. It is an integrated system which ensures that all areas of the business are controlled, to enable customers to consistently receive quality products that meet their needs and expectations. The approach requires collective responsibility and commitment at all levels in a business, and can only be achieved through trusting working relationships and good communications. Quality management systems are usually developed with reference to an international standard or specific legislative standards

2. General Agreement on Tariffs and Trade, later replaced by the World Trade Organisation (WTO).

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(e.g. 91/493 European standard for fisheries products). However, any reference standard is only a framework on which a company builds its own performance standards to meet the requirements of the law, the customers and the company's own requirements.

In outline, a TQM system covers the following areas:

- raw materials, purchasing and control (including agreed specifications, supplier auditing, raw material storage, stock control, traceability, inspection, investigation of non-conformity to specification)
- process control (including identification, verification and monitoring of critical control points in a HACCP scheme, hygienic design of plant and layouts to minimise cross-contamination, cleaning schedules, recording of critical production data, sampling procedures and contingency plans to cover safety issues)
- premises (including methods of construction to minimise contamination, maintenance, waste disposal)
- quality control (including product specifications and quality standards for non-safety quality issues, monitoring and verification of quality before distribution)
- personnel (including training, personal hygiene, clothing and medical screening)
- final product (including types and levels of inspection to determine conformity with quality specifications, isolating non-conforming products, packaging checks, inspection records, complaints monitoring systems)
- distribution (to maintain the product integrity throughout the chain, batch traceability and product recall systems).

Mann and Adebajo (1997) and Rose (2000) have produced overviews of TQM, and Dillon (1999) describes a practical approach to beginning TQM projects in smaller businesses.

A TQM system requires a company to have a level of organisation and management that enables it to meet the TQM objectives and this requires the company to:

- have a defined organisational structure
- clearly allocate authority and division of responsibilities
- define procedures
- link the components of the system
- prepare key documentation
- allocate sufficient resources for implementation of the system (Dillon and Griffith, 1996).

Rose (2000) has emphasised the need for commitment by senior management to implementation of a TQM system and the need for senior managers to review and update the effectiveness of systems that are in place. The component procedures for introducing a quality management system include:

- development of audit methods
- procedures for corrective action
- procedures for management review and
- documentation of the system.

Effective implementation requires the combined use of all resources, including people, and Dillon (1996) has emphasised that many systems fail because inadequate attention is paid to the staff who will implement the system. *Audits* are the regular systematic collection and feedback of objective information by competent independent personnel. They are used for example to monitor suppliers' ability to meet agreed

requirements or to monitor production routines. They are an effective tool for monitoring the success of a quality system and are described in detail by Sayle (1998), Mortimer and Wallace (1998) and Dillon and Griffith (1997). The types of *non-conformance* with specifications, performance standards, customer requirements or legislation for a particular operation in a factory department must be clearly defined and appropriate action agreed if a failure occurs. For example, if deviation is a legal issue, the appropriate action is to quarantine the product, or if it is deviation from a customer requirement, the action may involve informing customer and sale at reduced price.

Management review is an essential component of any system and managers must consider the feedback from the system and decide on appropriate action, using formal meetings with standard agendas, actions and responsibilities. The need to manage information by *document control* ensures that documents are approved, issued and stored in agreed places in filing cabinets, computer diskettes or hard drives or on CD. Agreed reference codes, directory structures, storage procedures, archiving instructions and backup mechanisms are essential. There is a hierarchy of documents, from manuals outlining policy, procedures that link key activities, detailed work instructions and output records which requires an organisation to prove that a system gives the necessary control. Document control rules therefore need to be agreed and put in place early in the development of a control system. Procedures for *corrective action* are needed to prevent a recurrence of any deficiencies within the system.

The benefits of a properly implemented TQM system are stated by Rose (2000) as:

- economic (more cost-effective production by 'getting it right first time', reduction in wasted materials, fewer customer complaints, improved machine efficiency and increased manufacturing capacity)
- marketing (consistently meeting customer needs, increased customer confidence and sales)
- internal (improved staff morale, increased levels of communication, better trained staff and awareness/commitment to quality, improved management control and confidence in the operation)
- legislative (demonstrating due diligence, providing evidence of commitment to quality and ability to improve).

1.8.1 HACCP

Hazard analysis is 'the identification of potentially hazardous ingredients, storage conditions, packaging, critical process points and relevant human factors which may affect product safety or quality'. HACCP enables potential hazards in a process to be identified, assessed, and controlled or eliminated. It sets tolerances for hazards and defines appropriate control measures, the frequency of their application, sampling procedures, specific tests to be used and the criteria for product acceptance. The system is based on monitoring of *critical control points*³ and the action to be taken when results of monitoring are outside the pre-set limits (Fig 1.18). HACCP is used throughout each stage of a process, and includes raw materials, processing, storage and distribution. It can be used for all potential hazards, including inadequate quality as well as safety, and can

3. These are processing factors of which a loss of control would result in an unacceptable food safety or quality risk.

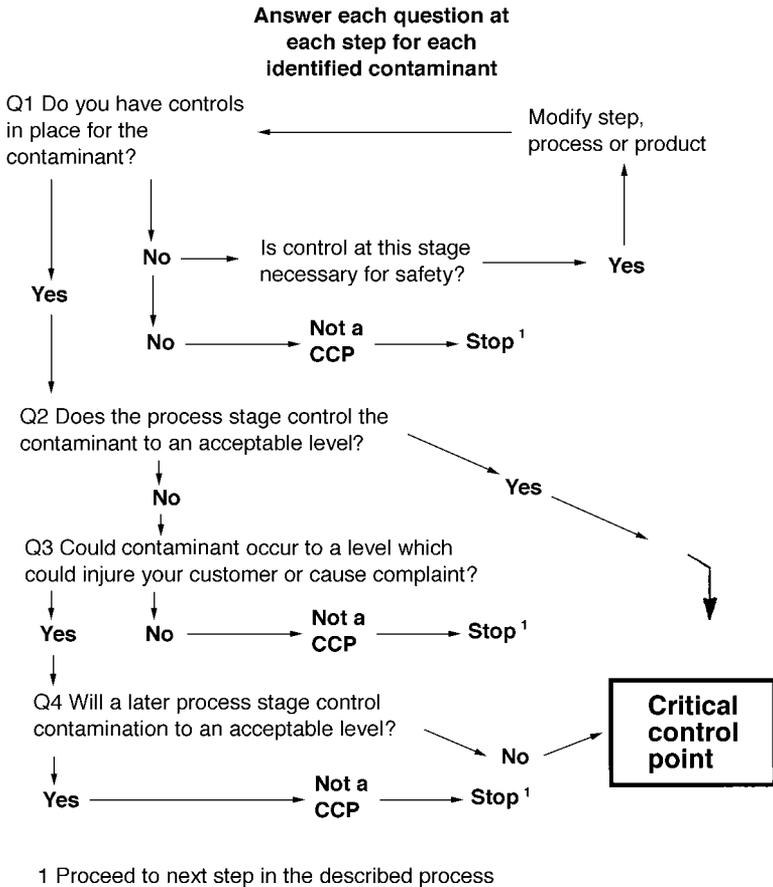


Fig. 1.18 Critical control point decision tree.
(From Fellows *et al.* (1995).)

identify areas of control where failure has not yet been experienced, making it particularly useful for new operations.

Implementation of a HACCP scheme involves the following stages:

1. Produce a detailed flow diagram of the process, including production methods and schedules, preparation and transport of raw materials, in-process stock etc., confirmed by a site visit.
2. Identify the essential characteristics of the product and its use and define the hazards or potential hazards that could threaten the consumer or the product. Included in this is the product formulation, handling procedures and storage conditions, packaging, expected customer handling and the target consumer groups.
3. Consider all stages in the process, including realistic process deviations, and identify critical stages (critical control points (CCPs)) which must be controlled to assure safety. The judgement of risk is made using one of three methods: probabilistic, comparative or pragmatic, and should be made by people who have a high degree of expertise and experience.
4. Devise target levels and critical limits for each CCP and produce effective procedures to monitor them, to verify them and to implement corrective action.

Monitoring may be by physical, microbiological or chemical tests, or by visual or sensory observations. All monitoring procedures should be recorded and they should also include the location of the CCP, the frequency of monitoring and satisfactory compliance criteria. Examples include cleaning procedures (what is cleaned, how and when it is cleaned, who cleans it and what with), temperatures of foods, processing conditions, recipe formulations, hygienic practices, opportunities for cross-contamination and workers' illness or infections.

5. Establish documentation to record the HACCP system and the procedures needed to review it.

Examples of HACCP applications are described by Dillon and Griffith (1996), Mortimer and Wallace (1998) and Fellows *et al.* (1995).

1.8.2 Hurdle technology

In traditionally preserved foods, such as smoked fish or meat, jams and other preserves, there are a combination of factors that ensure microbiological safety and stability of the food, and thus enable it to be preserved. In smoked products for example, this combination includes heat, reduced moisture content and anti-microbial chemicals deposited from the smoke onto the surface of the food. Some smoked foods may also be dipped or soaked in brine or rubbed with salt before smoking, to impregnate the flesh with salt and thus add a further preservative mechanism. Smoked products may also be chilled or packed in modified atmospheres to further extend the shelf life. In jams and other fruit preserves, the combined factors are heat, a high solids content (reduced water activity (Section 1.5)), and high acidity. These preservative factors also strongly influence the sensory characteristics of the product and contribute to important differences in flavour, texture or colour between different products. In vegetable fermentation (Chapter 7), the desired product quality and microbial stability are achieved by a sequence of factors that arise at different stages in the fermentation process: the addition of salt selects the initial microbial population which uses up the available oxygen in the brine. This reduces the redox potential and inhibits the growth of aerobic spoilage micro-organisms and favours the selection of lactic acid bacteria. These then acidify the product and stabilise it. Further treatments may include pasteurisation (Chapter 11) and packaging (Chapter 24) to extend the shelf life and facilitate distribution.

The demand by consumers for high quality foods having 'fresh' or 'natural' characteristics, that require a minimum amount of preparation has led to the development of ready-to-eat and convenience foods that are preserved using mild technologies. The main preservation technique is refrigeration (Chapter 19), but because of the difficulty in maintaining sufficiently low temperatures throughout the production, distribution and storage chain, additional barriers (or 'hurdles') are required to control the growth of spoilage or pathogenic micro-organisms. The concept of combining several factors to preserve foods has been developed by Leistner (1995) and others into the *Hurdle effect* (each factor is a hurdle that micro-organisms must overcome). This in turn has led to the application of Hurdle Technology,⁴ where an understanding of the complex interactions of temperature, water activity, pH, chemical preservatives, etc. (Table 1.17) is used to design a series of hurdles that ensure microbiological safety of processed foods. The

4. Also known as 'combined processes', 'combination preservation' or 'combination techniques'.

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Table 1.17 Examples of hurdles used to preserve foods

Type of hurdle	Examples	Chapter
Physical hurdles	Aseptic packaging	12, 25
	Electromagnetic energy (microwave, radio frequency, pulsed magnetic fields, high electric fields)	9, 18
	High temperatures (blanching, pasteurisation, sterilisation, evaporation, extrusion, baking, frying)	10–17
	Ionising radiation	8
	Low temperatures (chilling, freezing)	19, 21
	Modified atmospheres	20
	Packaging films (including active packaging, edible coatings)	24
	Photodynamic inactivation	9
	Ultra-high pressures	9
	Ultrasonication	9
Ultraviolet radiation	9	
Physico-chemical hurdles	Carbon dioxide	20
	Ethanol	7
	Lactic acid	7
	Lactoperoxidase	7
	Low pH	
	Low redox potential	
	Low water activity	15–16, 22
	Maillard reaction products	1, 16
	Organic acids	7
	Oxygen	
	Ozone	
	Phenols	
	Phosphates	
	Salt	
	Smoking	
	Sodium nitrite/nitrate	
Sodium or potassium sulphite		
Spices and herbs		
Surface treatment agents		
Microbially derived hurdles	Antibiotics	7
	Bacteriocins	7
	Competitive flora	
	Protective cultures	

Chapter numbers indicate sources of more detailed information.

Adapted from Leistner and Gorris (1995).

hurdles are also used to improve the quality of foods and the economic properties (for example, the weight of water that can be added to a food, consistent with its microbial stability). To be successful, the hurdles must take into account the initial numbers and types of micro-organisms that are likely to be present in the food. The hurdles that are selected should be ‘high enough’ so that the anticipated numbers of these micro-organisms cannot overcome them. However, the same hurdles that satisfactorily preserve a food when it is properly prepared (Fig. 1.19a), are overcome by a larger initial population of micro-organisms (Fig. 1.19b), when for example raw materials are not adequately cleaned (Chapter 3). In this example, the main hurdles are low water activity and chemical preservatives in the product, with storage temperature, pH and redox potential having a smaller effect. Blanching vegetables or fruits (Chapter 10) has a similar effect in reducing initial numbers of micro-organisms before freezing or drying. If

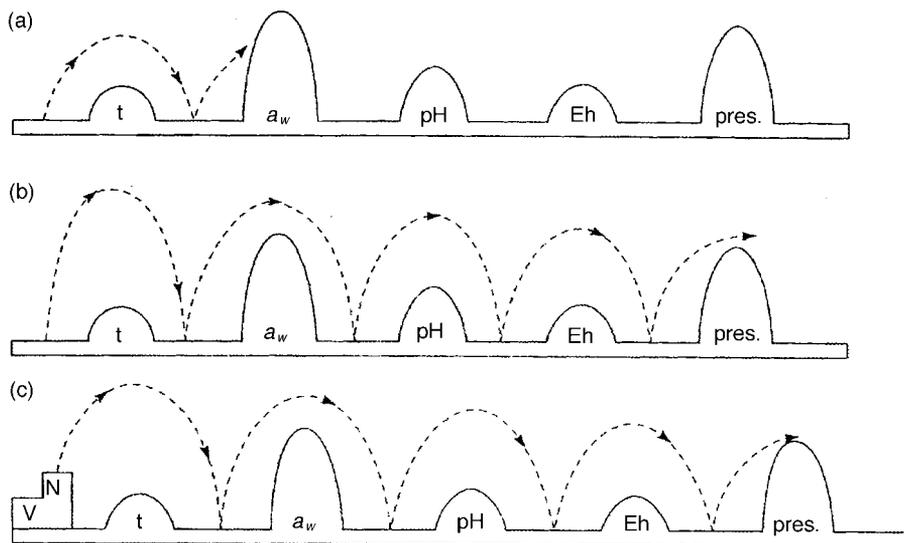


Fig. 1.19 Examples of hurdles in food processing.

(t = chilling, a_w = low water activity, pH = acidification, Eh = low redox potential, pres. = preservatives, V = vitamins, N = nutrients.) (Adapted from Leistner and Gorris (1995).)

in Fig 1.19, the same hurdles are used with a different product that is richer in nutrients that can support microbial growth (Fig. 1.19c), again the hurdles may be inadequate to preserve it and a different combination may be needed or the height of the hurdles increased. It should be noted that although the hurdles in Fig. 1.19 are represented as a sequence, in practice the different factors may operate simultaneously, synergistically or sequentially.

The combination of hurdle technology and HACCP in process design is described by Leistner (1994). By combining hurdles, the intensity of individual preservation techniques can be kept comparatively low to minimise loss of product quality, while overall there is a high impact on controlling microbial growth. Examples of novel mild processes that retain product quality are described in Chapter 9 ('minimal' processes), Chapter 18 (ohmic heating) and Chapters 19 and 20 (sous-vide cooking and modified atmospheres).

1.9 Acknowledgements

Grateful acknowledgement is made for information supplied by the Electricity Council, London SW1P 4RD, UK.

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2

Process control

The purpose of process control is to reduce the variability in final products so that legislative requirements and consumers' expectations of product quality and safety are met. It also aims to reduce wastage and production costs by improving the efficiency of processing. Simple control methods (for example, reading thermometers, noting liquid levels in tanks, adjusting valves to control the rate of heating or filling), have always been in place, but they have grown more sophisticated as the scale and complexity of processing has increased. With increased mechanisation, more valves need to be opened and more motors started or stopped. The timing and sequencing of these activities has become more critical and any errors by operators has led to more serious quality loss and financial consequences. This has caused a move away from controls based on the operators' skill and judgement to technology-based control systems. Initially, manually operated valves were replaced by electric or pneumatic operation and switches for motors were relocated onto control panels. Measurements of process variables, such as levels of liquids in tanks, pressures, pH, temperatures, etc., were no longer taken at the site of equipment, but were sent by transmitters to control panels and gradually processes became more automated.

The changes in process control technology over the past decade have been more widespread than at any other time and more influential than in any other area of food processing. Automatic control has been developed and applied in almost every sector of the industry. The impetus for these changes has come from:

- increased competition that forces manufacturers to produce a wider variety of products more quickly
- escalating labour costs and raw material costs
- increasingly stringent regulations that have resulted from increasing consumer demands for standardised, safe foods and international harmonisation of legislation and standards.

For some products, new laws require monitoring, reporting and traceability of all batches produced (Atkinson, 1997) which has further increased the need for more sophisticated process control.

All of these requirements have caused manufacturers to upgrade the effectiveness of their process control and management systems. Advances in microelectronics and developments in computer software technology, together with the steady reduction in the cost of computing power, have led to the development of very fast data processing. This has in turn led to efficient, sophisticated, interlinked, more operator-friendly and affordable process control systems being made available to manufacturers. These developments are now used at all stages in a manufacturing process, including:

- ordering and supplying raw materials
- detailed production planning and supervision
- management of orders, recipes and batches
- controlling the flow of product through the process
- controlling process conditions
- evaluation of process and product data (for example, monitoring temperature profiles during heat processing (Chapter 12) or chilling (Chapter 19))
- control of cleaning-in-place procedures (Chapter 26)
- packaging, warehouse storage and distribution.

In supermarkets, bar-code readers are used to automatically re-order stocks from manufacturers using Electronic Data Interchange (EDI). The manufacturer is then able to schedule production and order stocks automatically using Just-In-Time (JIT) and Material Resource Planning (MRP) software (Wallin, 1994). Individual processing machines are routinely fitted with powerful microprocessors, to monitor and control their operation, the product quality and energy consumption.

In this chapter, the principles of process control and automation, with selected examples of equipment, are described. Details of mathematical models used in computer control of canning, aseptic processing, evaporation, fermentation and dehydration are described by Teixeira and Shoemaker (1989). Aspects of the use of computers in management are discussed by Hamilton (1985), Sidebottom (1986), Pyle and Zarov (1997) and Marien (1987), and the stages used to implement a control system are described by Kirk (1987). Other examples of computer control are reported by Hollingsworth (1994), Bimbelet (1986), Shore (1988), Perry *et al.* (1983) (refrigeration), Green (1984) (temperature and relative humidity in stores) and Anon. (1986) (computer aided design of packages). Specific uses of microprocessors with individual processing equipment are described in later chapters.

2.1 Automatic control

Automation means that every action that is needed to control a process at optimum efficiency is controlled by a system that operates using instructions that have been programmed into it. The advantages of automatic process control can be summarised as:

- more consistent product quality (minor variations in processing that would cause changes to product quality are avoided)
- greater product stability and safety
- greater compliance with legal and customer specifications
- more efficient operation
- verification of correct inputs by operators (e.g. checking that operators specify the correct weight and types of ingredients)

- better use of resources (raw materials, energy, labour, etc.)
- reduced effluents or more uniform effluent loads (see also Chapter 26)
- increased production rates (e.g. through optimisation of equipment utilisation)
- improved safety (automatic and rapid fail-safe procedures with operator warnings in case of, for example, a valve failure or excessive temperature rise).

The main disadvantages relate to the social effects of reduced employment when the number of operators required to process a food is reduced. Other disadvantages include:

- not suitable for processes in which manual skill is necessary or economically more attractive
- higher set-up and maintenance costs
- increased risk, delays and cost if the automatic system fails
- the need for a precise understanding of the process for programming to achieve the required product quality
- reliance on accurate sensors to precisely measure process conditions.

The components of an automatic control system are as follows:

- sensors to detect process conditions and transmitters to send this information to the controller
- a controller to monitor and control a process
- actuators (for example a motor, solenoid or valve) to make changes to the process conditions
- a system of communication between a controller and actuators and transmitters
- an 'interface' for operators to communicate with the control system.

Control systems may also have facilities for collating information and producing analyses of performance, production statistics, management reports, etc. The types of information that are communicated between the different elements of a control system are as follows:

- analog input signals from sensors that give information on the status of process variables
- output signals from the controller which actuate motors, valves, etc.
- input signals (feedback) from motors, valves, etc., which indicate to the control system that the component has been switched on
- input signals from 'monitors' that indicate that a required process condition has been reached (e.g. minimum temperature, maximum flowrate or pressure).

The types of equipment that are used as components of an automatic system are described below.

2.1.1 Sensors

The pre-requisites for control of a process are sensors and instruments which measure specified process variables and transmit the information to a process controller. Parameters commonly measured by sensors are classified into:

- primary measurements (for example temperature, weight, flowrate and pressure)
- comparative measurements, obtained from comparison of primary measurements (for example specific gravity)
- inferred measurements, where the value of an easily measured variable is assumed to

Table 2.1 Examples of measured parameters and types of sensors used in the control of food processes

Parameter	Sensor/instrument type	Examples of applications
Bulk density	Radiowave detector	Granules, powders
Caffeine	Near infrared detector	Coffee processing
Colour	Ultraviolet, visible, near infrared light detector	Colour sorting, optical imaging to identify foods or measure dimensions
Conductivity	Capacitance gauge	Cleaning solution strength
Counting of food packs	Ultrasound, visible light	Most applications
Density	Mechanical resonance dipstick, gamma-rays	Solid or liquid foods
Dispersed droplets or bubbles*	Ultrasound	Foams
Fat, protein, carbohydrate content	Near infrared detector, microwaves	Wide variety of foods
Fill level (liquids or solids)	Ultrasound, mechanical resonance dipstick	Most processes
Flow rate (mass or volumetric)	Mechanical or electro-magnetic flowmeters, magnetic vortex meter, turbine meter, ultrasound, mechanical resonance dipstick, Coriolis meters	Most processes
Foreign body detection	X-rays (with imaging techniques), electromagnetic induction (metallic objects)	Most processes
Headspace volatiles	Near infrared detector	Canning, MAP
Humidity	Hygrometer, capacitance	Drying, freezing, chill storage
Interface between liquid and foam	Ultrasound	Foams
Level	Capacitance, nucleonic, mechanical float, vibronic, strain gauge, conductive level, static pressure, ultrasonic	Automatic filling of tanks and process vessels
Packaging film thickness	Near infrared detector	Many packaging applications, laminates
Particle size, shape, distribution	Radiowave detector	Dehydration
pH	Electrometric	Most liquid processing
Powder flow*	Acoustic emission monitoring	Dehydration, blending
Pressure or vacuum	Bourdon gauge, strain gauge	Concentration by boiling, extrusion, canning
Pump/motor speed	Tachometer	Most processes
Refractometric solids	Refractometer	Sugar processing, preserves
Salt content	Radiowave detector	–
Solid/liquid ratio*	NMR	–
Solute content	Ultrasound, electrical conductivity	Liquid processing, cleaning solutions
Specific micro-organisms*	Immunosensors	To be developed
Specific sugars, alcohols, amines*	Biosensors	To be developed
Specific toxins*	Immunosensors	To be developed
Suspended solids	Ultrasound	Wastewater streams

Table 2.1 Continued

Parameter	Sensor/instrument type	Examples of applications
Temperature	Thermocouples, resistance thermometers, near infrared detector (remote sensing and thermal imaging), fibre-optic probe with fluorescent tip	Heat processing, refrigeration, etc.
Turbidity	Absorbance meter	Fermentations, sugar processing
Valve position	Proximity switch	Most processes
Viscosity	Mechanical resonance dipstick	Dairy products, blending
Water content	Near infrared detector, microwaves (for powders), radio waves, NMR	Baking, drying, etc.
Water quality	Electrical conductivity	Beverage manufacture
Weight	Strain gauge, load cell	Accurate measurement of tank contents, check-weighers

* = Pre-commercial for food processing application.

Adapted from Hamilton (1985), Paschold (1980), McFarlane (1988), McFarlane (1991), Medlock and Furness (1990), Anon. (1993) and Kress-Rogers (1993).

be proportional to a phenomenon that is difficult to measure (for example hardness as a measure of texture)

- calculated measurements, found using qualitative and quantitative data from analytical instruments or mathematical models (for example biomass in a fermenter).

It is important to recognise that process variables that are measured and controlled are often only used indirectly as indicators of complex biochemical reactions that take place during processing. Examples include the combination of time and temperature needed to destroy micro-organisms (Chapters 1 and 12), temperature and pressure as measures of the changes that take place during extrusion (Chapter 14) or the time required to remove a specified amount of moisture by dehydration (Chapter 15). It is therefore necessary to know the relationship between the measured variable and the changes that take place in order to be able to exercise effective control.

Solid-state electronic sensors have largely replaced older mechanical or chemical types, due to their greater reliability, greater accuracy and precision, and faster response times. Examples of the types of sensors used in food processing are shown in Table 2.1.

Options for the positioning of sensors in a process are shown in Fig. 2.1(a–c), and may be summarised as ‘in-line,’ ‘on-line,’ ‘at-line’ and ‘off-line’ (the last being used in analytical laboratories using samples taken from sampling points). On-line and in-line sensors are widely used because of their rapid response time and accurate positioning. Their main requirements are as follows:

- a hygienic sensing head
- contaminant free (contains no reagents or micro-organisms that could contaminate foods)
- no potential hazard from foreign bodies (e.g. no glass components)
- robust to withstand processing temperatures or pressures (for example 200°C and 10 MPa in cooker-extruders (Chapter 14))
- able to withstand chemicals in food components or effluents

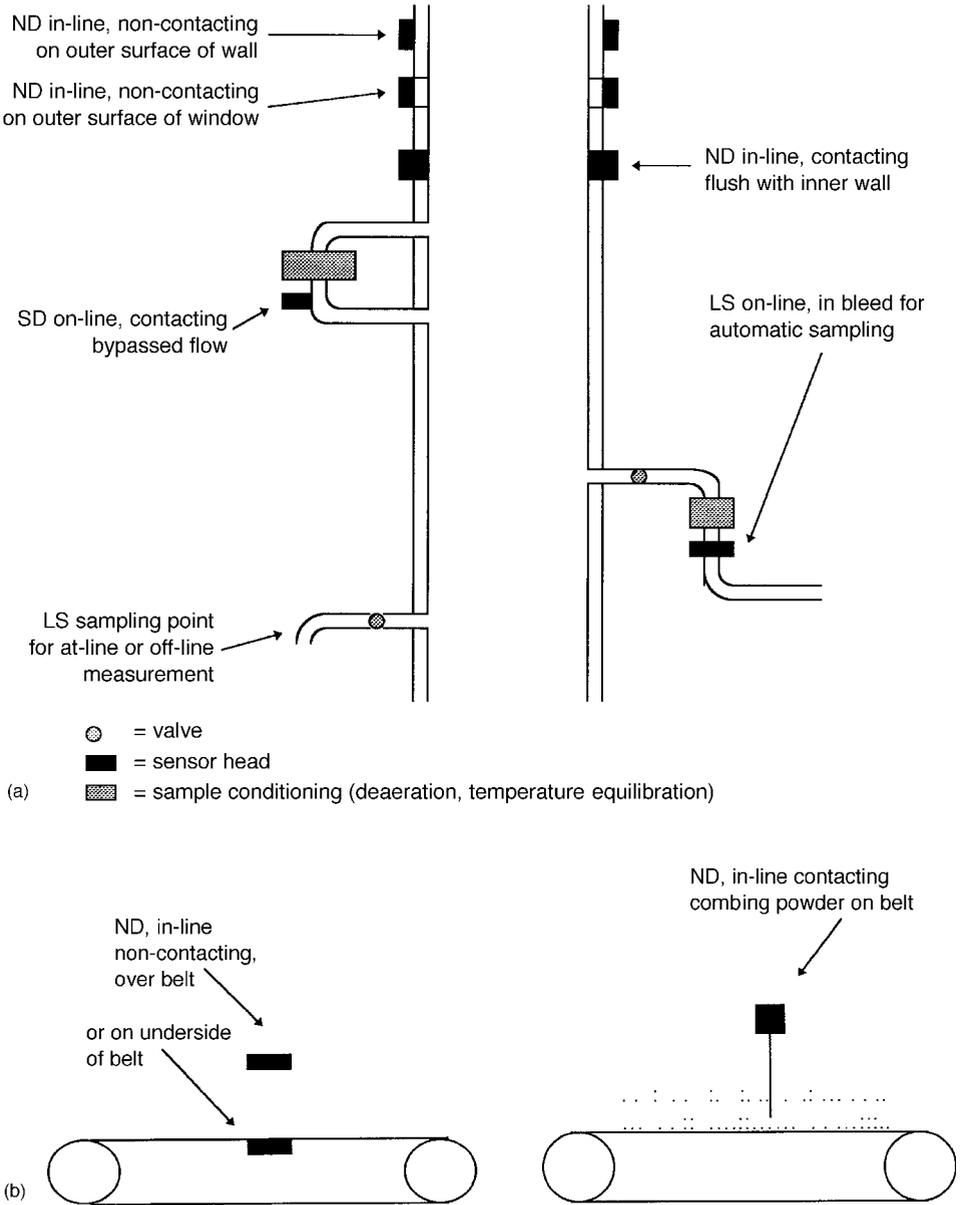


Fig. 2.1 a-c Options for the positioning of sensors in a process: (a) continuous processing; (b) on conveyors; (c) in batch processing.

(ND = non-destructive measurement, SD = slight damage to sample (e.g. deaeration), LS = sample lost.)

(Adapted from Kress-Rogers (1993).)

- tolerant to cleaning-in-place or having cheap, easily replaced, disposable sensing heads
- reliable with good reproducibility, even when exposed to moisture, steam, dust, food volatiles or fouling by fats, proteins or starches

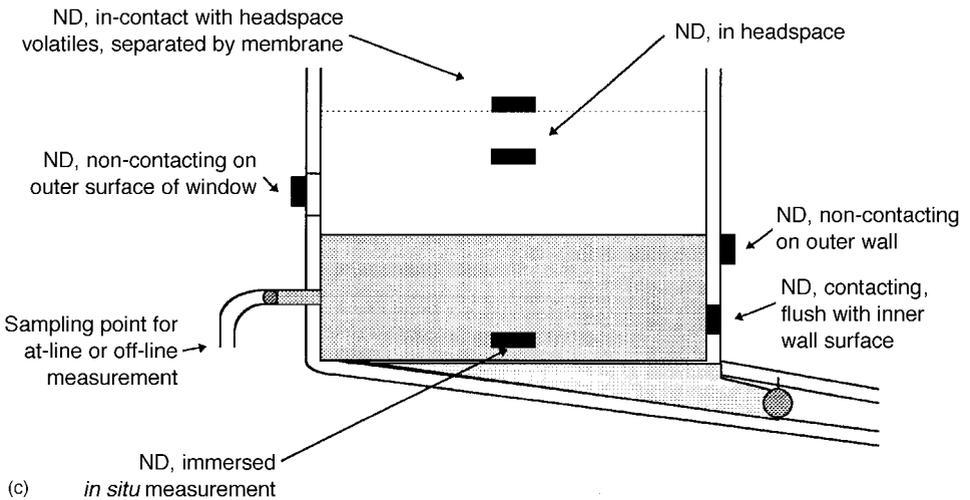


Fig. 2.1 Continued.

- resistance to electromagnetic interference in some applications (e.g. microwaves, ohmic heaters (Chapter 18))
- resistant to damage from mechanical vibration
- low maintenance requirement
- total cost (capital, operating and maintenance costs) in proportion to benefits gained.

(Adapted from Kress-Rogers, 1993.)

The principle of operation of a variety of in-line and on-line sensors and selected applications are described by Anon. (1993).

Given the sometimes hostile conditions that sensors face, non-contact, at-line sensors have advantages in many applications. These sensors include those using electromagnetic waves, light, infra-red radiation (Skjoldebrand and Scott, 1993), microwave or radio-frequency waves (Chapter 18), gamma-rays, or ultrasound. For example, a colour sensor described by Jennings (1998), which has an acrylic lens and is able to withstand impact and severe environmental conditions, is able to assess up to 10 000 operations per second. It was developed for printing presses but can assess surface brightness, texture, colour and surface mapping, and has found wide application in labelling and sensing registration marks on packaging materials (also Chapters 3 and 25). It is likely that non-contact sensors will have further significant development over the next few years, together with bio-sensors, and those based on nuclear magnetic resonance (NMR) or electron spin resonance (ESR). Other applications that are being met by new developments in sensors include measurement of chemical composition, complex rheological properties, the size and distribution of particles, droplets or bubbles and volatiles produced by drying, baking or frying (Kress-Rogers, 1993) (also Chapters 15–17 respectively). The development of sensors to measure sound from process machinery or from the product itself, termed 'acoustic emission' is described by Roberts and Wiltshire (1990), with potential applications to measurement of powder flowrate, cleaning-in-place, solids content in solid/liquid mixes and cooker-extruder performance. Advances in sensors are described in detail by Paschold (1980), McFarlane (1991) and Kress-Rogers (1993) and developments in biological sensors are described by Kress-Rogers (1985).

2.1.2 Controllers

The information from sensors on process and product variables is used by controllers to make changes to process conditions. Whereas previously, monitoring and control was achieved manually by operators, the increased mechanisation of most food processing means that this is now too time consuming, expensive and less reliable than automatic control. In all but the smallest scales of food processing, control is therefore achieved using automatic controllers.

Automatic controllers operate using logic in a similar way to the decision-making logic demonstrated by human thought. For example, in a confectionery plant, an operator may have manually changed from one sugar silo to another using the following sequence of questions and information:

1. How much sugar is left in the silo? (Read from level gauge.)
2. How long before I must change to the next silo? (From experience, about 5 minutes.)
3. Which silo should I choose? (From knowledge of number of silos in factory.)
4. Shall I choose silo 3? (Decide against using knowledge that discharge valve is under repair.)
5. Shall I choose silo 4? (Affirm after checking level reading to confirm that silo 4 is full.)
6. Is the current silo now empty? (Read from level gauge.)
7. Which valves shall I alter? (From knowledge of plant layout.)
8. Decide to alter valves. (Open valve 4, close valve 2.)

In automatic control, the same sequence of questions is 'asked' by the controller. Information is provided by sensors indicating the approach to a set limit for empty in the current silo and the level status in other silos. This, together with information from a sugar flowrate transmitter and an on-line engineering report of ongoing maintenance work, is used to select the next silo and calculate the delay before initiating a pre-programmed sequence of signals to change the motorised valves. Each part of a process can be analysed in this way and automatic controllers can be programmed with the control logic needed to produce the optimum level of control.

Details of the design, action and applications of controllers are described by Green (1984), Fell (1987) and Teixeira and Shoemaker (1989). There are two basic operational requirements of an automatic controller: a method of holding a specified process variable at a predetermined set-point, and a method to control the sequence of actions in an operation. These are supplemented in more advanced controllers with facilities for monitoring a process and providing management information (Section 2.2.3).

To meet the first requirement, sensors measure a process variable and then a transmitter sends a signal to the controller, where it is compared with a set-point. If the input deviates from the set-point (termed the *error*), the controller alters an actuator to correct the deviation and hold the variable constant at the set-point. The type of signals that are sent can be either *digital* (on or off) signals or *analog* (continuously variable) signals. For example, a digital signal could be sent to the controller from a motor, indicating whether it is switched on or off, or from a valve indicating whether it is in one of two possible positions (open or closed). Examples of analog control are continuously varying signals to alter the degree to which for example, a steam valve is open in order to control the rate of heating, or the signal sent from a temperature transmitter to record the product temperature. Other examples include signals from automatic weighing machines and those sent to control the speed of a pump.

Analog and digital signals are used together to control a process in different ways. In *closed-loop control*, there is a continuous flow of information around an electrical loop. Information from sensors is used by the controller to produce changes to the processing conditions via the actuator. These changes are then registered by the sensor and the loop starts again. A common example of closed-loop control is *feedback control* (Fig. 2.2). For example, a thermocouple and a thermostat automatically control an actuator on a steam valve, or the motor on a refrigeration unit to maintain a constant temperature. As the temperature changes are registered by the sensor, the thermostat automatically controls the actuator to maintain the set-point. Another type is *feed-forward control*, in which process conditions are monitored and compared with a model system that anticipates the required process conditions; if the operating conditions deviate from the model, they are altered by the controller, via the actuators. Where both types of control are possible, it is preferable to use feed-forward control, because the error can be anticipated and prevented, rather than wait for the error to be detected and then apply compensation to remove it (McFarlane, 1991). However, this is not always possible because it is necessary to know in advance what changes may take place in a product before corrective action can be taken.

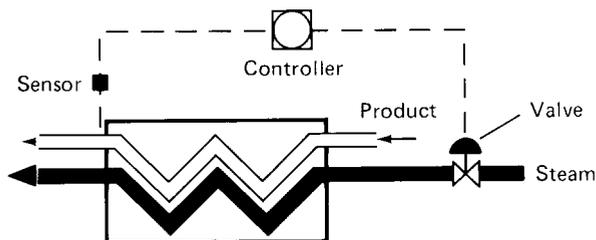


Fig. 2.2 Feedback control (Courtesy of APV Ltd.)

The second requirement of process controllers is the proper sequencing of the control loops in a system, using *sequence control*, in which the completion of one operation signals the controller to start the next operation, with or without a time delay. This has previously been achieved using hard-wired relay circuits (relays are a type of electrical switch), controlled by timers and counters, which automatically turn different circuits on or off at predetermined times or in a specified sequence. These are now replaced by computer systems in which the logic is stored in the computer memory, rather than in the physical arrangement of the wiring. An example of a simple control sequence is described above for the operations needed to change the supply from a sugar silo.

Two additional functions of controllers are to monitor process conditions and to provide management information. Examples include identification of faults and electronic interlocks to prevent a process continuing if a fault is detected or a required condition is not met (for example automatic cleaning schedules are prevented until a tank level signal indicates that it is empty). An important benefit of controllers is their ability to monitor a process for faults (self-diagnosis) and to automatically restart a process when a fault has been corrected. Other benefits of monitoring include the collation and analysis of management information at pre-set intervals (e.g. each shift, each day or month) and the use of this information to prepare cost analyses or maintenance programmes (for example, by using information on how many hours a machine has operated or a valve has opened since it was last serviced).

One aspect of the older electrical relay controllers is that they were ‘stand-alone’ systems that were not integrated with other factory systems to any appreciable extent. Although relays have the advantage of proven reliability, and are still widely used in food factories, they have limited flexibility to accommodate different products and with reductions in the cost of computing power, they are steadily being replaced by computer-based systems.

2.2 Computer-based systems

The increasingly widespread use of microprocessor-based process controllers over the last twenty years is due to their flexibility in operation, their ability to record (or ‘log’) data for subsequent calculations and the substantial reduction in their cost. Computers can not only be programmed to read data from sensors and send signals to process control devices, but they can also store and analyse data and be connected to printers, communications devices, other computers and controllers throughout a plant. They can also be easily reprogrammed by operators to accommodate new products or process changes. Examples of the different types of computer controlled systems are described below.

2.2.1 Programmable logic controllers (PLCs)

A significant development in process control during the 1980s was the introduction of PLCs. They are based on microcomputers, and have the same functions as relays, but with vastly greater flexibility. Historically, they were first used to replace relays in simple repetitive applications, but the greater power was quickly used to develop other functions, including recipe storage, data transfer and communications with higher level computers (Marien, 1989). PLCs have a fixed program stored in two modes in the computer memory using similar logic to relay circuits. The first (teach) mode allows instructions to be programmed into the memory via a keyboard by an operator. In the second (run) mode the program is executed automatically in response to data received from sensors. This is achieved using software building blocks termed *algorithms* which construct control sequences for a particular application and allow the operator to program the system. Each algorithm carries out a specific function, and the operator simply defines the series of algorithms and the data on which they are to operate, in response to a series of questions displayed on a screen. A display monitor provides information to the operator on the status or the progress of the control and a printed record gives a summary of the processing conditions used.

If a process parameter exceeds a pre-set limit, a warning is activated to attract the attention of the operator. Alternatively the program may automatically correct any deviation from the specified limits. Similarly a PLC can be programmed to monitor constantly the status of valves or other equipment and inform an operator of any malfunction, which greatly speeds up fault tracing and repairs.

PLCs are highly reliable, relatively low cost and easy to install and use. An important advantage is the ease and speed with which they can be reprogrammed by factory staff who do not have sophisticated computing knowledge. This allows great flexibility in being able to modify process conditions or change product formulations. An application of automatic control by PLCs is described below and an example is shown in Fig. 2.3.

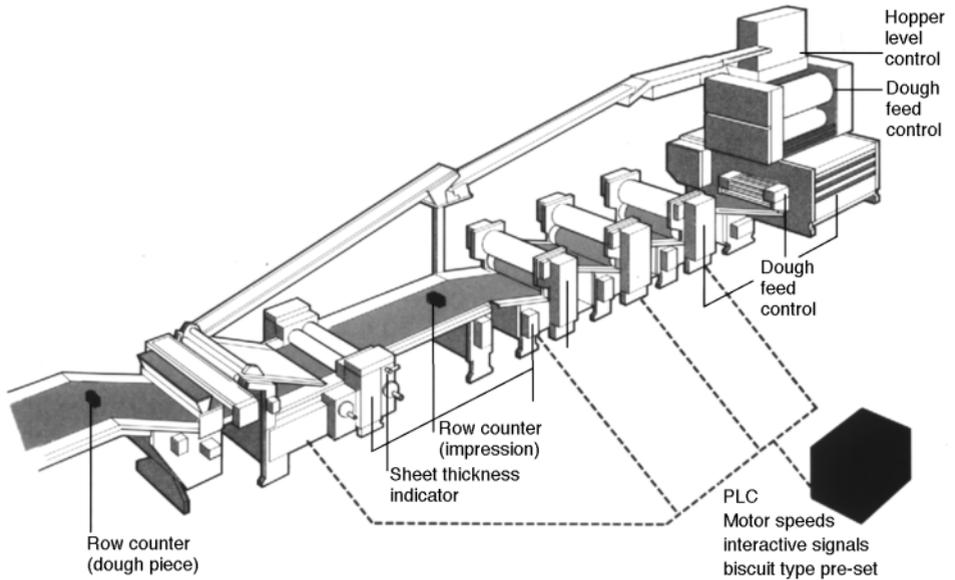


Fig. 2.3 PLC control of biscuit manufacture (Courtesy of Baker Perkins Ltd.)

Batching and blending

The increased range of products demanded by consumers has required manufacturers to produce smaller batches, with more frequent changes to product formulations and processing conditions during routine production. This is complex and time consuming if performed manually, but is well suited to automatic control by PLCs. The equipment (a *batcher*) has a microprocessor which stores information about the types and weights of ingredients for all products made on the production line (for example one system stores up to 2600 recipes and 30 different mix cycles (Kimber, 1983)). Each formulation is assigned a number and, when a number is entered by the operator, the PLC automatically controls the flow of ingredients from storage silos, through automatic weighers, to mixing vessels. This type of control is widely used in the production of baked goods, snackfoods, confectionery and ice cream.

A similar system is used for the automatic control of raw materials that have a variable composition but are used to produce a final product in which the composition is subject to legislation or trade standards. For example, in flow blending to adjust the alcoholic strength of beer to a pre-set specification, beer from the fermentation tanks, which has a higher strength than that required in a particular product, is mixed with deaerated water to the correct proportions. The operator enters the specific gravity of the beer, the specific gravity of the diluent and the required specific gravity of the product. The PLC then calculates the required ratio of the two fluid streams and adjusts one until the measured ratio meets the specification.

In another application, a computer is used to determine the least-cost formulation needed to produce a particular product specification from different combinations of raw materials. For example, the quality of meat products such as burgers and sausages, and the profitability of their production, are determined by both the fat content of the meat and accurate proportioning of meat and non-meat ingredients. Data on the composition of the raw materials is fed into the PLC, which simulates possible formulations and selects the one that has the lowest cost. Automatic control of the formulation also produces the

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exact lean-to-fat ratio and meat-to-non-meat ratio required in the product, whatever the composition of the batch of raw meat (Shields, 1981; Newman, 1986). This system is also used in buying departments to assess the implications of purchasing particular raw materials and hence to determine the overall financial savings from a given set of purchases.

2.2.2 Types of control systems

The different combinations in which PLCs and larger computers can be linked together in an integrated control system can be described in three categories:

1. dedicated systems
2. centralised systems
3. distributed systems.

These are described in more detail by Teixeira and Shoemaker (1989).

Dedicated control systems

These use local equipment controllers (PLCs) which are an integral part of the process plant, dedicated to the control of a single unit operation. Examples include controlling the temperature of a heat exchanger or blending different ingredients into a formulated batch. They do not communicate information to other computers but simply receive on/off instructions from a central control panel. They are relatively unsophisticated computers that are able to receive data from sensors and send signals to actuators. They may also have the capability for data-logging, report generation and automatic set-point adjustment. They have remained popular because they are easy to fit to existing processes without requiring significant changes to the control system, they are easy to use and low cost. However, they are usually designed for a particular application and the pre-set operating sequence is difficult to change.

Centralised control systems

In these systems, a mainframe computer or large mini-computer, located in a centralised control room, monitors and controls different on-line controllers that in turn control the process in specified zones. Each on-line controller may have a printer, data logger and graphics display to inform operators of the status of the process. They can be reprogrammed relatively easily to accommodate process changes and can have facilities for report generation and communication with other computers. An example is a fully automated milk processing plant described by Anon. (1987), in which each piece of equipment is automatically controlled to maintain pre-set temperatures, pressures and flow rates. Each process area has a *mimic panel* to indicate continuously the status of the process variables. Closed-circuit television cameras view the plant and relay the information to monitors located in the central control room. The central computer checks the positions of valves, fluid levels, pressures, flow rates, densities and temperatures in the processing equipment, at a rate of 998 inputs every 7 s. When a fault occurs, the computer sounds an alarm and produces a printout for the operators in the control room of the faulty equipment, its location and the nature of the fault. The computer also prints detailed production data and the status of stocks at any time. Larger systems are able to control 200 plant actuators and monitor 5000 inputs at a rate of 2000 per second.

Although centralised computer control systems have been used in large companies for several years, their major disadvantage is that any failure in the central computer could

cause a total plant shutdown, unless an expensive standby computer of equal capacity is available to take over. For this reason, distributed control systems which do not have this disadvantage, are now more commonly installed.

Distributed control systems (DCS)

These are an integrated system of control in which each area of a process is independently controlled by a PLC, and the PLCs are both linked together (process interlocking), and linked to a central computer via a communications network (Lasslett, 1988). Each PLC controller is located close to the equipment that it controls to reduce the cost of wiring, and each has an operator's console with a graphics display and control inputs. Although the capital cost and programming costs are higher than the other systems, distributed control systems are highly flexible in being able to change processing conditions and do not have the vulnerability to total plant shutdown if one component fails (Persson, 1987; Dahm and Mathur, 1990).

Integrated control systems

When distributed control systems are used in different sections of a factory, they can be integrated into a larger management information system, known as an Integrated Control System. A central computer is used for mass data storage, sophisticated data manipulation, control of printers, plotters and communications with other management computers. This allows it to be used for other functions, including administration, marketing, quality assurance and plant maintenance, in addition to process control. Each distributed control system forms an independent but unified component of the total system and thus if one component fails, the others maintain full control of their process area (Teixeira and Shoemaker, 1989). Further details of an integrated system having three layers of control are given by Selman (1990).

Process control systems

More recent developments (Williams, 1998) involve using computers to operate a control programme that does not require specialist hardware (often referred to as 'soft-logic' or 'PC-based control'). These are hybrids of PLC and distributed control systems which are now being termed *Process Control Systems* (PCS). They enable complex combinations of continuous control, batch sequencing and processing to give complete automation using a single highly flexible program. This enables considerable time savings in system design, commissioning and engineering. These systems are able to collect and process data to show the performance of the process plant (for example length and causes of stoppages and energy consumption), and to prepare reports for managers. Factory engineers can use the data to design more effective maintenance programmes and locate faults more quickly. Summaries of processing costs and production line efficiencies are used by production staff to improve materials handling and scheduling procedures and hence to improve the efficiency of production. Managers then use this information to control stocks of products and raw materials and to compare actual production levels with daily or weekly targets.

2.2.3 Software developments

One of the most important software developments in the late 1980s was the *Supervisory Control and Data Acquisition* (SCADA) software. This collects data from a PLC that is controlling a process and displays it to plant operators in real-time as animated graphics



Fig. 2.4 PLC controller display for plant operators in real-time as animated graphics. (Based on FRIGOSCAN system used to control a freezer, courtesy of Frigoscandia.)

(Fig 2.4). Thus, for example, an operator can see a tank filling or a valve change colour as it opens or closes. The graphics are interactive to allow the operator to start a motor, adjust a process variable or control equipment. Alarm messages are displayed on the screen when a pre-set processing condition is exceeded.

However, a major limitation of SCADA systems was their inability to analyse trends or recall historical data. This was corrected by new software in the 1990s, based on Microsoft's 'Windows' operating system, which allows data to be transferred between different programs and applications, using a *Dynamic Data Exchange* (DDE). This enables analysis and reporting of simple trends and historical data using spreadsheets and is linked in real-time to office automation systems. With this software, the *office* software can be used for real-time process control to adjust recipes, schedule batches, produce historical information or management reports.

In an example, described by Atkinson (1997), such a system is used in a large ice cream factory to reduce costs by closer monitoring and control of the refrigerator's compressors, to display real-time running costs and to produce records of refrigeration plant performance. Gore (1997) describes two new types of software. The first monitors machine performance in applications such as packaging, where stoppages due to material jamming are common. The program calculates performance statistics such as throughput, rejects and downtime. It describes the reason for every stoppage and calculates how much downtime results from each cause, presenting the information as a performance report. Substantial improvements in plant efficiency are possible because managers can more easily identify and solve process problems. The second type of software is used to monitor details of the processing received by an individual batch of food (for example time and temperature of heating or cooling) and store this together with the batch number and data on the final product. This allows each batch of food to be traced for possible

statutory food hygiene requirements or to address any customer complaints. Trends in processing conditions of successive batches can also be analysed to monitor the performance of a process.

Previously, it has been difficult to make different software systems communicate with each other, but more recent developments in software, including the *open data base connectivity* (ODBC) standard have enabled different information databases to be linked together and accessed by anyone who is connected to a network. Information such as master recipes, production schedules and plant status can thus be incorporated into company business systems. Additionally, the development of *object linking and embedding* (OLE) for process control, known as OPC, greatly simplifies the linking together of different software. An example of this type of software is a batch automation system, which has an easy-to-use highly graphical program that enables operators to simulate the production process, alter equipment settings, change batch recipes, control the process and generate reports, as well as providing the facility to link directly production control to check-weighers or bar-code readers. The system is compatible with other management programs and is used to share production information with other departments within a company, such as sales and marketing.

Future software developments are expected to build on a newly introduced system termed *Common Object Resource Based Architecture* (CORBA). This acts as an information broker that not only links process control systems, SCADA systems, OPC and office business systems, but also exchanges information from bar-code readers, checkweighing systems, formulation programs, equipment controllers and laboratory information systems. The system also has spreadsheet and Internet programs for producing and accessing information. It is anticipated that this system will be used to connect the many disparate types of control systems that are in use, or as described by Williams (1998), 'it will provide a means to link up the islands of automation that exist in most food plants and create cohesive systems in which information is freely available'.

2.2.4 Neural networks

Where complex relationships exist between a measured variable and the process or product, it has not yet been possible to automate the process. Recent developments of 'expert systems' or 'neural networks' may have the potential to solve such problems. These are able to automatically deduce complex relationships and also to quickly 'learn' from experience. Wallin and May (1995) describe the use of neural networks for a number of applications including automatic control of highly complex extrusion cookers (Chapter 14) by 'intelligent' interpretation of the range of variables in raw materials, processing conditions and final product quality. They are also being developed for applications in fermentation processes, production line robotics, analysis of leanness of meat and inspection of fruits and vegetables. In the last example, a neural network vision system checks fruits for defects such as mis-shapes, poor colour, undersize items and foreign bodies. When analysing grapefruits for area, circularity and diameter range, the system was able to correctly detect over 96% of misshapen fruits (also Chapter 3). Future applications may include monitoring the correct position and proportion of ingredients on prepared foods such as pizza, correct positioning of labels on packs, inspection of containers for damage or leakage and 'intelligent' automation of chemical analyses. These systems are reported to offer reductions in labour costs and wastage, higher production rates and generation of improved information for more accurate production scheduling and sales forecasting.

Advances in neural systems, together with vision systems, pressure sensitive grippers and laser guidance systems have also been applied to robotics. Production line robots have so far found applications in meat deboning, cake decoration, mushroom picking, packaging assorted chocolates, carton erection and palletising cases (Wallin, 1994). This area of development is expected to become significantly more important during the next few years.

2.3 Acknowledgements

Grateful acknowledgement is made for information supplied by the following: Mettler Instrument Corporation, New Jersey 08520, USA; Ferranti Computer Systems, Manchester M22 5LA, UK; APV International Ltd, Crawley, West Sussex RH10 2QB, UK; Baker Perkins Ltd, Peterborough PE3 6TA, UK; Alfa Laval Ltd, Brentford, Middlesex TW8 9BT, UK; Endress and Hauser Ltd, Manchester M23 9NF, UK; Honeywell Industrial Automation and Control, Bracknell RG12 1EB, UK.

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Part II

Ambient-temperature processing

Methods used to prepare freshly harvested or slaughtered food for further processing (Chapter 3), to alter the size of foods (Chapter 4), to mix ingredients (Chapter 5) or to separate components of food (Chapter 6) are each essential unit operations in nearly all food processes. They are used to prepare specific formulations, to aid subsequent processing, or to alter the sensory characteristics of foods to meet the required quality. In each of these unit operations the sensory characteristics and nutritional properties of foods may be changed by removal of components or by the action of naturally occurring enzymes, but there is negligible damage to food quality due to heat.

Over the last ten years, consumer demand has increasingly required processed foods to have a more 'natural' flavour and colour, with a shelf life that is sufficient for distribution and home storage before consumption. There have been significant developments in processes that do not significantly heat the food and are thus able to retain to a greater extent their nutritional quality and sensory characteristics. Traditionally, fermented foods (Chapter 7) have many of these characteristics, and irradiation (Chapter 8) has been adopted in some countries as a minimal method of food preservation. There has also been increasing interest in developing other novel methods to achieve mild preservation, for example processing using electric fields, high hydrostatic pressure, pulsed light and ultrasound (Chapter 9). The principle underlying the use of mild processing involves the use of combinations of these low temperature unit operations with refrigerated storage and distribution (Chapter 19) and packaging (Chapters 24 and 25). Each minimal processing method destroys or inhibits microbial growth, and in some cases enzyme activity, but there are no substantial increases in product temperature. There is therefore little damage to pigments, flavour compounds or vitamins and, in contrast to heat processing (Part III), the sensory characteristics and nutritional value of foods are largely retained.

3

Raw material preparation

At the time of harvest or slaughter, most foods are likely to contain contaminants, to have components which are inedible or to have variable physical characteristics (for example shape, size or colour). It is therefore necessary to perform one or more of the unit operations of cleaning, sorting, grading or peeling to ensure that foods with a uniformly high quality are prepared for subsequent processing. It is not possible to produce high quality processed foods from substandard raw materials and these mechanical separation procedures, which are applied near the beginning of a process, are a highly cost-effective method of improving the quality of the raw material. Further details are given by Leniger and Beverloo (1975) and applications of these techniques to fruit processing are described by Woodroof (1975). Other separation operations are described in Chapter 6.

3.1 Cleaning

Cleaning is the unit operation in which contaminating materials are removed from the food and separated to leave the surface of the food in a suitable condition for further processing. A classification of the type of contaminants found on raw foods is shown in Table 3.1.

Peeling fruits and vegetables (Section 3.4), skinning meat or descaling fish may also be considered as cleaning operations. In vegetable processing, blanching (Chapter 10) also helps to clean the product.

The presence of contaminants (or foreign bodies) in processed foods is the main cause of prosecution of food companies. An analysis of the types of contaminants is given in Fig. 3.1. Methods that are used to remove foreign bodies are discussed below.

Cleaning should take place at the earliest opportunity in a food process both to prevent damage to subsequent processing equipment by stones, bone or metals, and to prevent time and money from being spent on processing contaminants which are then discarded. In addition, the early removal of small quantities of food contaminated by micro-organisms prevents the subsequent loss of the remaining bulk by microbial growth during storage or delays before processing. Cleaning is thus an effective method

Table 3.1 Contaminants found on raw foods

Type of contaminant	Examples
Metals	Ferrous and non-ferrous metals, bolts, filings
Mineral	Soil, engine oil, grease, stones
Plant	Leaves, twigs, weed seeds, pods and skins
Animal	Hair, bone, excreta, blood, insects, larvae
Chemical ^a	Fertiliser, pesticides, herbicides
Microbial cells	Soft rots, fungal growth, yeasts
Microbial products	Colours, flavours, toxins

^a Not to be confused with adulterants (chemicals intentionally added to food which are forbidden by law) or additives (chemicals added to food to improve eating qualities or shelf life).

Adapted from Brennan *et al.* (1990).

of reducing food wastage, improving the economics of processing and protecting the consumer.

Equipment for cleaning is categorised into wet procedures (for example soaking, spraying, flotation washing and ultrasonic cleaning) and dry procedures (separation by air, magnetism or physical methods). The selection of a cleaning procedure is determined by the nature of the product to be cleaned and by the types of contaminant to be removed. In general, more than one type of cleaning procedure is required to remove the variety of contaminants found on most foods.

3.1.1 Wet cleaning

Wet cleaning is more effective than dry methods for removing soil from root crops or dust and pesticide residues from soft fruits or vegetables. It is also dustless and causes less damage to foods than dry methods. Different combinations of detergents and sterilants at different temperatures allow flexibility in operation. However, the use of warm cleaning water may accelerate chemical and microbiological spoilage unless careful control is exercised over washing times and subsequent delays before processing. Furthermore wet procedures produce large volumes of effluent, often with high

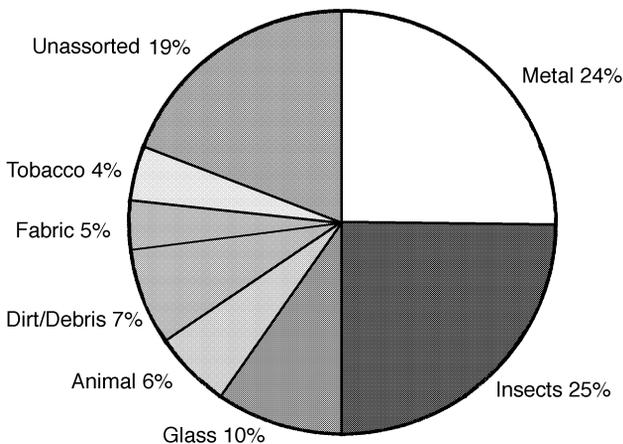


Fig. 3.1 Types of contaminants leading to prosecution in UK (1988–1994).
(From Graves *et al.* (1998).)

concentrations of dissolved and suspended solids (measured as biological oxidation demand (BOD) or chemical oxidation demand (COD)). There is then a requirement both to purchase clean water and to either pay for high effluent disposal charges or build in-factory water treatment facilities (also Chapter 26). To reduce costs, recirculated, filtered and chlorinated water is used whenever possible. Examples of wet-cleaning equipment include spray washers, brush washers, drum or rod washers, ultrasonic cleaners and flotation tanks. They are described in detail by Brennan *et al.* (1990).

3.1.2 Dry cleaning

Dry cleaning procedures are used for products that are smaller, have greater mechanical strength and possess a lower moisture content (for example grains and nuts). After cleaning, the surfaces are dry, to aid preservation or further drying. Dry procedures generally involve smaller cheaper equipment than wet procedures do and produce a concentrated dry effluent which may be disposed of more cheaply. In addition, plant cleaning is simpler and chemical and microbial deterioration of the food is reduced compared to wet cleaning. However, additional capital expenditure may be necessary to prevent the creation of dust, which not only creates a health and explosion hazard but also recontaminates the product.

The main groups of equipment used for dry cleaning are:

- air classifiers
- magnetic separators
- separators based on screening of foods (Section 3.2.1).

Classifiers (for example Fig. 3.2) use a moving stream of air to separate contaminants from foods by differences in their densities. They are widely used in harvesting machines to separate heavy contaminants (for example stones) and light contaminants (for example leaves, stalks and husks) from grain or vegetables. Calculation of the air velocity required for separation is described in Chapter 1 (Equation (1.11)).

3.1.3 Removing contaminants and foreign bodies

Physical separation of contaminants from foods is possible when the food has a regular well-defined shape. For example round foods (peas, blackcurrants and rapeseed) are

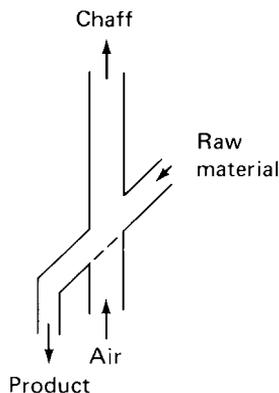


Fig. 3.2 Separation of chaff from grain by aspiration cleaning.

separated from contaminants by exploiting their ability to roll down an inclined, upward moving conveyor belt. Contaminants, such as weed seeds in rape-seed or snails in blackcurrants, are carried up the conveyor and separated. A disc separator, used to separate grain from weed seeds, consists of a series of vertical metal discs with precisely engineered indentations in the sides that match the shape of the grain. As the discs rotate, the grain is lifted out and removed (Brennan *et al.*, 1990). Screens (Section 3.2.1) are also used to remove contaminants from foods.

Contamination by metal fragments or bolts from machinery is a potential hazard in all processing. Raw materials may pass through metal detectors before processing and all packaged foods are checked for contamination. Details are given in Chapter 25. Ferrous metals are removed by either permanent magnets or electromagnets. Electromagnets are easier to clean (by switching off the power supply) but permanent magnets are cheaper. However, unless regularly inspected, permanent magnets may build up a mass of metal which is lost into the food all at once to cause gross recontamination (Anon., 1991).

Small-particulate foods may be automatically checked for contaminants using microprocessor controlled colour sorting equipment (also Section 3.2.2). For example, coffee beans are viewed in ultraviolet light to cause bacterial contaminants to fluoresce (Anon., 1982). More recent developments enable contaminants having the same colour, but a different shape to the product, to be removed (for example green stalks from green beans).

X-rays are used to detect metals and other types of solid contaminant in both raw materials and inside packaged foods. The X-rays pass through the food as it passes on a conveyor and are converted to visible light by a phosphor strip or screen. The light is magnified and transmitted by fibre optic cables to an image intensifier and video camera. The final image is displayed on a television monitor. The system activates a warning and also automatically rejects the contaminated item (Anon., 1984a; Williams *et al.*, 1983). The system is limited to products that are larger than 15 cm and to date has been mainly applied to glass jar inspection. New developments include the use of solid-state, X-ray sensitive elements which collect a sample of information as the product passes over the

Table 3.2 Summary of techniques used in foreign body food inspection

Technique	Wavelength	Food product	Foreign bodies
Magnetic	N/A	Loose and packaged foods	Metals
Capacitance Microwave	N/A 1–100 mm	Products <5 mm thick Fruits, possible others but needs more research	More research needed Fruit pits
Nuclear magnetic resonance	1–10 mm + magnetic field	Fruits and vegetables	Fruit pits and stones
Infrared Optical	700 nm–1 mm 400–700 nm	Nuts, fruits, vegetables Any loose product, fruit and vegetables	Nut shells, stones and pits Stones, stalks
Ultraviolet	1–400 nm	Meat, fruits, vegetables	Fat, sinews, stones and pits
X-rays	<1 nm	All loose and packaged foods	Stone, plastic, metal, glass, rubber, bone
Ultrasonics	N/A	Potatoes in water, more research needed	Stones

N/A = not applicable.

From Graves *et al.* (1998).

sensors. This information is modified by sophisticated computer image processing techniques that can compare 300 million points of information from digital images per second, to create a two-dimensional image of the product. Applications include detection of stones, bone fragments, plastics, seafood shells and ceramics or concrete in addition to metals, and also bag-in-box packaging and metallised pouches (Chapter 25), and missing or under-filled packages (Greaves, 1997). Other techniques that are currently under development include nuclear magnetic resonance imaging, microwave, capacitance and ultrasonic detectors (Table 3.2) described by Graves *et al.* (1998).

3.2 Sorting

Sorting is the separation of foods into categories on the basis of a measurable physical property. Like cleaning, sorting should be employed as early as possible to ensure a uniform product for subsequent processing. The four main physical properties used to sort foods are size, shape, weight and colour.

The effectiveness of a sorting procedure is calculated using

$$\text{effectiveness} = \frac{P\bar{x}_p R(1 - \bar{x}_r)}{F\bar{x}_f F(1 - \bar{x}_f)} \quad (3.1)$$

where P (kg s^{-1}) = product flow rate, F (kg s^{-1}) = feed flow rate, R (kg s^{-1}) = rejected food flow rate, \bar{x}_p = the mass fraction of desired material in the product, \bar{x}_f = the mass fraction of desired material in the feed and \bar{x}_r = the mass fraction of desired material in the rejected food.

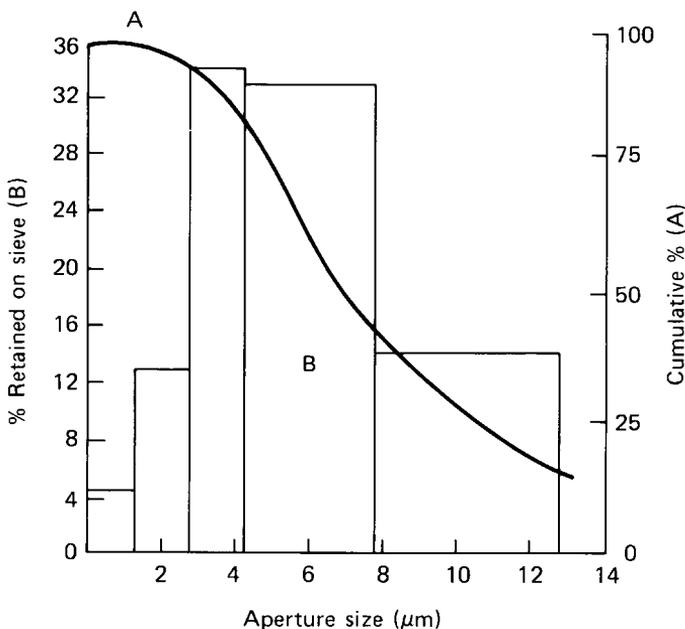


Fig. 3.3 Retention of particles on sieves: (A) cumulative percentage, (B) mass fraction.

3.2.1 Shape and size sorting

The particle size distribution of a material is expressed as either the mass fraction of material that is retained on each sieve or the cumulative percentage of material retained (Fig. 3.3) (data from Sample problem 3.1). The mean overall diameter of particles (volume or mass mean diameter) is found using

$$d_v = \frac{\sum d^3}{\sum m} \tag{3.2}$$

where d_v (μm) = volume or mass mean diameter, d (μm) = the average diameter and m (g) = mass retained on the sieve.

Sample problem 3.1

A sieve analysis of powdered sugar showed the following results. Calculate the mass mean diameter of the sample.

Sieve aperture (μm)	Mass retained (%)
12.50	13.8
7.50	33.6
4.00	35.2
2.50	12.8
0.75	4.6

Solution to Sample problem 3.1

The cumulative percentages are as follows.

To find the mass mean diameter, find d as follows.

Average diameter of particles d (μm)	m (%)	d
0.375	4.6	1.725
1.625	12.8	20.8
3.25	35.2	114.4
5.75	33.6	193.2
10.0	13.8	138.0
Total	100.0	468.125

From equation (3.2),

$$\text{mass mean diameter} = \frac{468.125}{100} = 4.68\mu\text{m}$$

Data plotted for cumulative % in Fig. 3.3

Aperture size (μm)	12.50	7.50	4.00	2.50	0.75
Cumulative percentage	13.8	47.4	82.6	95.4	100.0

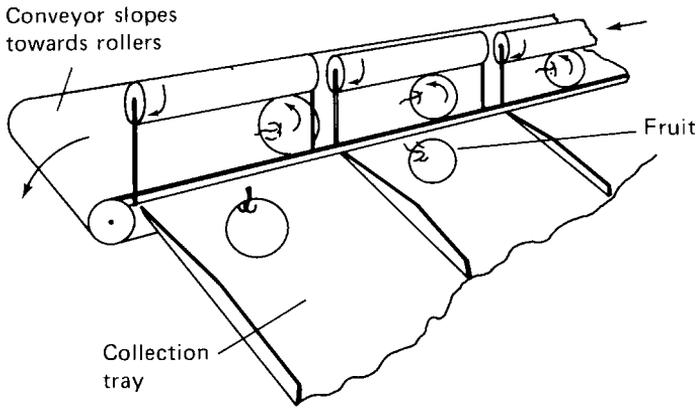


Fig. 3.4 Belt-and-roller sorter.

The shape of some foods is important in determining their suitability for processing or their retail value. For example, for economical peeling, potatoes should have a uniform oval or round shape without protuberances. Cucumbers and gherkins are more easily packaged if they are straight, and foods with a characteristic shape (for example pears) have a higher retail value if the shape is uniform. Shape sorting is accomplished either manually or mechanically (for example the belt-and-roller sorter in Fig. 3.4, or the disc sorter (Section 3.1.2)) or by image processing.

Size sorting (termed *sieving* or *screening*) is the separation of solids into two or more fractions on the basis of differences in size. It is particularly important when the food is to be heated or cooled as the rate of heat transfer is in part determined by the size of the individual pieces and variation in size would cause over-processing or under-processing. Additionally, foods which have a uniform size are said to be preferred by consumers. Screens with either fixed or variable apertures are used for size sorting. The screen may be stationary or, more commonly, rotating or vibrating.

Fixed aperture screens

Two common types of fixed aperture screen are the flat bed screen (or sieve) and the drum screen (rotary screen or reel). The multideck flat bed screen (Fig. 3.5) has a number of inclined or horizontal mesh screens, which have aperture sizes from $20\ \mu\text{m}$ to $125\ \text{mm}$, stacked inside a vibrating frame. Food particles that are smaller than the screen apertures pass through under gravity until they reach a screen with an aperture size that retains them. The smallest particles that are separated commercially are of the order of $50\ \mu\text{m}$.

The capacity of a screen is the amount of food that passes through per square metre per second. The rate of separation is controlled by:

- the shape and size distribution of the particles
- the nature of the sieve material
- the amplitude and frequency of shaking
- the effectiveness of methods used to prevent blocking (or blinding) of the sieves.

These types of screen are widely used for sorting dry foods (for example flour, sugar and spices). The main problems encountered are:

- excessive moisture or high humidity, which causes small particles to stick to the screen or to agglomerate and form larger particles, which are then discharged as oversize

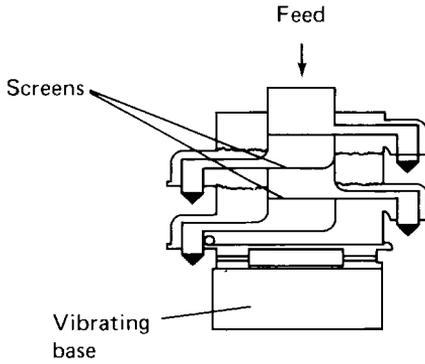


Fig. 3.5 Multideck flat bed screen.
(Courtesy of Gough Engineering Ltd.)

- blinding, particularly if the particle size is close to that of the screen aperture
- high feed rates, which cause the screens to become overloaded and small particles are discharged with the oversized particles.

Where vibration alone is insufficient to separate particles adequately, a gyratory movement is used to spread the food over the entire sieve area, and a vertical jolting action breaks up agglomerates and dislodges particles that block sieve apertures.

Many types of drum screen are used for sorting small-particulate foods (for example nuts, peas or beans) that have sufficient mechanical strength to withstand the tumbling action inside the screen. Drum screens are almost horizontal ($5\text{--}10^\circ$ inclination), perforated metal or mesh cylinders. They may be *concentric* (one inside another), *parallel* (foods leave one screen and enter the next (Fig. 3.6)) or *series* (a single drum



Fig. 3.6 Parallel drum screen.
(Courtesy of FlowMech Ltd.)

constructed from sections with different sized apertures). All types have a higher capacity than flat bed screens and problems associated with blinding are less severe than with flat bed screens. The capacity of drum screens increases with their speed of rotation up to a critical point. Above this the food is held against the screen by centrifugal force and results in poor separation. Similarly there is an increase in capacity with the angle of the screen up to a critical angle. Above this the residence time is too short and products pass through without separation.

Variable-aperture screens

Variable-aperture screens have either a continuously diverging aperture or a stepwise increase in aperture. Both types handle foods more gently than drum screens and are therefore used to sort fruits and other foods that are easily damaged. Continuously variable screens employ pairs of diverging rollers, cables or felt-lined conveyor belts. These may be driven at different speeds to rotate the food and thus to align it, to present the smallest dimension to the aperture (Fig. 3.7).

Stepwise increases in aperture are produced by adjusting the gap between driven rollers and an inclined conveyor belt (Fig. 3.4). The food rotates and the same dimension is therefore used as the basis for sorting (for example the diameter along the core of a fruit).



Fig. 3.7 Sorting lemons on a roller sorter.
(Courtesy of Sunkist Growers.)

Image processing

Image processing is used to sort foods on the basis of length, diameter, number of surface defects and orientation of the food on a conveyor as well as colour (Section 3.2.2). It has been used for example with maize cobs, which pass beneath three video cameras, placed 120° apart above a conveyor belt. The images of the surface of the cob are recorded and stored in the memory of a microprocessor. The information is then analysed and compared with pre-programmed specifications for the product, and the cob is either rejected or moved into a group with similar characteristics. In another system a video camera views foods and an operator compares the shapes with an electronic template overlaid on a monitor screen. The template reduces operator fatigue and allows greater concentration on the selection process.

3.2.2 Colour sorting

Manual sorting by colour is still widely used but is increasingly expensive in both labour costs, operator training and the space required for sorting tables. There has therefore been considerable development of machine vision sorting systems which are said to have lower operating costs and greater accuracy than manual methods. These include monochrome (black and white), bichrome (4100 shades of red and green) and trichromatic or full colour (262 000 shades of red, green and blue, with optional infra-red). Each is controlled by a programmable logic controller (Chapter 2) which has pre-set programs for different products that are easily changeable by operators using a video display. They are used for example, to sort potatoes for defects and blemishes by identifying dark areas on the potato surface. Light sensitive cells in the camera (termed 'pixels') produce a voltage that is proportional to the intensity of light received. An electronic circuit that receives a lower voltage than the pre-set value can thus detect darker objects or areas which reflect less light than normal. The voltage produced in the electronic circuit can be adjusted to alter the sensitivity of detection. Up to 10 tonnes of product per hour pass beneath the cameras on conveyors operating at 150–180 m per min. Defective items are removed by electronically controlled air jets that can operate for 20 milliseconds, thus covering 50 mm of the belt length in a single blast (Heffington and Nilsson, 1990). In another system, vegetables in free-fall are scanned 1000 times per second, as they leave a conveyor belt, using concentrated helium-neon or laser light beams and a high-speed rotating mirror. The machine detects differences in reflectivity between good product and unwanted material. Gangi *et al.* (1983) describe a similar system to sort tomatoes as they are discharged from a conveyor.

Small-particulate foods may be automatically sorted at high rates (up to 16 tonnes h⁻¹) using microprocessor controlled colour sorting equipment (Fig. 3.8). Particles are fed into the chute one at a time. The angle, shape and lining material of the chute are altered to control the velocity of the pieces as they pass a photodetector. The colour of the background and the type and intensity of the light used for illuminating the food (including infrared and ultraviolet options) are closely controlled for each product. Photodetectors measure the reflected colour of each piece and compare it with pre-set standards, and defective foods are separated by a short blast of compressed air. The computer can store 100 named product configurations to enable rapid changeover to different products using an operator touchpad. Typical applications include peanuts, Michigan Navy beans (for baked beans), rice, diced carrot, maize kernels, cereals, snackfoods and small fruits. Developments in colour measurement are described in detail by Brimelow and Groesbeck (1993) and advances in colour sorting described by Low and Maughan (1993).

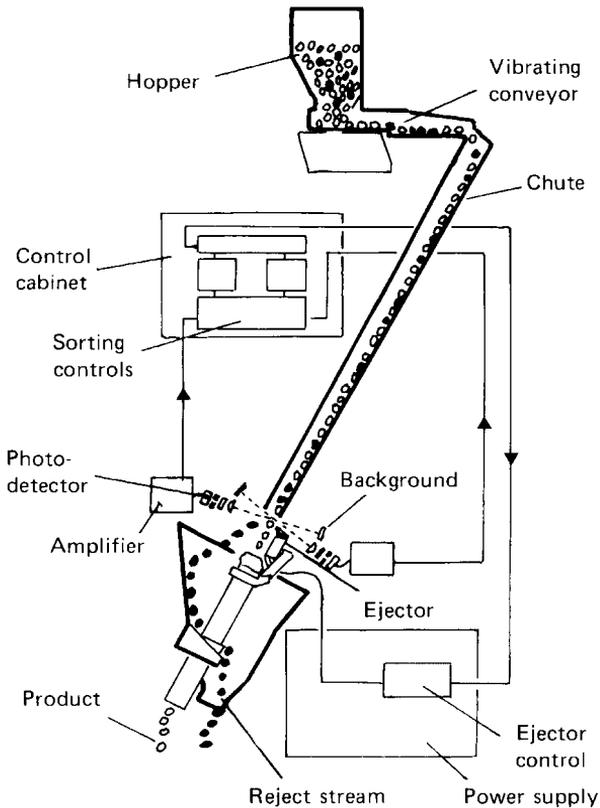


Fig. 3.8 Colour sorter.
(Courtesy of Sortex Ltd.)

A different type of equipment employs a sensor located above a conveyor belt, which views products as they pass beneath. The sensor detects up to eight colours and provides an alarm or control signal whenever a pre-selected colour passes the detector beam. It is also able to distinguish between different coloured foods which are to be processed separately. In a more sophisticated system, foods which have variations in colour over their surface are colour sorted by image processing. The foods are fed in rows on a roller conveyor beneath a video camera. The relative intensities of reflected red, green and yellow light are transmitted to the microcomputer which constructs a composite image of each piece of food, showing both the spread of colour and the mean colour of inspected foods. The computer compares the constructed image with pre-set specifications and activates a compressed air ejector or a mechanical deflector to remove rejected food. When this type of system is used to sort baked goods, it is also used to control directly the gas or electricity supply to the ovens, which is reported to reduce energy consumption in ovens by 20% (Philpotts, 1983). The sorter can be easily adapted to different foods, by operators using the microprocessor keypad (see also Chapters 2, 16 and 26).

3.2.3 Weight sorting

Weight sorting is more accurate than other methods and is therefore used for more valuable foods (for example eggs, cut meats and some tropical fruits). Eggs are sorted at

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up to $12\,000\text{ h}^{-1}$ into six to nine categories with a tolerance of 0.5 g. They are first graded by 'candling' (Section 3.3) and then pass to the weight sorter (Fig. 3.9). This consists of a slatted conveyor which transports the eggs above a series of counterbalanced arms. The conveyor operates intermittently and while stationary, the arms raise and weigh the eggs. Heavy eggs are discharged into a padded chute and lighter eggs are replaced on the conveyor to travel to the next weigher.

Aspiration and flotation sorting use differences in density to sort foods and are similar in principle and operation to aspiration and flotation cleaning. Grains, nuts and pulses are sorted by aspiration. Peas and lima beans are sorted by flotation in brine (specific gravity, 1.1162–1.1362). The denser, starchy, over-mature pieces sink whereas the younger pieces float.

The collation of foods which have variable weight, for example frozen fish fillets, into bulk packs which have a uniform declared weight is time consuming and laborious. It is normally performed by operators who select items of food from a pool of materials and collate them by trial and error into a pack which is as close as possible to the required weight. There is frequently a large give-away to ensure compliance with fill-weight legislation. Collation sorting is now performed automatically by a microcomputer. Items of food are weighed and placed in a magazine. Their weights are stored by a microcomputer which then selects the best combination of items to produce the desired number in a pack, with a minimum give-away. The foods are packed and the next best combination is selected until the limit on allowable weight cannot be achieved. Other examples of microprocessor-controlled weighing are described in Chapters 2 and 26.



Fig. 3.9 Egg sorter.
(Courtesy of Ben Nevis Packaging Ltd.)

3.3 Grading

This term is often used interchangeably with sorting but strictly means ‘the assessment of overall quality of a food using a number of attributes’. Sorting (that is separation on the basis of one characteristic) may therefore be used as part of a grading operation but not vice versa. Grading is carried out by operators who are trained to simultaneously assess a number of variables. For example, eggs are visually inspected over tungsten lights (termed ‘candling’) to assess up to twenty factors and remove those that are for example, fertilised or malformed and those that contain blood spots or rot. Meats, for example, are examined by inspectors for disease, fat distribution, bone to flesh ratio and carcass size and shape. Developments in meat inspection using image processing and computer analysis to assess a large number of factors, including bruising, skin colour and damage on chicken meat are described by Ade-Hall *et al.* (1996) (see also Chapter 2). Other graded foods include cheese and tea, which are assessed for flavour, aroma, colour, etc. Apples are graded with the assistance of coloured cards that show the required characteristics of different grades in terms of colour distribution across the fruit, surface blemishes and size and shape of the fruit.

In some cases the grade of food is determined from the results of laboratory analyses (for example wheat flour is assessed for protein content, dough extensibility, colour, moisture content and presence of insects). In general, grading is more expensive than sorting owing to the higher costs of skilled operators. However, many attributes that cannot be examined automatically can be simultaneously assessed, and this produces a more uniform high-quality product.

3.4 Peeling

Peeling is used in the processing of many fruits and vegetables to remove unwanted or inedible material, and to improve the appearance of the final product. The main consideration is to minimise costs by removing as little of the underlying food as possible and reducing energy, labour and material costs to a minimum. The peeled surface should be clean and undamaged. There are five main methods of peeling:

1. flash steam peeling
2. knife peeling
3. abrasion peeling
4. caustic peeling
5. flame peeling.

3.4.1 Flash steam peeling

Foods (for example root crops) are fed in batches into a pressure vessel which is rotated at 4–6 rpm. High-pressure steam (1500×10^3 Pa) is introduced and all food surfaces are exposed to the steam by the rotation of the vessel for a predetermined time, which differs according to the type of food. The high temperatures cause rapid heating of the surface layer (within 15–30 s) but the low thermal conductivity of the product prevents further heat penetration, and the product is not cooked. Texture and colour are therefore preserved. The pressure is then instantly released which causes steam to form under the skin, and the surface of the food ‘flashes off’. Most of the peeled material is discharged with the steam, and water sprays are needed only to remove any remaining traces. This

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type of peeler is gaining in popularity owing to the lower water consumption, minimum product loss, good appearance of the peeled surfaces, a high throughput (up to 4500 kg h^{-1}) with automatic control of the peeling cycle, and the production of a more easily disposable concentrated waste (Anon., 1984b).

3.4.2 Knife peeling

Stationary blades are pressed against the surface of rotating fruits or vegetables to remove the skin. Alternatively the blades may rotate against stationary foods. This method is particularly suitable for citrus fruits where the skin is easily removed and there is little damage or loss of fruit.

3.4.3 Abrasion peeling

Food is fed onto carborundum rollers or placed into a rotating bowl which is lined with carborundum. The abrasive surface removes the skin and it is washed away by a copious supply of water. The advantages of the method include low energy costs as the process operates at room temperature, low capital costs, no heat damage and a good surface appearance of the food. Irregular product surfaces (for example 'eyes' on potatoes) may mar the appearance of the peeled product and require hand finishing. The limitations of the method are:

- a higher product loss than flash peeling (25% compared with 8–18% losses, for vegetables)
- the production of large volumes of dilute waste which are difficult and expensive to dispose of
- relatively low throughputs as all pieces of food need to contact the abrasive surfaces.

An exception is the peeling of onions where the skin is easily removed by abrasive rollers at production rates of up to 2500 kg h^{-1} .

3.4.4 Caustic peeling

A dilute solution of sodium hydroxide (named lye) is heated to $100\text{--}120^\circ\text{C}$. In the older method of lye peeling, food is passed through a bath of 1–2% lye which softens the skin and the skin is then removed by high-pressure water sprays. Product losses are of the order of 17%. Although once popular for root crops, this method causes changes in the colour of some products and incurs higher costs. It is now largely replaced by steam or flash peeling. A development of lye peeling is named dry caustic peeling. Food is dipped in 10% sodium hydroxide and the softened skin is removed with rubber discs or rollers. This both reduces water consumption and product losses and gives a concentrated skin 'paste' which is more easily disposed of.

3.4.5 Flame peeling

Developed for onions, this peeler consists of a conveyor belt which carries and rotates the food through a furnace heated to 1000°C . The outer 'paper shell' and root hairs are burned off, and the charred skin is removed by high-pressure water sprays. Average product losses are 9%.

3.5 Acknowledgements

Grateful acknowledgement is made for information supplied by the following: Sortex Ltd, London E15 2PJ, UK; Loma Engineering Ltd, Farnborough, Hants GU14 0NY, UK; Spectron Instruments Ltd, Abingdon, Oxfordshire, UK; Gough and Co. Ltd, Hanley, Stoke on Trent, Staffordshire ST1 4AP, UK; Backus Sormac BV, Venlo, Holland; Goring Kerr, Windsor, Berkshire, UK; Ben Nevis Packaging Ltd, Trowbridge, Wiltshire BA14 8AB, UK; Sunkist Growers Ltd, California, USA; Flo-Mech Ltd, Peterborough PE2 0YA, UK.

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4

Size reduction

Size reduction or ‘comminution’ is the unit operation in which the average size of solid pieces of food is reduced by the application of grinding, compression or impact forces. When applied to the reduction in size of globules of immiscible liquids (for example oil globules in water) size reduction is more frequently referred to as homogenisation or emulsification. The size reduction of liquids to droplets (by atomisation) is described in Chapter 15. Size enlargement is achieved by extrusion (Chapter 14), agglomeration (Chapter 15) or forming (Chapter 5).

Size reduction has the following benefits in food processing:

- There is an increase in the surface-area-to-volume ratio of the food which increases the rate of drying, heating or cooling and improves the efficiency and rate of extraction of liquid components (for example fruit juice or cooking oil extraction (Chapter 6)).
- When combined with screening (Chapter 3), a predetermined range of particle sizes is produced which is important for the correct functional or processing properties of some products (for example icing sugar, spices and cornstarch).
- A similar range of particle sizes allows more complete mixing of ingredients (Chapter 5) (for example dried soup and cake mixes).

Size reduction and emulsification have little or no preservative effect. They are used to improve the eating quality or suitability of foods for further processing and to increase the range of products available. In some foods they may promote degradation by the release of naturally occurring enzymes from damaged tissues, or by microbial activity and oxidation at the increased area of exposed surfaces, unless other preservative treatments are employed.

Different methods of size reduction are classified according to the size range of particles produced:

1. *Chopping, cutting, slicing and dicing:*
 - (a) large to medium (stewing steak, cheese and sliced fruit for canning)
 - (b) medium to small (bacon, sliced green beans and diced carrot)

- (c) small to granular (minced or shredded meat, flaked fish or nuts and shredded vegetables).
2. *Milling* to powders or pastes of increasing fineness (grated products > spices > flours > fruit nectars > powdered sugar > starches > smooth pastes)
 3. *Emulsification* and *homogenisation* (mayonnaise, milk, essential oils, butter, ice cream and margarine).

4.1 Size reduction of solid foods

4.1.1 Theory

In all types of size reduction there are three types of force used to reduce the size of foods:

1. compression forces
2. impact forces
3. shearing (or attrition) forces.

In most size reduction equipment, all three forces are present, but often one is more important than the others. When stress (force) is applied to a food the resulting internal strains are first absorbed, to cause deformation of the tissues. If the strain does not exceed a certain critical level named the *elastic stress limit* (*E*), the tissues return to their original shape when the stress is removed, and the stored energy is released as heat (elastic region (O–E) in Fig. 4.1).

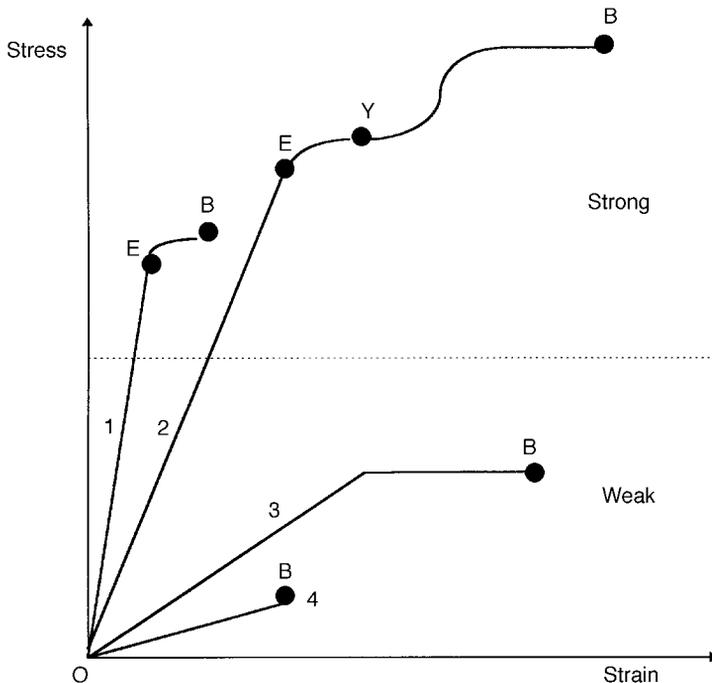


Fig. 4.1 Stress-strain diagram for various foods.

(E = elastic limit; Y = yield point; B = breaking point; O–E = elastic region; E–Y = inelastic deformation; Y–B = region of ductility; (1) = hard, strong, brittle material; (2) = hard, strong, ductile material; (3) = soft, weak, ductile material and (4) = soft, weak brittle material.) (After Loncin and Merson (1979).)

However, when the strain within a localised area exceeds the elastic stress limit, the food is permanently deformed. If the stress is continued, the strain reaches a *yield point* (Y). Above the yield point the food begins to flow (known as the ‘region of ductility’ ($Y-B$) in Fig. 4.1). Finally, the *breaking stress* is exceeded at the breaking point (B) and the food fractures along a line of weakness. Part of the stored energy is then released as sound and heat. As little as 1% of applied energy may actually be used for size reduction. As the size of the piece is reduced, there are fewer lines of weakness available, and the breaking stress that must be exceeded increases. When no lines of weakness remain, new fissures must be created to reduce the particle size further, and this requires an additional input of energy. There is therefore a substantial increase in energy requirement as the size of the particles is reduced (see Sample problem 4.1). It is important to specify the required size distribution in the product to avoid unnecessary expenditure of time and energy in creating smaller particles than are required for a particular application.

The amount of energy that is needed to fracture a food is determined by its hardness and tendency to crack (its *friability*) which in turn depends on the structure of the food. The fewer the lines of weakness in a food, the higher is the energy input needed to cause fracturing. Harder foods absorb more energy and consequently require a greater energy input to create fractures.

Compression forces are used to fracture friable or crystalline foods; combined impact and shearing forces are necessary for fibrous foods, and shearing forces are used for fine grinding of softer foods. It is thought that foods fracture at lower stress levels if force is applied for longer times. The extent of size reduction, the energy expended and the amount of heat generated in the food therefore depend on both the size of the forces that are applied and the time that food is subjected to the forces.

Other factors which influence the energy input are the moisture content and heat sensitivity of the food. The moisture content significantly affects both the degree of size reduction and the mechanism of breakdown in some foods. For example, before milling wheat is ‘conditioned’ to optimum moisture content and maize is thoroughly soaked and wet milled in order to obtain complete disintegration of the starchy material. Further details are given by Kent (1983). However, excessive moisture in a ‘dry’ food can lead to agglomeration of particles which then block the mill and very dry foods create excessive dust which causes a health hazard, and is extremely inflammable and potentially explosive.

Substantial amounts of heat are generated in high-speed mills. The heat sensitivity of the food determines the permissible temperature rise and the necessity to cool the mill. In *cryogenic grinding*, liquid nitrogen or solid carbon dioxide are mixed with foods (for example spices) before milling, to cool the product and to retain volatiles or other heat sensitive components. Solid carbon dioxide is also used to cool meat during size reduction in the manufacture of sausage meat.

The energy required to reduce the size of solid foods is calculated using one of three equations, as follows:

1. Kick’s law states that the energy required to reduce the size of particles is proportional to the ratio of the initial size of a typical dimension (for example the diameter of the pieces) to the final size of that dimension:

$$E = K_K \ln \left(\frac{d_1}{d_2} \right) \quad \boxed{4.1}$$

where E (J) = the energy required per mass of feed, K_K = Kick’s constant, d_1 (m) = the average initial size of pieces, and d_2 (m) = the average size of ground particles.

d_1/d_2 is known as the *size reduction ratio (RR)* and is used to evaluate the relative performance of different types of equipment. Coarse grinding has *RRs* below 8:1, whereas in fine grinding, ratios can exceed 100:1 (Brennan *et al.*, 1990).

2. Rittinger's law states that the energy required for size reduction is proportional to the change in surface area of the pieces of food (instead of a change in dimension described in Kick's law):

$$E = K_R \left(\frac{1}{d_2} - \frac{1}{d_1} \right) \quad \boxed{4.2}$$

where K_R = Rittinger's constant.

3. Bond's law is used to calculate the energy required for size reduction from:

$$\frac{E}{W} = \sqrt{\left(\frac{100}{d_2} \right)} - \sqrt{\left(\frac{100}{d_1} \right)} \quad \boxed{4.3}$$

where W (J kg^{-1}) = the Bond Work Index (40 000–80 000 J kg^{-1} for hard foods such as sugar or grain (Loncin and Merson, 1979)), d_1 (m) = diameter of sieve aperture that allows 80% of the mass of the feed to pass and d_2 (m) = diameter of sieve aperture that allows 80% of the mass of the ground material to pass.

In practice it has been found that Kick's law gives reasonably good results for coarse grinding in which there is a relatively small increase in surface area per unit mass. Rittinger's law gives better results with fine grinding where there is a much larger increase in surface area and Bond's law is intermediate between these two. However, equations (4.2) and (4.3) were developed from studies of hard materials (coal and limestone) and deviation from predicted results is likely with many foods.

Sample problem 4.1

Food is milled from 6 mm to 0.0012 mm using a 10 hp motor. Would this motor be adequate to reduce the size of the particles to 0.0008 mm? Assume Rittinger's equation and that 1 hp = 745.7 W.

Solution to Sample problem 4.1

From Equation (4.2),

$$7457 = K_R \left(\frac{1}{0.0012 \times 10^{-3}} \right) - \left(\frac{1}{6 \times 10^{-3}} \right)$$

Therefore,

$$K_R = \frac{7457}{1/1.2 \times 10^{-6} - 1/6 \times 10^{-3}} = 0.0089$$

To produce particles of 0.0008 mm

$$E = 0.0089 \frac{1}{0.0008 \times 10^{-3}} - \frac{1}{6 \times 10^{-3}} = 11123 \text{ W} \\ = 15 \text{ hp}$$

Therefore the motor is unsuitable and an increase in power of 50% is required.

4.1.2 Equipment

This section describes selected equipment used to reduce the size of both fibrous foods to smaller pieces or pulps, and dry particulate foods to powders. Summaries of the main applications are shown in Tables 4.1 and 4.2. Further details of the properties of powders are given by Lewis (1996) and in Chapter 15.

Most meats, fruits and vegetables fall into the general category of 'fibrous' foods. Meats are frozen or 'tempered' to just below their freezing point (Chapters 19 and 21) to improve the efficiency of cutting. Fruits and vegetables have an inherently firmer texture and are cut at ambient or chill temperatures. All types of cutters require the blade to be forced through the food with as little resistance as possible. Knife blades must be kept sharp, to both minimise the force needed to cut the food and to reduce cell rupture and consequent product damage and reduced yield. In moist foods, water acts as a lubricant, but in some sticky products, such as dates or candied fruits, food grade lubricants may be needed to cut them successfully. In general blades are not coated with non-slip materials, such as 'Teflon' or poly-tetra-fluoro-ethylene (PTFE) as these may wear off and contaminate the product, and are instead mirror-polished during manufacture.

During the 1990s improved cutting has been achieved with the introduction of *ultrasonic cutters*. These use knife blades or 'horns' (probes) which vibrate longitudinally (as a piston) at 20 kHz, with a cutting stroke of 50–100 μm . Details of the component parts and method of cutting are described by Rawson (1998). They are readily automated and have the following benefits:

- quality of the cut face is visually excellent
- the product is virtually undisturbed
- the required cutting force is significantly reduced
- multi-layered products or hard particles contained in a soft matrix can be cut
- the blade is self-cleaning
- crumbs and debris are significantly reduced
- it is cost effective, having low running costs
- less sharp blades are needed and longer intervals between sharpening, compared to conventional blades (Rawson, 1998).

Table 4.1 Applications of size reduction equipment

Equipment	Type of product ^a					Fineness ^b			
	1	2	3	4	5	a	b	c	d
Slicers			*	*	*	*			
Dicers			*	*	*	*			
Shredders				*	*	*	*		
Bowl choppers			*	*	*		*	*	
Pre-crushers	*			*	*		*		
Hammer mills	*	*		*	*		*	*	
Fine impact mills	*			*	*		*	*	*
Classifier mills	*				*				*
Air jets mills	*	*			*				*
Ball mills		*							*
Disc mills	*							*	*
Roller mills	*			*	*			*	*
Pulpers				*				*	*

^a 1 = soft brittle crystalline; 2 = hard abrasive; 3 = elastic tough cuttable; 4 = fibrous; 5 = heat sensitive greasy.

^b a = coarse lumps; b = coarse grits; c = medium to fine; d = fine to ultra-fine.

Adapted from Anon. (1986)

Table 4.2 Properties and applications of selected size reduction equipment

Type of equipment	Type(s) of force	Peripheral velocity (m s ⁻¹)	Typical products
Pin-and-disc mill	Impact	80–160	Sugar, starch, cocoa powder, nutmeg, pepper, roasted nuts, cloves
Wing-beater mill	Impact and shear	50–70	Alginates, pepper, pectin, paprika, dried vegetables
Disc-beater mill	Impact and shear	70–90	Milk powder, lactose, cereals, dried whey
Vertical toothed disc mill	Shear	4–8 17	Frozen coffee extract, plastic materials Coarse grinding of rye, maize, wheat, fennel, pepper, juniper berry
Cutting granulator	Impact (and shear)	5–18	Fish meal, pectin, dry fruit and vegetables
Hammer mill	Impact	40–50	Sugar, tapioca, dry vegetables, extracted bones, dried milk, spices, pepper
Ball mill	Impact and shear	–	Food colours
Roller mills	Compression and shear	–	Sugar cane, wheat (fluted rollers) Chocolate refining (smooth rollers)

After Loncin and Merson (1979).

The technique is particularly suitable for products that are difficult to cut using other methods (for example, sticky confectionery, hot bread and soft cake) and is increasingly used for bakery products of all types, frozen pies, ice cream, and fresh meats, fish and vegetables.

Size reduction of fibrous foods

There are four main types of size reduction equipment, classified in order of decreasing particle size as follows:

1. slicing and flaking equipment
2. dicing equipment
3. shredding equipment
4. pulping equipment.

Slicing and flaking equipment

The growth of the chilled sandwich market (also Chapter 19) has stimulated development of high speed slicers for both cutting bread precisely from corner to corner and for slicing fillings. In some designs (Fig. 4.2(a)) food is held against the slicer blades by centrifugal force and each slice falls away freely. This eliminates the problems found in earlier cutters, where multiple knife blades caused compression of the food and damage as it passed between the blades. High speed cutters are used to slice bacon and 'wafer thin' cooked meats at up to 2000 slices per minute and vegetables at up to 6 tonnes per hour. Newer designs are computer controlled and can be programmed easily by operators to bulk slice and stack a range of products including cheeses, pizza toppings, cooked meats, cucumber and tomato, and then apply them onto sandwich bread. Meats are also cut using circular rotary knives with a blade at right angles to the path of the meat. An 'intelligent' cheese cutter weighs and measures each block to determine the maximum number of portions that can be cut to the required weight with the minimum amount of waste (Sharp, 1998).

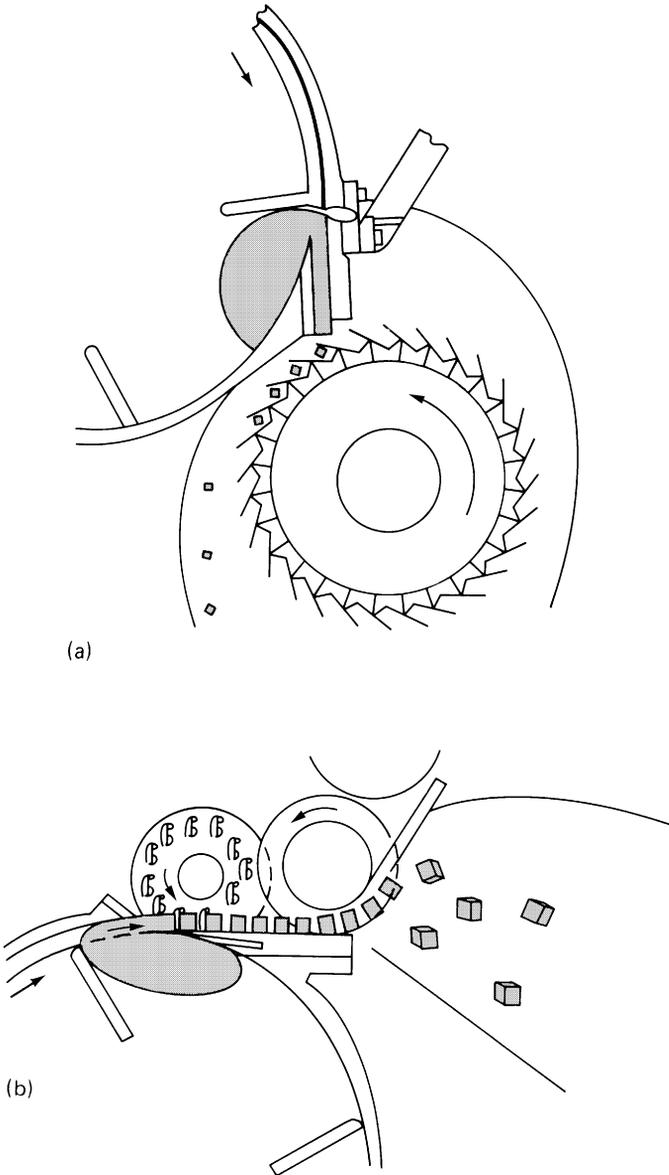


Fig. 4.2 (a) Slicing equipment; (b) dicing equipment.
(Courtesy of Urschel Ltd.)

Harder fruits such as apples are simultaneously sliced and de-cored as they are forced over stationary knives fitted inside a tube. In a similar design (the *hydrocutter*) foods are conveyed by water at high speed over fixed blades. More sophisticated slicers are able to cut vegetables into tagliatelle or garland shapes. Intermittent guillotine cutters are used to cut confectionery products, such as liquorice. The blade advances with the product on the conveyor to ensure a square cut edge regardless of the conveyor speed or cut length. The size of the cut can be adjusted from the control panel, without mechanical adjustment or downtime (Sharp, 1998). Flaking equipment for flaked fish, nuts or meat is similar to slicing equipment. Adjustment of the blade type and spacing is used to produce the flakes.

Dicing equipment

For dicing, vegetables, fruits and meats are first sliced and then cut into strips by rotating blades. The strips are fed to a second set of rotating knives which operate at right angles to the first set and cut the strips into cubes (Fig. 4.2(b)).

Shredding equipment

Typical equipment is a modified hammer mill (see Fig. 4.4(b)) in which knives are used instead of hammers to produce a cutting action. A second type of shredder, known as the *squirrel cage disintegrator*, has two concentric cylindrical cages inside a casing. They are fitted with knife blades along their length and the two cages rotate in opposite directions. Food is subjected to powerful shearing and cutting forces as it passes between them.

Pulping equipment

This uses a combination of compression and shearing forces for juice extraction from fruits or vegetables, for cooking oil production and for producing puréed and pulped meats. For example a rotary fruit crusher consists of a cylindrical metal screen fitted internally with high-speed rotating brushes or paddles (Nelson and Tressler, 1980). Grapes, tomatoes or other soft fruits are heated if necessary to soften the tissues, and pulp is forced through the perforations of the screen by the brushes. The size of the perforations determines the fineness of the pulp. Skins, stalks and seeds are discarded from the end of the screen. Other types of pulper, including roller presses and screw presses, are used for juice expression or cold extraction of cooking oils (Chapter 6). A *bowl chopper* (Fig. 4.3) is used to chop meat and harder fruits and vegetables into a pulp (for example for sausagemeat or mincemeat preserve). A horizontal, slowly rotating bowl moves the ingredients beneath a set of high-speed rotating blades. Food may be passed several times beneath the knives until the required degree of size reduction and mixing has been achieved.

Size reduction of dry foods

There are a large number of mills available for specific types of food. In this section a selection of common types is described and a summary of their properties and applications is shown in Table 4.2. Other types of equipment are described by Loncin and Merson (1979) and Leniger and Beverloo (1975). More recently, nibblers which use a grating rather than grinding action, have been used to replace mills, and are claimed to reduce problems of noise, increased temperatures and dust (Sharp, 1998). In an alternative design, sharp knives are arranged in a 152 mm diameter cylinder and an impeller operating at 2000–12 000 rpm pushes the product over the knives to give a controlled comminution to micro-fine powder. At this speed, products such as rice pass the blades at speeds in excess of 90 m s^{-1} (320 kph or 200 mph) and are rapidly reduced to a flour (Urschel, 1988).

Ball mills

These have a slowly rotating, horizontal steel cylinder which is half filled with steel balls 2.5–15 cm in diameter. At low speeds or when small balls are used, shearing forces predominate. With larger balls or at higher speeds, impact forces become more important. They are used to produce fine powders, such as food colourants. A modification of the ball mill named a *rod mill* has rods instead of balls to overcome problems associated with the balls sticking in adhesive foods.

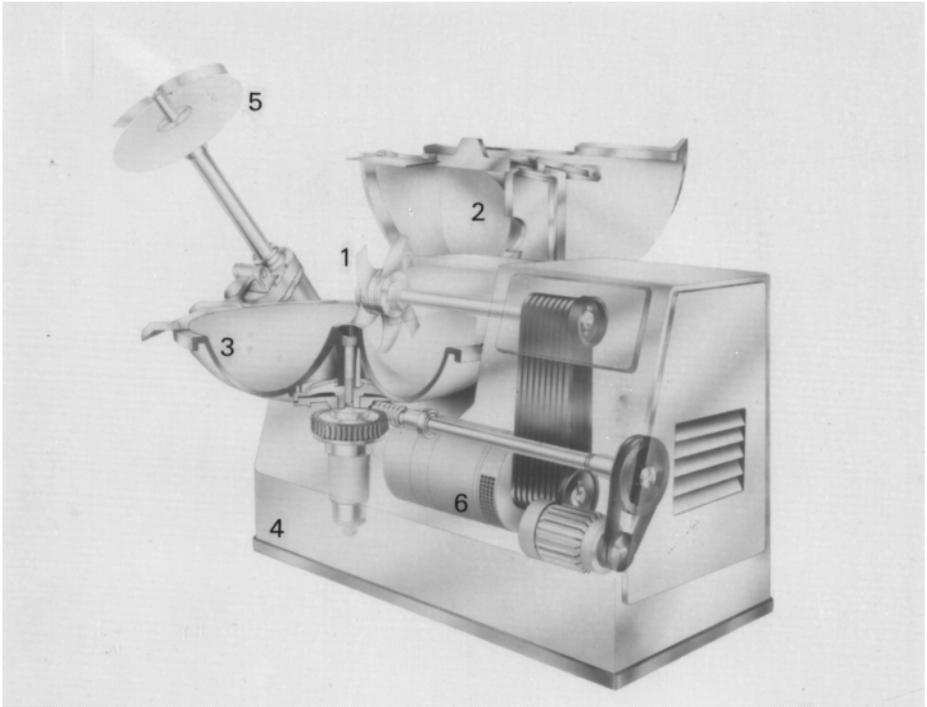


Fig. 4.3 Bowl chopper: 1, cutting blades; 2, cover; 3, rotating cutter bowl; 4, casing; 5, rotating unloader disc; 6, main motor.
(Courtesy of Hoegger Alpina Ltd.)

Disc mills

There are a large number of designs of *disc mill*, each employing shearing forces for fine grinding or shearing and impact forces for coarser grinding. For example:

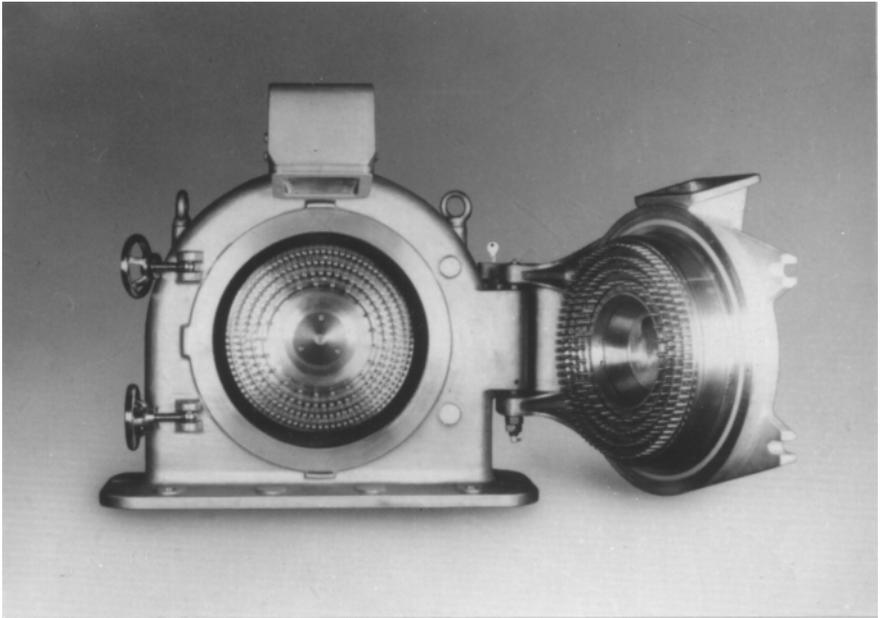
- single-disc mills in which food passes through an adjustable gap between a stationary casing and a grooved disc, which rotates at high speed
- double-disc mills which have two discs that rotate in opposite directions to produce greater shearing forces
- pin-and-disc mills which have intermeshing pins fixed either to the single disc and casing or to double discs (Fig. 4.4(a)). These improve the effectiveness of milling by creating additional impact and shearing forces (see also Section 4.2.2, colloid mills).

Hammer mills

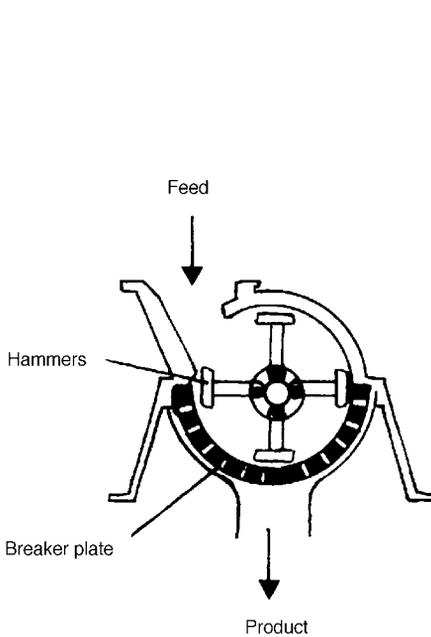
These have a horizontal cylindrical chamber, lined with a toughened steel breaker plate. A high-speed rotor inside the chamber is fitted with swinging hammers along its length (Fig. 4.4(b)). Food is disintegrated mainly by impact forces as the hammers drive it against the breaker plate. Hammer mills are widely used for crystalline and fibrous materials including spices and sugar.

The above mills can be operated in three modes:

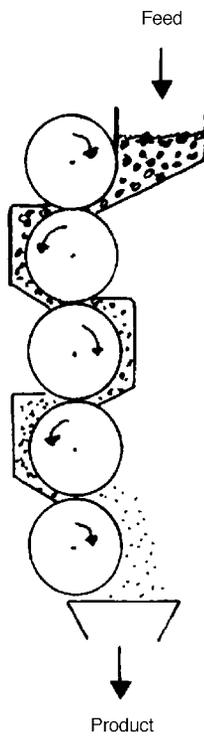
1. free flow of materials through the mill in a single pass
2. the exit from the mill is restricted by a screen and food remains in the mill until the particles are sufficiently small to pass through the screen apertures (under these 'choke' conditions, shearing forces play a larger part in the size reduction)



(a)



(b)



(c)

Fig. 4.4 Mills: (a) pin and disc mill (Courtesy of Alpine Process Technology); (b) hammer mill; (c) roller mill. (After Leniger and Beverloo (1975).)

3. recirculation through the mill of all material or larger pieces until sufficient size reduction has been achieved.

Roller mills

Roller mills are widely used to mill wheat. Two or more steel rollers revolve towards each other and pull particles of food through the 'nip' (the space between the rollers) (Fig. 4.4(c)). The main force is compression but, if the rollers are rotated at different speeds, or if the rollers are fluted,¹ additional shearing forces are exerted on the food. The size of the nip is adjustable for different foods and overload springs protect against accidental damage from metal or stones.

4.1.3 Effect on foods

Size reduction is used in processing to control the textural or rheological properties of foods and to improve the efficiency of mixing and heat transfer. The texture of many foods (for example bread, hamburgers and juices) is controlled by the conditions used during size reduction of the ingredients. There is also an indirect effect on the aroma and flavour of some foods. The disruption of cells and resulting increase in surface area promotes oxidative deterioration and higher rates of microbiological and enzymic activity. Size reduction therefore has little or no preservative effect. Dry foods (for example grains or nuts) have a sufficiently low a_w (Chapter 1) to permit storage for several months after milling without substantial changes in nutritional value or eating quality. However, moist foods deteriorate rapidly if other preservative measures (for example chilling, freezing and heat processing) are not taken.

Sensory characteristics

There are small but largely unreported changes in the colour, flavour and aroma of dry foods during size reduction. Oxidation of carotenes bleaches flour and reduces the nutritional value. There is a loss of volatile constituents from spices and some nuts, which is accelerated if the temperature is allowed to rise during milling. In moist foods the disruption of cells allows enzymes and substrates to become more intimately mixed, which causes accelerated deterioration of flavour, aroma and colour. Additionally the release of cellular materials provides a suitable substrate for microbiological growth and this can also result in the development of off-flavours and aromas.

The texture of foods is substantially altered by size reduction, both by the physical reduction in the size of tissues and also by the release of hydrolytic enzymes. The type and duration of size reduction and the delay before subsequent preservation operations are closely controlled to achieve the desired texture. The relationship between the size of food particles and perceived texture is discussed by Stanley and Tung (1976) and Sherman (1976).

Nutritional value

The increase in surface area of foods during size reduction causes loss of nutritional value due to oxidation of fatty acids and carotenes. Losses of vitamin C and thiamin in chopped or sliced fruits and vegetables are substantial (for example 78% reduction in vitamin C during slicing of cucumber) (Erdman and Erdman, 1982). Losses during storage depend on the temperature and moisture content of the food and on the concentration of oxygen

1. Shallow ridges along the length of the roller.

Table 4.3 Effect of milling on vitamin content of selected grains

Product	Content per 100 g									
	Vitamin A (IU)	a-Tocopherol (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)	Vitamin C (mg)	Pantothenic acid (mg)	Vitamin B ₆ (mg)	Folic acid (µg)	Biotin (µg)
Maize										
Kernel	400	1.43	0.15	0.12	1.7	12	0.54	0.16	26.8	11.0
Flour	340	–	0.20	0.06	1.4	0	–	–	–	–
Rice										
Grain	0	0.68	0.34	0.05	4.7	0	1.10	0.55	20.2	12.0
White grain	0	0.10	0.07	0.03	1.6	0	0.55	0.17	14.1	5.0
Bran	0	–	2.26	0.25	29.8	0	2.8	2.5	150	60
Wheat										
Grain (hard)	0	1.35	0.57	0.12	4.3	0	1.5	0.4	14.4	12
80% extraction ^a	–	–	0.25	0.08	1.6	–	0.9	0.11	13	1.4
70% extraction ^a	–	–	0.08	0.05	1.1	–	0.7	0.06	10	1.1
Bran	0	1.71	0.72	0.35	21.0	0	2.9	0.82	155	49

^a Percentage extraction = weight of flour per 100 parts of flour milled.

Adapted from Houston and Kohler (1970), Bauernfeind (1977), Toepfer *et al.* (1951) and Frigg (1976).

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in the storage atmosphere. In dry foods the main loss in nutritional value results from separation of the product components after size reduction (for example the separation of bran from rice, wheat or maize in Table 4.3).

4.2 Size reduction in liquid foods (emulsification and homogenisation)

The terms *emulsifiers* and *homogenisers* are often used interchangeably for equipment used to produce emulsions: emulsification is the formation of a stable emulsion by the intimate mixing of two or more immiscible liquids, so that one (the dispersed phase) is formed into very small droplets within the second (the continuous phase). Homogenisation is the reduction in size (to 0.5–30 μm), and hence the increase in number, of solid or liquid particles in the dispersed phase by the application of intense shearing forces. Homogenisation is therefore a more severe operation than emulsification. Both operations are used to change the functional properties or eating quality of foods and have little or no effect on nutritional value or shelf life. Examples of emulsified products include margarine and low-fat spreads, salad cream and mayonnaise, sausagemeat, ice cream and cakes.

4.2.1 Theory

The two types of liquid–liquid emulsion are:

1. oil in water (o/w) (for example milk)
2. water in oil (w/o) (for example margarine).

These are relatively simple systems and more complex emulsions are found in such products as ice cream, sausagemeat and cakes (Section 4.2.3).

The stability of emulsions is determined by:

- the type and quantity of emulsifying agent (Appendix C)
- the size of the globules in the dispersed phase
- the interfacial forces acting at the surfaces of the globules
- the viscosity of the continuous phase
- the difference between the densities of the dispersed and continuous phases (see Chapter 1, Section 1.1.3).

The action of homogenisers reduces the size of droplets in the dispersed phase and emulsifying agents that are present in, or added to, a food form micelles around each droplet. This reduces the interfacial tension between the phases and prevents the droplets from coalescing (the higher the interfacial tension between the continuous and dispersed phases, the more difficult it is to form and maintain a stable emulsion). Emulsifying agents therefore lower the energy input needed to form an emulsion.

Naturally occurring proteins and phospholipids act as emulsifying agents, but in food processing synthetic agents (including esters of glycerol or sorbitan esters of fatty acids) are more effective and these are normally used. Synthetic emulsifying agents are classified into polar and non-polar types. Those that contain mostly polar groups bind to water and therefore produce o/w emulsions. Non-polar agents are adsorbed to oils to produce w/o emulsions. They are characterised by their hydrophile–lipophile balance (HLB) value (Table 4.4). Agents with low HLB values (below 9) are lipophilic and used for w/o emulsions; those with HLB values between 8 and 11 are intermediate and used as

Table 4.4 Selected emulsifying agents used in food processing

Emulsifier	HLB value	Function and typical application
<i>Ionic</i>		
Phospholipids (e.g. lecithin)	18–20	Crumb softening (baked goods)
Potassium or sodium salts of oleic acid		Aid to extrusion and reduction in stickiness (pasta, snackfoods, chewing gum)
Protein (e.g. gelatin, egg albumin)		Improved whipping and aeration (instant potato, frozen cream and toppings)
Sodium stearyl-2-lactylates		Dispersion (coffee whiteners)
<i>Non-ionic</i>		
Glycerol monostearate	2.8	Anti-staling, crumb softening (most baked products)
Polyglycerol esters		
Polyoxyethylene sorbitol fatty acids	14.9	Fat crystal modification (peanut butter, coatings – see Chapter 23)
Propylene glycol fatty acid esters	3.4	
Sorbitol esters of fatty acids	4.7	Bloom retardation (chocolate, coatings) Overrun control (ice cream)
<i>Hydrocolloids</i>		
Alginates		
Carboxymethyl cellulose		
Carrageenan		
Guar		
Gum arabic		
Locust bean		
Methyl cellulose	10.5	
Pectin		
Tragacanth	11.9	
Xanthan		

Adapted from Lewis (1990) and Lissant (1974).

wetting agents; and those with high values (11 to 20) are hydrophilic and are used for o/w emulsions, detergents and solubilisers (Lewis, 1990). Polar emulsifying agents are also classified into ionic and non-ionic types. Ionic types have different surface activities over the pH range, owing to differences in their dissociation behaviour. The activity of non-ionic emulsifiers is independent of pH. Careful selection of the type of emulsifying agent is therefore needed to create the required emulsion in a given food system. Details are given in Lissant (1984).

Stabilisers (Appendix C) are polysaccharide hydrocolloids which dissolve in water to form viscous solutions or gels. In o/w emulsions, they increase the viscosity and form a three-dimensional network that stabilises the emulsion and prevents coalescence. Microcrystalline cellulose and related cellulose powders are able to stabilise w/o emulsions.

The factors that influence the stability of an emulsion are related by *Stoke's Law*:

$$v = \frac{d^2 g (\rho_p - \rho_s)}{18\mu} \quad \boxed{4.4}$$

where v (m s^{-1}) = terminal velocity (i.e. velocity of separation of the phases), d (m) = diameter of droplets in the dispersed phase, g = acceleration due to gravity = 9.81 m s^{-2} , ρ_p (kg m^{-3}) = density of dispersed phase, ρ_s (kg m^{-3}) = density of continuous phase, and μ (N s m^{-2}) = viscosity of continuous phase.

The equation indicates that stable emulsions are formed when droplet sizes are small (in practice between $1\ \mu\text{m}$ and $10\ \mu\text{m}$), the densities of the two phases are reasonably close and the viscosity of the continuous phase is high. Physical changes to droplets, and equations which relate droplet distortion to shear rate, are described by Loncin and Merson (1979).

4.2.2 Equipment

The five main types of homogeniser are:

1. high-speed mixers
2. pressure homogenisers
3. colloid mills
4. ultrasonic homogenisers
5. hydroshear homogenisers and microfluidisers.

They are described in more detail by Rees (1967) and Brennan *et al.* (1990).

High-speed mixers

High-speed mixers use turbines or propellers (see Chapter 5, Fig. 5.6), to pre-mix emulsions of low-viscosity liquids. They operate by a shearing action on the food at the edges and tips of the blades.

Pressure homogenisers

Pressure homogenisers consist of a high-pressure pump, operating at $10\ 000\text{--}70\ 000 \times 10^3\ \text{Pa}$, which is fitted with a homogenising valve on the discharge side (Fig. 4.5). When liquid is pumped through the small adjustable gap (up to $300\ \mu\text{m}$) between the valve and the valve seat, the high pressure produces a high liquid velocity ($80\text{--}150\ \text{m s}^{-1}$). There is then an almost instantaneous drop in velocity as the liquid emerges from the valve. These extreme conditions of turbulence produce powerful shearing forces and the droplets in the dispersed phase become disrupted. The collapse of air bubbles (termed cavitation) and impact forces created in some valves by placing a hard surface (a breaker ring) in the path of the liquid, further reduce the globule size. In some foods, for example milk products,

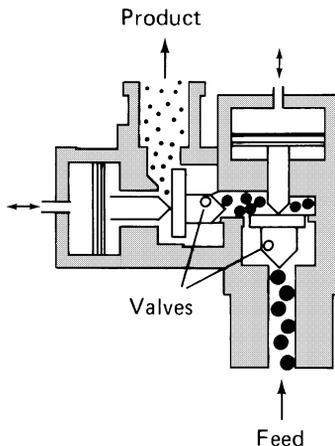


Fig. 4.5 Hydraulic two-stage pressure homogenising valve.
(Courtesy of APV Crepaco Inc.)

there may be inadequate distribution of the emulsifying agent over the newly formed surfaces, which causes fat globules to clump together. A second similar valve is then used to break up the clusters of globules. Pressure homogenisers are widely used before pasteurisation (Chapter 11) and ultra high-temperature sterilisation (Chapter 12) of milk, and in the production of salad creams, ice cream and some soups and sauces.

Colloid mills

Colloid mills are essentially disc mills with a small clearance (0.05–1.3 mm) between a stationary disc and a vertical disc rotating at 3000–15 000 rpm. They create high shearing forces and are more effective than pressure homogenisers for high-viscosity liquids. With intermediate-viscosity liquids they tend to produce larger droplet sizes than pressure homogenisers do. Numerous designs of disc, including flat, corrugated and conical shapes, are available for different applications. Modifications of this design include the use of two counter-rotating discs or intermeshing pins on the surface of the discs to increase the shearing action. For highly viscous foods (for example peanut butter, meat or fish pastes) the discs may be mounted horizontally as in the *paste mill*. The greater friction created in viscous foods may require these mills to be cooled by recirculating water.

Ultrasonic homogenisers

Ultrasonic homogenisers use high-frequency sound waves (18–30 kHz) to cause alternate cycles of compression and tension in low-viscosity liquids and cavitation of air bubbles, to form emulsions with droplet sizes of 1–2 μm . The two phases of an emulsion are pumped through the homogeniser at pressures of $340\text{--}1400 \times 10^3$ Pa. The ultrasonic energy is produced by a vibrating metal blade (Fig. 4.6). The frequency of vibration is controlled by adjusting the clamping position of the blade. This type of homogeniser is used for the production of salad creams, ice cream, synthetic creams, baby foods and essential oil emulsions. It is also used for dispersing powders in liquids (Chapter 5).

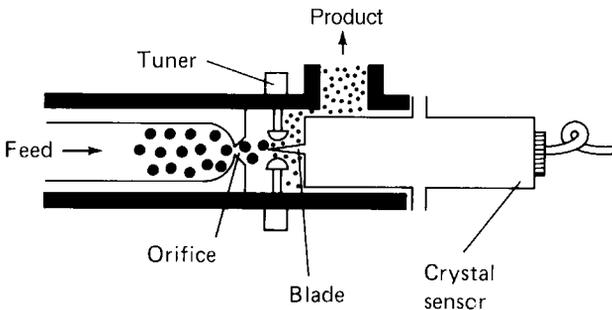


Fig. 4.6 Ultrasonic homogeniser.
(After Loncin and Merson (1979).)

Hydro shear homogenisers and microfluidisers

The *hydro shear homogeniser* is a double-cone shaped chamber which has a tangential feed pipe at the centre and outlet pipes at the end of each cone. The feed liquid enters the chamber at high velocity and is made to spin in increasingly smaller circles and increasing velocity until it reaches the centre and is discharged. The differences in velocity between adjacent layers of liquid causes high shearing forces, which together with cavitation and ultra-high frequency vibration, break droplets in the dispersed phase

to within a range of 2–8 μm . A similar type of equipment, termed a *microfluidiser* operates by pumping fluids into a chamber and causing shear and turbulence when they interact and producing droplets of less than 1 μm in diameter, within a narrow size range (Brennan *et al.*, 1990).

4.2.3 Effect on foods

Viscosity or texture

In many liquid and semi-liquid foods, the desired mouthfeel is achieved by careful selection of the type of emulsifying agent and stabiliser and by control over homogenisation conditions. In milk, homogenisation reduces the average size of fat globules from 4 μm to less than 1 μm , thereby giving the milk a creamier texture. The increase in viscosity is due to the higher number of globules and adsorption of casein onto the globule surface. These changes are discussed in detail by Harper (1979).

In solid food emulsions the texture is determined by the composition of the food, the homogenisation conditions and post-processing operations such as heating or freezing. Meat emulsions (for example sausage and paté) are o/w emulsions in which the continuous phase is a complex colloidal system of gelatin, proteins, minerals and vitamins, and the dispersed phase is fat globules. The stability of the continuous phase is determined in part by the water-holding capacity (WHC) and fat-holding capacity (FHC) of the meat proteins. The factors which affect WHC and FHC are described by Laurie (1985). The quality of the emulsion is influenced by:

- the ratios of meat:ice:water:fat
- use of polyphosphates to bind water
- the time, temperature and speed of homogenisation.

The emulsion is set by heat during subsequent cooking.

Cream is an o/w emulsion that is mechanically agitated (churned) to cause a partial breakdown of the emulsion when it is made into butter. During this stage, air is incorporated to produce a foam. Liquid fat is released from globules at the surfaces of air bubbles, and this binds together clumps of solid fat to form butter 'grains'. These are then mixed at low speed (worked) to disperse water as fine droplets throughout the mass and to rupture any fat globules remaining from the cream. Although butter is thought of as a w/o emulsion, the complete inversion of the o/w emulsion of cream does not take place. The final product has a continuous phase of 85% fat which contains globules and crystals of solid fat and air bubbles. The dispersed phase (15%) consists of water droplets and buttermilk. The stability of butter is mostly due to its semi-solid nature which prevents migration of bacteria trapped in water droplets, and not due to the action of an emulsifying agent. Details of butter production are given by Lane (1992).

Margarine and low-fat spreads are w/o emulsions. They are produced from a blend of oils, which is heated with a solution of skim milk, salt, added vitamins and emulsifying agents. The warm mixture is emulsified and then chilled and worked to the desired consistency in a continuous operation, using a high pressure tubular chiller. The fats crystallise as they cool, to form a three-dimensional network of long thin needles, which produce the desired smooth texture. Fats are polymorphic and it is the β' -form that is required; the β -form is larger and causes a grainy texture and the α -form rapidly undergoes transition to the β' -form (see also a discussion of fats in chocolate in Chapter 23). The fat content of margarine is similar to butter, whereas

low-fat spreads have approximately 40% fat. The oils are chosen to have low melting points and these products are therefore spreadable at refrigeration temperatures. Details are given by Lane (1992).

In ice cream and cake batters, the emulsion is formed as a liquid, and the texture of the final product is partly determined by subsequent unit operations of freezing and baking respectively. Ice cream is a thick o/w emulsion which has a complex continuous phase of ice crystals, colloidal milk solids, dissolved sugar, flavouring, colouring and stabilisers, and a solid–air foam. The dispersed phase is milk fat. Air is incorporated into the emulsion during freezing to create the foam having air cells $<100\mu$ in diameter. This increases the softness and lightness of the product and allows it to be easily scooped. The amount of air is measured as the overrun (see Chapter 1, Section 1.1.1). Commercial ice creams have overruns of 60–100%.

Freezing partially destabilises the emulsion to produce a degree of clumping of fat globules, which improves the texture. Commercial ice creams usually have a softer texture than home-made products due to faster freezing, which produces smaller (40–50 μ) ice crystals (Chapter 21), the overrun, and emulsifiers (e.g. esters of mono- and diglycerides) and stabilisers (e.g. alginates, carrageenan, gums or gelatin) (Appendix C), which cause a larger proportion of the aqueous phase to remain unfrozen. This prevents lactose crystallisation and reduces graininess. As a result, less heat is needed to melt the ice cream and it does not therefore feel excessively cold when eaten. Details of ice cream production are given by Jaspersen (1989) and Andreasen and Nielsen (1992).

Cake batters are similarly o/w emulsions, in which the continuous phase is colloidal starch, a solution of sugar and flavours, and a foam produced during mixing. The dispersed phase is added fats or oils. Details of the changes to cake batters during mixing and baking, and the effects of variations in their formulation are described by Mizukoshi (1990).

Colour, aroma, nutritional value and shelf life

Homogenisation has an effect on the colour of some foods (for example milk) because the larger number of globules causes greater reflectance and scattering of light. Flavour and aroma are improved in many emulsified foods because volatile components are dispersed throughout the food and hence have greater contact with taste buds when eaten. The nutritional value of emulsified foods (Table 4.5) is changed if components are separated (for example in butter making), and there is improved digestibility of fats and proteins owing to the reduction in particle size. The nutritional value of other foods is determined by the formulation used and is not directly affected by emulsification or homogenisation. However, the additional unit operations (for example chilling, freezing and baking), which are necessary to extend the shelf life, may cause changes to nutritional value. In all food emulsions, degradative changes such as hydrolysis or oxidation of pigments, aroma compounds and vitamins, and microbial growth on the finely dispersed material, are minimised by careful control over the processing, packaging and storage conditions. In many countries, special regulations are in force to control hygienic standards during preparation of food emulsions (particularly meat and dairy emulsions) owing to the risk of dispersing pathogenic bacteria throughout the food.

Table 4.5 Effect of emulsification on nutritional value

Nutrient (per 100 g food)	Amount in the following	
	Cream (double)	Butter (salted)
Water (g)	48	15.4
Protein (g)	1.5	0.4
Fat (g)	48	82
Carbohydrate (g)	2.0	0
Energy (kJ)	1850	3040
Vitamin A (μg)	430	730
Vitamin D (μg)	0.28	0.50
Thiamin (μg)	20	0
Riboflavin (μg)	80	0

Adapted from Rolls (1982).

4.3 Acknowledgements

Grateful acknowledgement is made for information supplied by the following: Gerstenberg & Agger A/S, DK-1809 Frederiksberg C, Copenhagen, Denmark; Alpine Process Technology Ltd, Runcorn, Cheshire WA7 3DS, UK; Urschel International Ltd, Leicester LE6 OFH, UK; Peter Holland Ltd, Stamford, Lincolnshire PE9 2PE, UK; Hoegger Alpina Ltd, CH-9202 Gossau, Switzerland; Grindsted Products A/S, DK-8220 Brabrand, Denmark; Rannie, DK-2620 Albertslund, Denmark; Crepaco Inc., c/o Alfred & Co. Ltd, Wembley, Middlesex HA0 1WD, UK; Pasilac A/S, DK-8600 Silkeborg, Denmark; Soavi B and Figli, 43026 Parma, Italy.

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5

Mixing and forming

Mixing (or blending) is a unit operation in which a uniform mixture is obtained from two or more components, by dispersing one within the other(s). The larger component is sometimes called the *continuous phase* and the smaller component the *dispersed phase* by analogy with emulsions (Chapter 4), but these terms do not imply emulsification when used in this context. Mixing has no preservative effect and is intended solely as a processing aid or to alter the eating quality of foods. It has very wide applications in many food industries where it is used to combine ingredients to achieve different functional properties or sensory characteristics. Examples include texture development in doughs and ice cream, control of sugar crystallisation and aeration of batters and some chocolate products. In some foods, adequate mixing is necessary to ensure that the proportion of each component complies with legislative standards (for example mixed vegetables, mixed nuts, sausages and other meat products). Extruders (Chapter 14) and some types of size reduction equipment (Chapter 4) also have a mixing action.

Forming is a size enlargement operation in which foods that have a high viscosity or a dough-like texture are moulded into a variety of shapes and sizes, often immediately after a mixing operation. It is used as a processing aid to increase the variety and convenience of baked goods, confectionery and snackfoods. It has no direct effect on the shelf life or nutritional value of foods. Close control over the size of formed pieces is critical (for example to ensure uniform rates of heat transfer to the centre of baked foods, to control the weight pieces of food, and to ensure the uniformity of smaller foods and hence to control fill weights). Extrusion (Chapter 14) also has a forming function.

5.1 Mixing

When food products are mixed there are a number of aspects that are different to other industrial mixing applications:

- mixing is often used primarily to develop desirable product characteristics, rather than simply ensure homogeneity

- it is often multi-component, involving ingredients of different physical properties and quantities
- it may often involve high viscosity or non-Newtonian liquids
- some components may be fragile and damaged by over-mixing
- there may be complex relationships between mixing patterns and product characteristics

The criteria for successful mixing have been described as first achieving an acceptable product quality (in terms of sensory properties, functionality, homogeneity, particulate integrity, etc.) followed by adequate safety, hygienic design, legality (compositional standards for some foods), process and energy efficiency, and flexibility to changes in processing (Campbell, 1995). A detailed review of mixing operations is given by Lindley (1991a–c).

5.1.1 Theory of solids mixing

In contrast with liquids and viscous pastes (Section 5.1.2) it is not possible to achieve a completely uniform mixture of dry powders or particulate solids. The degree of mixing that is achieved depends on:

- the relative particle size, shape and density of each component
- the moisture content, surface characteristics and flow characteristics of each component
- the tendency of the materials to aggregate
- the efficiency of a particular mixer for those components.

In general, materials that are similar in size, shape and density are able to form a more uniform mixture than are dissimilar materials. During a mixing operation, differences in these properties also cause *unmixing* (or separation) of the component parts. In some mixtures, uniformity is achieved after a given period and then unmixing begins. It is therefore important in such cases to time the mixing operation accurately. The uniformity of the final product depends on the equilibrium achieved between the mechanisms of mixing and unmixing, which in turn is related to the type of mixer, the operating conditions and the component foods.

If a two-component mixture is sampled at the start of mixing (in the unmixed state), most samples will consist entirely of one of the components. As mixing proceeds, the composition of each sample becomes more uniform and approaches the average composition of the mixture. One method of determining the changes in composition is to calculate the standard deviation of each fraction in successive samples:

$$\sigma_m = \sqrt{\left[\frac{1}{n-1} \sum (c - \bar{c})^2 \right]} \quad \boxed{5.1}$$

where σ_m = standard deviation, n = number of samples, c = concentration of the component in each sample and \bar{c} = the mean concentration of samples. Lower standard deviations are found as the uniformity of the mixture increases.

A number of mixing indices are available to monitor the extent of mixing and to compare alternative types of equipment:

$$M_1 = \frac{\sigma_m - \sigma_\infty}{\sigma_0 - \sigma_\infty} \quad \boxed{5.2}$$

$$M_2 = \frac{\log \sigma_m - \log \sigma_\infty}{\log \sigma_0 - \log \sigma_\infty} \quad [5.3]$$

$$M_3 = \frac{\sigma_m^2 - \sigma_\infty^2}{\sigma_0^2 - \sigma_\infty^2} \quad [5.4]$$

where σ_∞ = the standard deviation of a 'perfectly mixed' sample, σ_0 = the standard deviation of a sample at the start of mixing and σ_m = the standard deviation of a sample taken during mixing. σ_0 is found using:

$$\sigma_0 = \sqrt{[V_1(1 - V_1)]} \quad [5.5]$$

where V = the average fractional volume or mass of a component in the mixture.

In practice, perfect mixing (where $\sigma_\infty = 0$) cannot be achieved, but in efficient mixers the value becomes very low after a reasonable period. The mixing index M_1 is used when approximately equal masses of components are mixed and/or at relatively low mixing rates, M_2 is used when a small quantity of one component is incorporated into a larger bulk of material and/or at higher mixing rates, and M_3 is used for liquids or solids mixing in a similar way to M_1 . In practice, all three are examined and the one that is most suitable for the particular ingredients and type of mixer is selected.

The mixing time is related to the mixing index using:

$$\ln M = -Kt_m \quad [5.6]$$

where K = mixing rate constant, which varies with the type of mixer and the nature of the components, and t_m (s) = mixing time.

Sample problem 5.1

During preparation of a dough, 700 g of sugar are mixed with 100 kg of flour. Ten 100 g samples are taken after 1, 5 and 10 min and analysed for the percentage sugar. The results are as follows.

Percentage after	1 min	0.21	0.32	0.46	0.17	0.89	1.00	0.98	0.23	0.10	0.14
Percentage after	5 min	0.85	0.80	0.62	0.78	0.75	0.39	0.84	0.96	0.58	0.47
Percentage after	10 min	0.72	0.69	0.71	0.70	0.68	0.71	0.70	0.72	0.70	0.70

Calculate the mixing index for each mixing time and draw conclusions regarding the efficiency of mixing. Assume that for 'perfect mixing' there is a probability that 99.7% of samples will fall within three standard deviations of the mean composition ($\sigma = 0.01\%$).

Solution to Sample problem 5.1

Average fractional mass V_1 of sugar in the mix

$$\begin{aligned} &= \frac{700}{100 \times 10^3} \\ &= 7 \times 10^{-3} \end{aligned}$$

From equation (5.5),

$$\begin{aligned}\sigma_0 &= \sqrt{[7 \times 10^{-3}(1 - 7 \times 10^{-3})]} \\ &= 0.08337 \\ &= 8.337\%\end{aligned}$$

After 10 min

$$\text{mean } \bar{c} \text{ of the samples} = 0.703$$

Using equation (5.1), after 1 min,

$$\sigma_m = \sqrt{\left[\frac{1}{10-1} \sum (c - 0.703)^2 \right]}$$

(that is subtract 0.703 from c for each of the ten samples, square the result and sum the squares):

$$\begin{aligned}\sigma_m &= \sqrt{(0.11 \times 1.837)} \\ &= \sqrt{0.2020} \\ &= 0.4495\%\end{aligned}$$

After 5 min,

$$\sigma_m = 0.0772\%$$

and, after 10 min,

$$\sigma_m = 0.0125\%$$

Using equation (5.3), after 1 min,

$$\begin{aligned}M_2 &= \frac{\log 0.4495 - \log 0.01}{\log 8.337 - \log 0.01} \\ &= 0.566\end{aligned}$$

After 5 min,

$$M_2 = 0.304$$

and, after 10 min,

$$M_2 = 0.0326$$

Interpretation: if the $\log M_2$ is plotted against time, the linear relationship indicates that the mixing index gives a good description of the mixing process and that mixing takes place uniformly and efficiently.

Using equation (5.6), after 10 min,

$$\ln 0.0326 = -k \times 600$$

Therefore,

$$k = 0.0057$$

The time required for $\sigma_m = \sigma_\infty = 0.01\%$ is then found:

$$\ln 0.01 = -0.0057 t_m$$

$$t_m = 808 \text{ s}$$

Therefore

$$\begin{aligned} \text{remaing mixing time} &= 808 - 600 \\ &= 208 \\ &\approx 3.5 \text{ min} \end{aligned}$$

5.1.2 Theory of liquids mixing

The component velocities induced in low viscosity liquids by a mixer are as follows (Fig. 5.1a):

- A. a longitudinal velocity (parallel to the mixer shaft)
- B. a rotational velocity (tangential to the mixer shaft)
- C. a radial velocity which acts in a direction perpendicular to the mixer shaft.

To achieve successful mixing, the radial and longitudinal velocities imparted to the liquid are maximised by baffles, off-centre or angled mixer shafts, or angled blades (Fig 5.1b).

To mix low-viscosity liquids adequately, turbulence must be induced throughout the bulk of the liquid to entrain slow-moving parts within faster moving parts. A vortex should be avoided because adjoining layers of circulating liquid travel at a similar speed and mixing does not take place. The liquids simply rotate around the mixer.

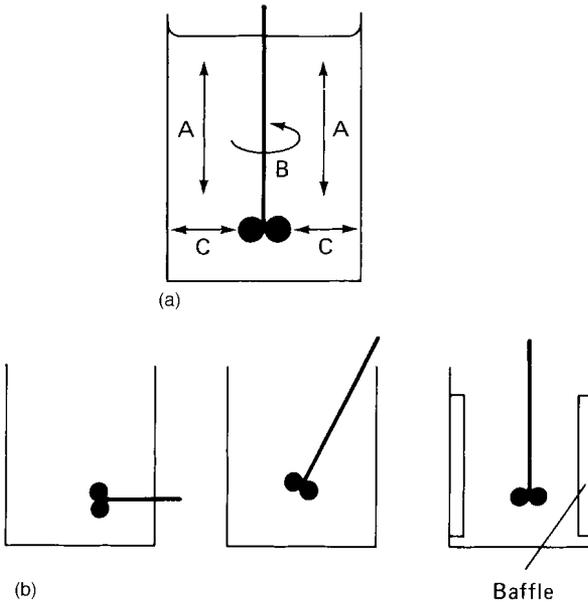


Fig. 5.1 (a) Component velocities in fluid mixing: A, longitudinal; B, rotational; C, radial; (b) Position of agitators for effective mixing of liquids.

In high-viscosity liquids, pastes or doughs, a different action is needed. Here, mixing occurs by:

- *kneading* the material against the vessel wall or into other material
- *folding* unmixed food into the mixed part
- *shearing* to stretch the material.

Efficient mixing is achieved by creating and recombining fresh surfaces in the food as often as possible. However, because the material does not easily flow, it is necessary either to move the mixer blades throughout the vessel or to move the food to the mixer blades.

Most liquid foods are non-Newtonian¹ and the most common types are pseudoplastic,² dilatant³ and viscoelastic.⁴ These properties are described in detail by Lewis (1990) and in Chapter 1 (Section 1.1.2). The design of equipment should enable thorough mixing without overloading the motor or reducing the mixing efficiency.

Pseudoplastic foods (for example sauces) form a zone of thinned material around a small agitator as mixing proceeds, and the bulk of the food does not move. The higher the agitator speed, the more quickly the zone becomes apparent. Planetary or gate mixers or roller mills (Section 5.1.3) are used to ensure that all food is subjected to the mixing action. *Dilatant* foods (for example cornflour and chocolate) should be mixed with great care. If adequate power is not available in the mixer, the increase in viscosity causes damage to drive mechanisms and shafts. A folding or cutting action, as for example in some planetary mixers or paddle mixers, is suitable for this type of food (Section 5.1.3). *Viscoelastic* foods (for example bread dough) require a folding and stretching action to shear the material. Suitable equipment includes twin-shaft mixers and planetary mixers with intermeshing blades.

The rate of mixing is characterised by a mixing index (Section 5.1.1). The mixing rate constant (equation (5.6)) depends on the characteristics of both the mixer and the liquids. The effect of the mixer characteristics on K is given by:

$$K \propto \frac{D^3 N}{D_t^2 z} \quad \boxed{5.7}$$

where D (m) = the diameter of the agitator, N (rev s⁻¹) = the agitator speed, D_t (m) = the vessel diameter and z (m) = the height of liquid.

The power requirements of a mixer vary according to

- the nature, amount and viscosity of the foods in the mixer
- the position, type, speed and size of the impeller.

Liquid flow is defined by a series of dimensionless numbers: the Reynolds number Re (equation (5.8), also Chapter 1), the Froude number Fr (equation (5.9)) and the Power number Po (equation (5.10)):

$$Re = \frac{D^2 N \rho_m}{\mu_m} \quad \boxed{5.8}$$

1. The viscosity changes with rate of shear.
2. The viscosity decreases with increasing shear rate.
3. The viscosity increases with shear rate.
4. Materials which exhibit viscous and elastic properties including stress relaxation, creep and recoil.

$$Fr = \frac{DN^2}{g} \tag{5.9}$$

$$Po = \frac{P}{\rho_m N^3 D^5} \tag{5.10}$$

where P (W) = the power transmitted via the agitator, ρ_m (kg m^{-3}) = the density of the mixture and μ_m (N s m^{-2}) = the viscosity of the mixture. These are related as follows:

$$Po = K(Re)^n (Fr)^m \tag{5.11}$$

where K , n and m are factors related to the geometry of the agitator, which are found by experiment (for example Rushton *et al.*, 1950). The Froude number is only important when a vortex is formed in an unbaffled vessel and is therefore omitted from equation (5.11).

The density of a mixture is found by addition of component densities of the continuous and dispersed phases:

$$\rho_m = V_1 \rho_1 + V_2 \rho_2 \tag{5.12}$$

where V = the volume fraction. The subscripts 1 and 2 are the continuous phase and dispersed phase respectively.

The viscosity of a mixture is found using the following equations for baffled mixers and for unbaffled mixers:

$$\mu_m(\text{unbaffled}) = \mu_1^{V_1} \mu_2^{V_2} \tag{5.13}$$

$$\mu_m(\text{baffled}) = \frac{\mu_1}{V_1} \left(\frac{1 + 1.5 \mu_2 V_2}{\mu_1 + \mu_2} \right) \tag{5.14}$$

(Jackson and Lamb, 1981).

Characteristic changes in power consumption P_o of propellers at different Reynolds numbers are shown in Fig. 5.2.

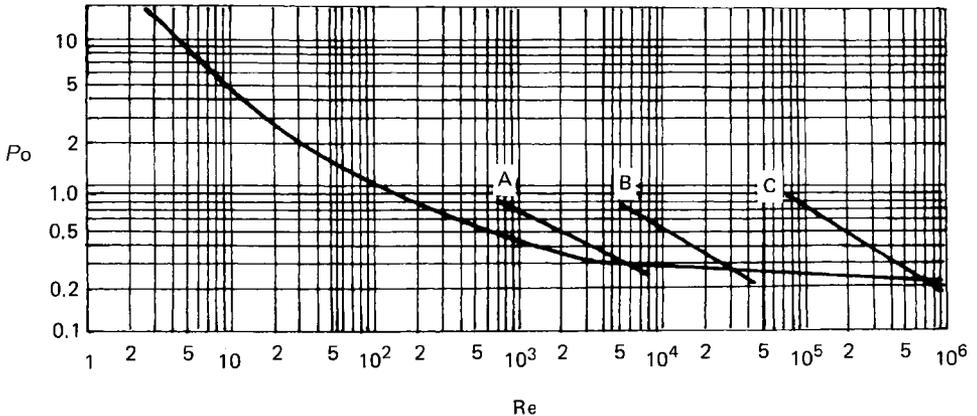


Fig. 5.2 Changes in power number ($P_o = P/\rho_m N^3 D^5$) versus Reynolds Number ($Re = D^2 N \rho_m / \mu_m$) for propeller agitator. (30 cm propeller in 137 cm diameter tank, liquid depth 137 cm, propeller 30 cm above base. (A) viscosity = 0.189 N s m^{-2} , (B) viscosity = 0.028 N s m^{-2} , (C) viscosity = 0.109 N s m^{-2} . (Propeller speed varied from 100–500 rpm). (After Rushton *et al.* (1950).)

Sample problem 5.2

Olive oil and rape-seed oil are blended in a ratio of 1 to 5 by a propeller agitator 20 cm in diameter operating at 750 rev min^{-1} in a cylindrical tank 1 m in diameter at 20°C . Calculate the size of the motor required.

Solution to Sample problem 5.2

From Table 1.2, the viscosity of olive oil at 20°C is 0.084 N s m^{-2} , the density of olive oil 910 kg m^{-3} , the viscosity of rape-seed oil 0.118 N s m^{-2} and the density of rape-seed oil 900 kg m^{-3} . From equation (5.13),

$$\begin{aligned}\mu_m &= 0.084^{0.2} 0.118^{0.8} \\ &= 0.110 \text{ N s m}^{-2}\end{aligned}$$

From equation (5.12),

$$\begin{aligned}\rho_m &= 0.2 \times 910 + 0.8 \times 900 \\ &= 902 \text{ kg m}^{-3}\end{aligned}$$

From equation (5.8),

$$\begin{aligned}\text{Re} &= (0.2)^2 \frac{750}{60} \frac{902}{0.110} \\ &= 4100\end{aligned}$$

From Fig. 5.2, for $\text{Re} = 4100$, $\text{Po} = 0.5$. From equation (5.10),

$$\begin{aligned}P &= 0.5 \times 902 \left(\frac{750}{60} \right)^3 (0.2)^5 \\ &= 281.9 \text{ J s}^{-1} \\ &= 0.28 \text{ kW}\end{aligned}$$

Since $1 \text{ hp} = 745.4 \text{ J s}^{-1}$, the size of the motor required is $281.9/745.4 = 0.38 \text{ hp} = 0.28 \text{ kW}$.

Computer-aided systems are used to determine the optimum performance for a particular mixer in a given application or to select an appropriate mixer for a particular food. These systems take account of the type and size of the impeller, the shape of the vessel, the power input, the speed of mixing and limitations on temperature changes for a specific mix (also Chapter 2).

5.1.3 Equipment

The selection of a correct type and size of mixer depends on the type and amount of food being mixed and the speed of operation needed to achieve the required degree of mixing with minimum energy consumption. There are a very large variety of mixers available, due to the large number of mixing applications and the empirical nature of mixer design and development.

Table 5.1 Some factors used in the selection of a mixer

	Tumbling mixer	Simple vertical screw	Orbital screw	Double ribbon mixer	Pan mixer	Z-blade mixer
1. Will it mix						
free-flowing powders	✓	✓	✓			
cohesive powders	✗	✓	✓			
damp powders	✗	✗	✓			
pastes	✗	✗	✓			
slurries	✗	✗	✓\✗			
materials having varying shape	✗	✗	✓			
materials having varying density	✗	✓	✓			
materials of varying size	✗	✗	✓			
2. Is it						
prone to de-mixing	✓	✗	✗			
high shear	✗	✗	✗			
low shear	✓	✓	✓			
self-cleaning	✓	✗	✓			
self-emptying	✓	✓				
3. Can it be						
cleaned by brushing	✓	✓				
cleaned by washing	✓	✓				
cleaned by sterilisation	✗	✗				
heated or cooled	✗	✓				
adapted easily to pressure or vacuum operation	✓	✗				
4. Does it						
produce light out-of-balance loading	✗	✗	✓	✗	✓	✗
produce heavy out-of-balance loading	✓	✗	✗	✗	✗	✗
require external guards	✓	✗	✗	✗	✓	✗
have low starting torque	✗	✓	✓	✗	✓	✗
have high starting torque	✓	✗	✗	✓	✗	✓
5. Power requirement						
< 5hp/tonne	✗	✓	✓	✗	✗	✗
5–10 hp/tonne	✓	✗	✗	✗	✗	✗
>10 hp/tonne	✓	✗	✗	✓	✓	✓

✓ = yes, ✗ = no, ✓\✗ = dependent on detailed design.

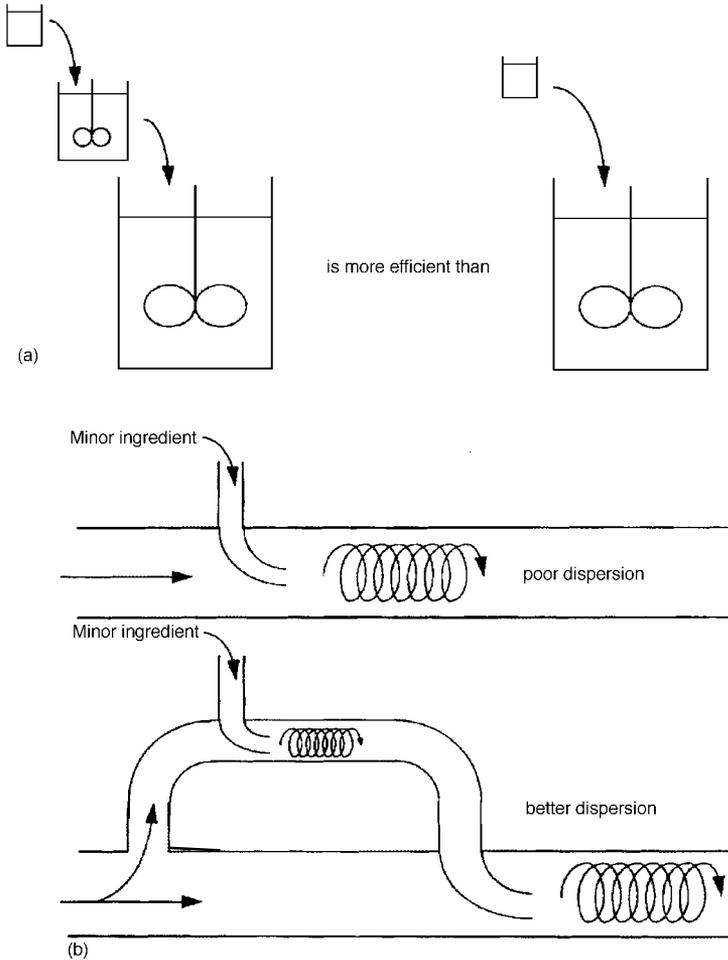


Fig. 5.3 (a) Multi-stage batch mixing, (b) dispersion of ingredients in continuous mixing. (After Campbell (1995).)

Mixers are classified into types that are suitable for:

1. dry powders or particulate solids
2. low- or medium-viscosity liquids
3. high-viscosity liquids and pastes
4. dispersion of powders in liquids.

Pownall (1986) has surveyed mixing equipment available for each category and some factors used to select mixing equipment are described in Table 5.1. In general, mixing efficiency can be improved in both batch and continuous mixers by mixing in several stages (Fig. 5.3). For example, if 1 kg of an ingredient is to be mixed into 500 kg of water, it is mixed more efficiently if it is first mixed with about 25 kg of water and this is then mixed with the remainder of the water (Campbell, 1995).

Mixers for dry powders and particulate solids

These mixers have two basic designs: the tumbling action of rotating vessels and the positive movement of materials in screw types. They are used for blending grains, flours

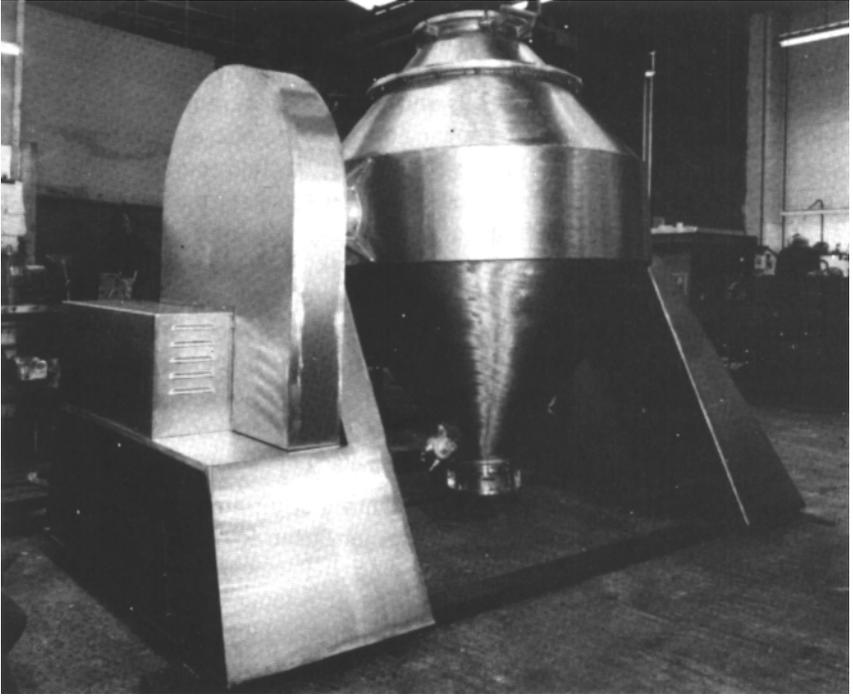


Fig. 5.4 Double-cone mixer.
(Courtesy of Winkworth Engineering Ltd.)

and the preparation of powdered mixes (for example cake mixes and dried soups). *Tumbling mixers* include drum, double-cone (Fig. 5.4), Y-cone and V-cone mixers. They are filled approximately half full and rotate at speeds of $20\text{--}100\text{ rev min}^{-1}$. Optimum mixing for a particular blend of ingredients depends on the shape and speed of the vessel, but speeds should be lower than the 'critical speed', when centrifugal force exceeds gravity. The efficiency of mixing is improved by internal baffles or counter-rotating arms. These mixers are also used for coating applications (Chapter 23).

Ribbon mixers have two or more thin narrow metal blades (Fig. 5.5) formed into helices which counter-rotate in a closed hemispherical trough. The pitch of the ribbons is different so that one moves the material rapidly forwards through the trough, and the second moves the material slowly backwards, to produce a net forward movement of material. This type of mixer is used for dry ingredients and small-particulate foods.

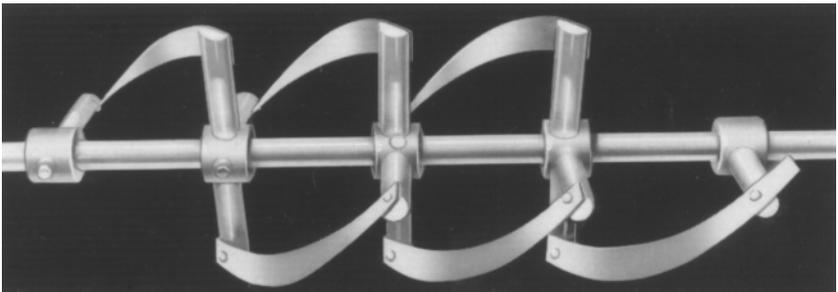


Fig. 5.5 Ribbon mixer.
(Courtesy of Winkworth Engineering Ltd.)

Vertical-screw mixers have a rotating vertical screw, contained within a conical vessel which orbits around a central axis to mix the contents. This type of equipment is particularly useful for the incorporation of small quantities of ingredients into a bulk of material.

Mixers for low- or medium-viscosity liquids

A large number of designs of agitator are used to mix liquids in unbaffled or baffled vessels. The advantages and limitations of each vary according to the particular application but are summarised in Table 5.2.

The simplest *paddle agitators* are wide flat blades (Fig. 5.6(a)) which measure 50–75% of the vessel diameter and rotate at 20–150 rev min⁻¹. The blades are often pitched to promote longitudinal flow in unbaffled tanks. *Impeller agitators* consist of two or more blades attached to a rotating shaft. The blades may be flat, angled (pitched) or curved. Turbine agitators are impeller agitators which have more than four blades mounted together. The size is 30–50% of the diameter of the vessel and they operate at 30–500 rev min⁻¹. The blades are flat, pitched or curved to increase radial and longitudinal flow. In addition blades may be mounted on a flat disc (the *vaned disc impeller* (Fig. 5.6(b))), mounted vertically in baffled tanks. High shearing forces are developed at the edges of the impeller blades and they are therefore used for pre-mixing emulsions (Chapter 4).

Impellers which have short blades (less than a quarter of the diameter of the vessel) are known as propeller agitators (Fig. 5.6(c)). In each type the agitator is located in one of the positions shown in Fig. 5.1(b) to promote longitudinal and radial movement of the liquids and to prevent vortex formation. Alternatively, baffles are fitted to the vessel wall to increase shearing of the liquids and to interrupt rotational flow, but care is necessary in the design to ensure that the vessel may be adequately cleaned (Chapter 26). Propeller agitators operate at 400–1500 rev min⁻¹ and are used for blending miscible liquids, diluting concentrated solutions, preparing syrups or brines and dissolving other ingredients.

Powder-liquid contacting devices are short-residence-time mixers which are used to incorporate powders into liquids. They operate by mixing a uniform stream of powder into sprays of liquid and may also involve subsequent mixing by blades or rotors. Typical examples are shown in Fig. 5.7. Powders may also be mixed with liquids by pumping them through pipes that are fitted internally with stationary mixing blades. *Pumps* mix ingredients by creating turbulent flow both in the pump itself and in the pipework (Chapter 1). There are a large variety of pumps available for handling different fluids and suspensions: the different designs and applications are discussed by Leniger and Beverloo (1975) and in Chapter 26 (Section 26.1.2).

Table 5.2 Advantages and limitations of selected liquid mixers

Type of mixer	Advantages	Limitations
Paddle agitator	Good radial and rotational flow, cheap	Poor perpendicular flow, high vortex risk at higher speeds
Multiple-paddle agitator	Good flow in all three directions	More expensive, higher energy requirements
Propeller impeller	Good flow in all three directions	More expensive than paddle agitator
Turbine agitator	Very good mixing	Expensive and risk of blockage

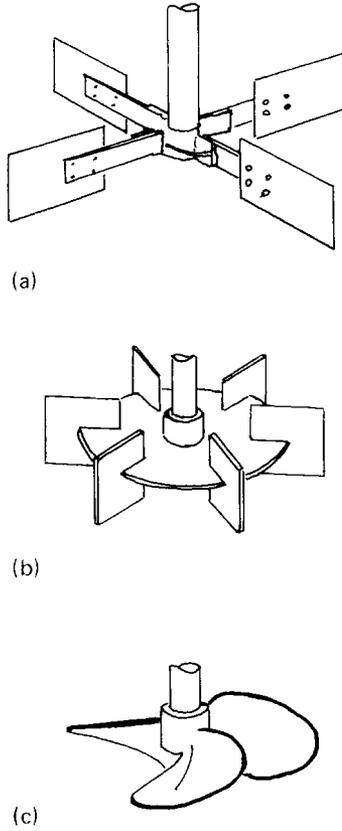


Fig. 5.6 Agitators: (a) flat blade agitator; (b) vaned disc impellor; (c) propeller agitator. (After Smith (1985).)

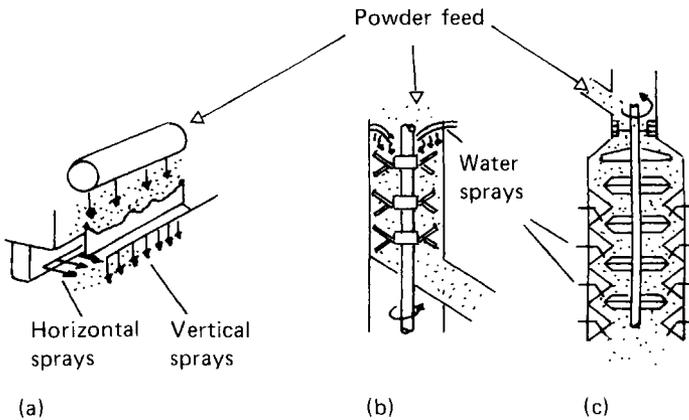


Fig. 5.7 Powder-liquid contacting devices: (a) Neptune Chemix (part); (b) Schugi mixer; (c) Buss mixer. (After McDonagh (1987).)

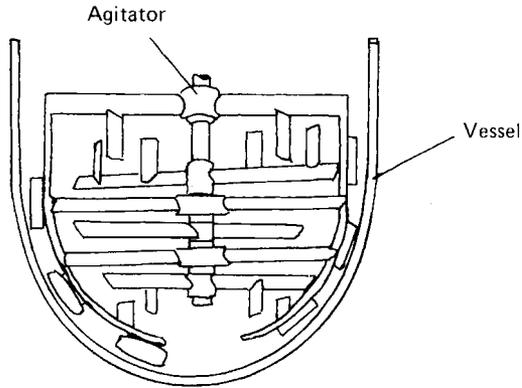


Fig. 5.8 Anchor-and-gate agitator.
(After McDonagh (1987).)

Mixers for high-viscosity liquids and pastes

More viscous liquids are mixed using slow-speed vertical-shaft impellers such as *multiple-paddle (gate) agitators* or, more commonly, counter-rotating agitators to develop high shearing forces. The basic design in this group is the *anchor and gate agitator* (Fig. 5.8). It is often used with heated mixing vessels, when the anchor is fitted with scraper blades to prevent food from burning onto the hot surface. Some complex designs have arms on the gate which intermesh with stationary arms on the anchor to increase the shearing action, whereas others have inclined vertical blades to promote radial movement in the food.

The most common design of twin-shaft horizontal blade mixers is the *Z-blade (or sigma-blade) mixer* (Fig. 5.9). This consists of two heavy-duty blades which are mounted horizontally in a metal trough. The blades intermesh and rotate towards each other at either similar or different speeds ($14\text{--}60\text{ rev min}^{-1}$) to produce shearing forces between

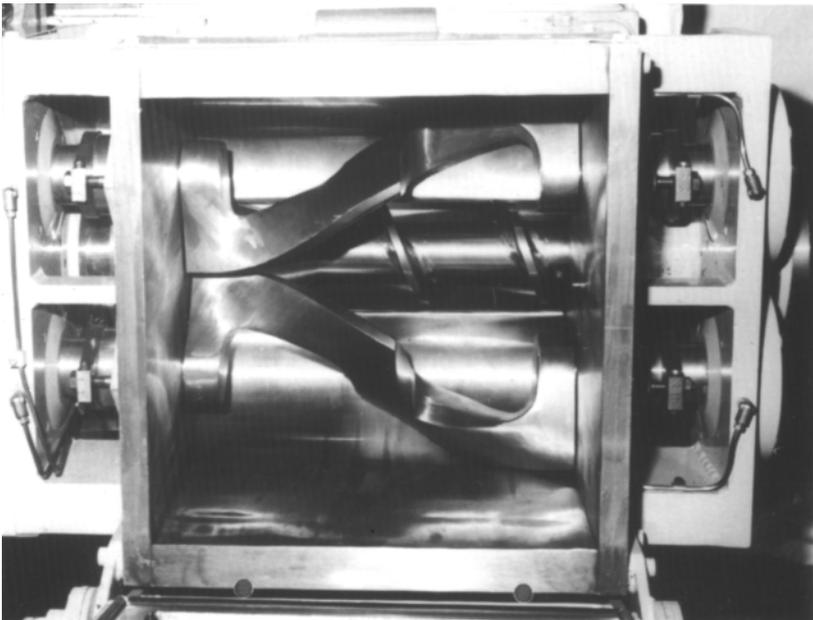


Fig. 5.9 Z-blade mixer.
(Courtesy of Winkworth Engineering Ltd.)

the two blades and between the blades and the specially designed trough base. These mixers use a substantial amount of power which is dissipated in the product as heat. Mixing efficiency should therefore be high to reduce the mixing time. If necessary the walls of the trough are jacketed for temperature control. Special designs for shredding and mixing have serrated blades, and other blade configurations including the gridlap, double naben and double claw are available (McDonagh, 1987).

Planetary mixers are commonly found in both industrial and domestic applications, and take their name from the path followed by rotating blades (at 40–370 rev min⁻¹), which include all parts of the vessel in the mixing action. An alternative design employs fixed rotating blades which are offset from the centre of a co-currently or counter-currently revolving vessel. In both types there is a small clearance between the blades and the vessel wall. Gate blades are used for mixing pastes, blending ingredients and preparation of spreads; hooks are used for dough mixing and whisks are used for batter preparation.

Screw conveyor mixers are typical of the type known as continuous rotor-stator mixers. A horizontal rotor fits closely into a slotted stationary casing (or 'barrel'). Single or twin screws are used to convey viscous foods and pastes through the barrel and to force it through perforated plates or grids. The small clearance between the screw and the barrel wall causes a shearing and kneading action. This is supplemented by shearing and mixing as the food emerges from the end plate or grid. The screw may be interposed with pins to increase the shearing action. This type of equipment is also used for extrusion (Chapter 14) and butter or margarine manufacture (Chapter 4). Recent developments include automatic microprocessor control with recipe storage for rapid change of products, process monitoring and control and logging of process and product data (Chapter 2). These continuous mixers are used to produce doughs for crackers, biscuits, breads, crispbreads, rusks, cakes and confectionery products.

A number of other designs, including butter churns, bowl choppers and rollers are each used in specific applications to mix foods, often with simultaneous homogenisation or size reduction. Roller mills and colloid mills are suitable for mixing high-viscosity materials in addition to their function as size reduction equipment (Chapter 4).

More recently, static or 'motionless' mixers have been developed for viscous materials and fluids. These mixers comprise a series of precisely aligned static mixing elements contained within a housing that is installed in the processing line. The elements split, rotate and integrate the food material in a precisely defined pattern, according to the type of food to be mixed and the degree of mixing required. They operate using three mixing actions: radial mixing, flow division and transient mixing. In radial mixing, the fluid is deflected by the elements through a series of 180° rotations which forces the fluid from the centre to the wall of the pipe and back again. In flow division, the material is split into two components by the first mixing element and then rotated through 180° before being split into four streams by the second element and so on past succeeding elements until the required degree of mixing has been achieved (Fig. 5.10). Transient mixing employs spaces between the elements to allow relaxation of viscous material after successive radial mixings. It has been used in chocolate manufacture for the processing of cocoa mass (Richards, 1997). Static mixers eliminate the need for tanks, agitators and moving parts, thus reducing capital costs and maintenance requirements.

5.1.4 Effect on foods

The action of a mixer has no direct effect on either the nutritional quality or the shelf life of a food but may have an indirect effect by allowing components of the mixture to react

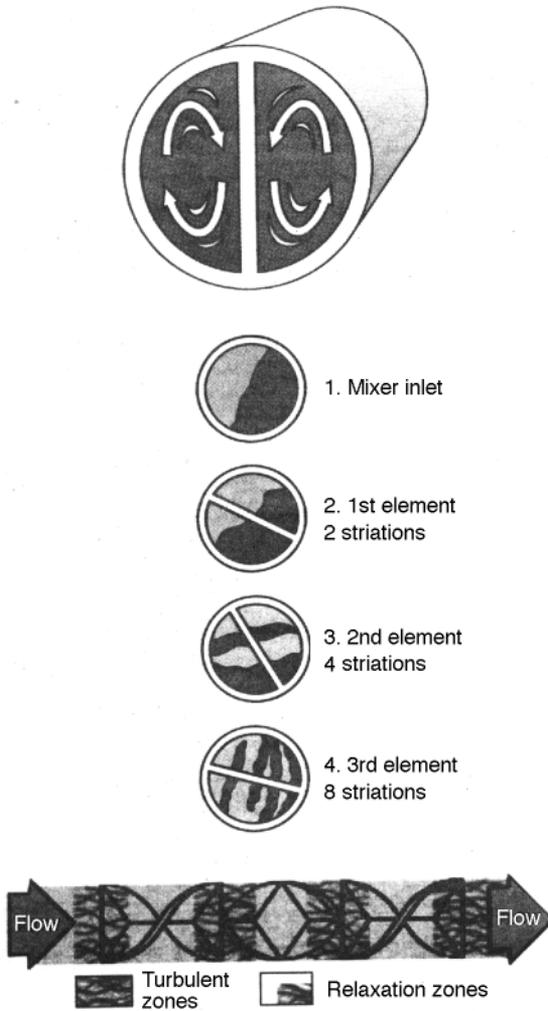


Fig. 5.10 Static mixer.
(Courtesy of Richards (1997).)

together. The nature and extent of the reaction depend on the components involved but may be accelerated if significant heat is generated in the mixer. In general, mixing has a substantial effect on sensory qualities and functional properties of foods. For example, gluten development is promoted during dough making by the stretching and folding action which aligns, uncoils and extends protein molecules and develops the strength of the gluten structure to produce the desired texture in the bread. The main effects are to increase the uniformity of products by evenly distributing ingredients throughout the bulk.

5.2 Forming

There are many designs of moulding and forming equipment made specifically for individual products. In this section the equipment used for bread, biscuits, pies, snackfoods and confectionery is described.

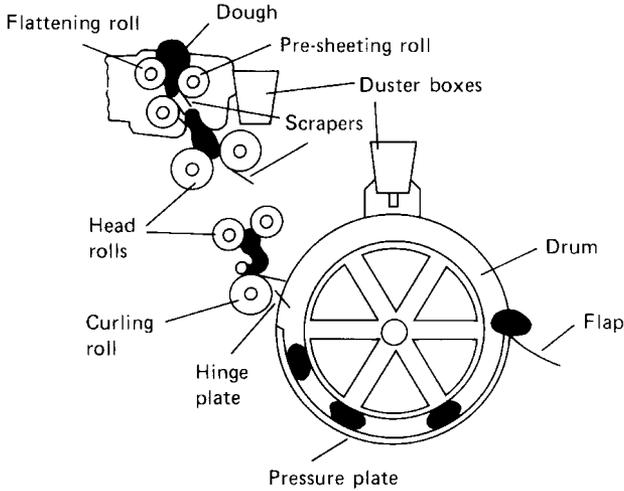


Fig. 5.11 Drum moulder for bread doughs.
(After Matz (1972).)

5.2.1 Bread moulders

This equipment (Fig. 5.11) shapes the dough into cylinders that will expand to the required loaf shape when proofed. The three stages are

1. sheeting
2. curling
3. rolling-sealing.

The first three sets of rollers have successively smaller gaps (or 'nips') to roll the dough gently into sheets without tearing. The sheet is loosely curled, rolled into a cylinder and then sealed by a revolving drum, which presses the dough against a pressure plate. The pressure is gradually increased to expel trapped air. Compression of the dough structure causes the moisture content of the sheet to increase at the trailing end. It is preferable to have the moist part of the dough at the centre of the cylinder, and a variety of designs are used to change the direction of the sheet to roll the trailing edge first (for example *cross-grain* moulders and *reverse sheeting* moulders) (Matz, 1972).

Equipment for forming and encasing balls of dough with other materials is described by Hayashi (1989). In this process, the inner material and outer material are co-extruded and then divided and shaped by two 'encrusting discs' (Fig. 5.12(a)). In contrast to conventional forming techniques, where the size of the product is determined by the size of the feed material, the relative thickness of the outer layer and the diameter of the inner sphere are determined by the flow rate of each material. It is therefore possible to alter the relative thickness of inner and outer layers (Fig. 5.12(b)) simply by adjusting the flowrates, giving a high degree of flexibility for the production of different products. This equipment was developed in Japan for production of cakes having an outer layer of rice dough and filled with bean paste, but they have found wide application and are used to produce sweetbreads filled with jam, doughnuts, meat pies, hamburgers filled with cheese and fish filled with vegetables.

5.2.2 Pie and biscuit formers

Pie casings are formed by depositing a piece of dough into aluminium foil containers or re-usable pie moulds and pressing it with a die. A filling is then deposited into the casing

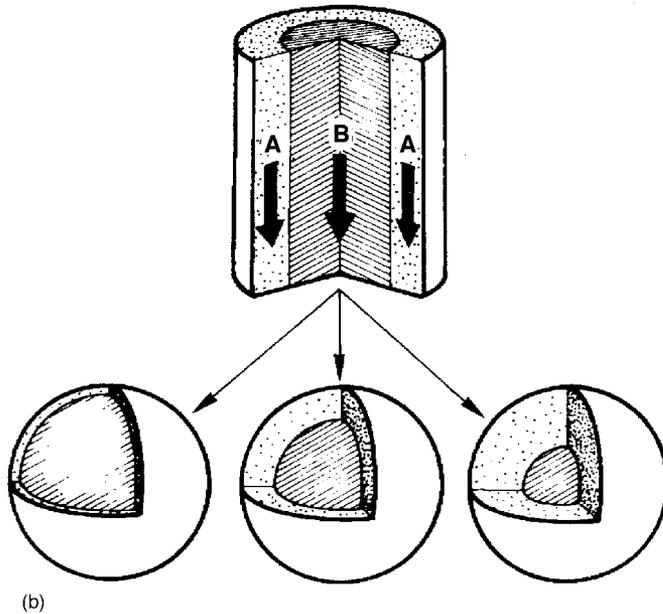
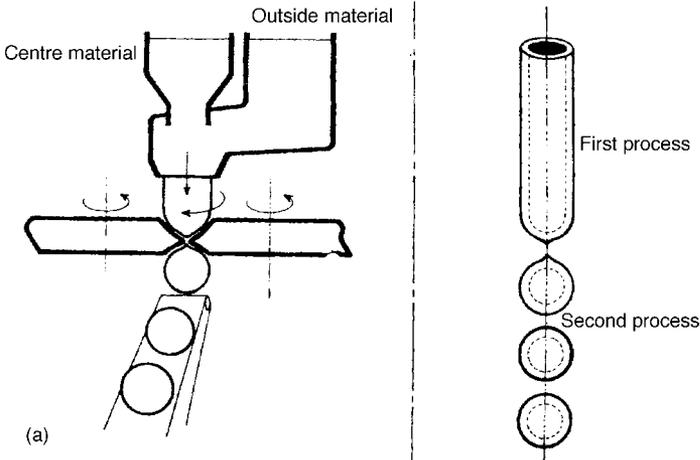


Fig. 5.12 (a) Two revolving encrusting discs continuously divide food and shape it into balls; (b) differences in thickness of outer layer (A) and inner layer (B) result from different material flowrates.

(Courtesy of Hayashi (1989).)

and a continuous sheet of dough is laid over the top. Finally the lids are cut by reciprocating blades (Fig. 5.13).

Biscuits are formed by one of four methods:

1. the dough is pressed into shaped cavities in a *metal moulding roller* (die forming) (Fig. 5.14(a))
2. shapes are cut from a sheet of dough using a *cutting roller*. Raised characters on a *printing roller* simultaneously imprint a design on the upper surface of the biscuit (Fig. 5.14(b))
3. soft dough is extruded through a series of dies in a *wire-cut machine* (Fig. 5.14(c))

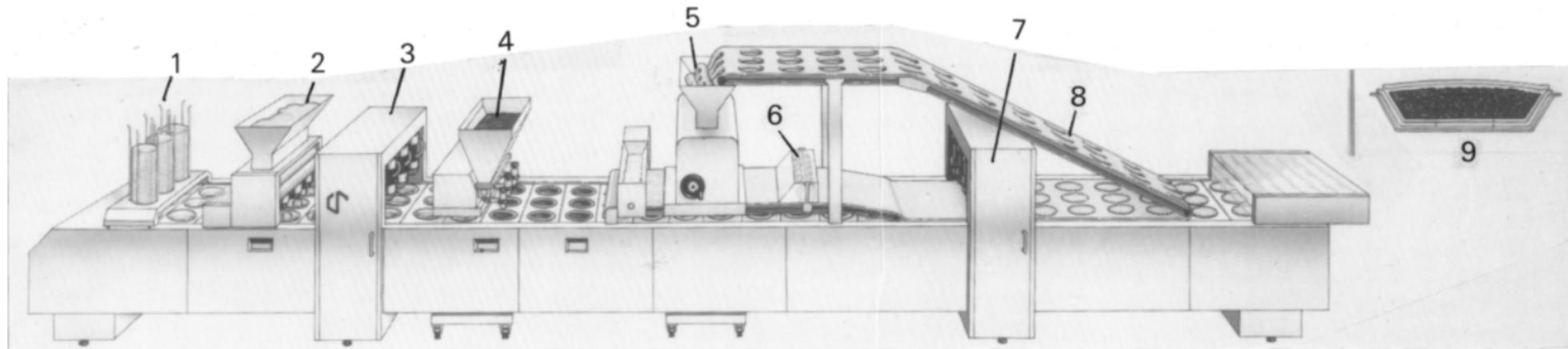
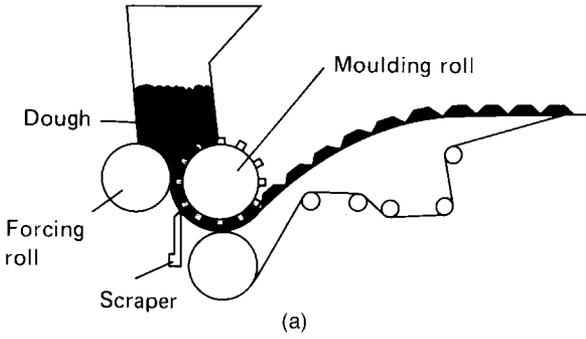
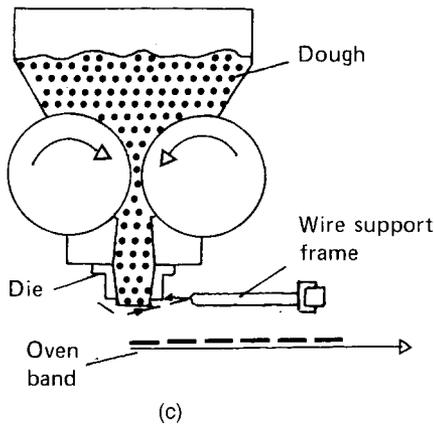


Fig. 5.13 Pie manufacture: 1, foil dishes; 2, dough divider; 3, blocking unit; 4, filling depositor; 5, pastry lid sheeting machine; 6, rotary lattice cutter; 7, crimping/lidding unit; 8, scrap return conveyor; 9, pie cross section.
(Courtesy of Machinefabriek C Rijckaart BV.)



(b)



(c)

Fig. 5.14 Biscuit formers: (a) rotary moulder; (b) moulding rollers; (c) wire-cut machine. (Courtesy of Baker Perkins Ltd.)

- a continuous ribbon of dough is extruded from a *roul press* (similar to a wirecut machine but without the cutting wires), and the ribbon is then cut to the required length using a reciprocating blade.

There are also numerous designs of equipment for laminating sheets of dough with fat (for croissants and pastries), folding doughs (to form pasties and rolls) and filling doughs (to form sausage rolls, fruit bars such as ‘fig rolls’ and cakes), described by Levine and Drew (1994).

5.2.3 Confectionery moulders

Confectionery depositing-moulding equipment consists of individual moulds, which have the required size and shape for a specific product, attached to a continuous conveyor. They are carried below a depositor, which has a piston filler to deposit accurately the required volume of hot sugar mass into each mould. Depositors can place food of a single type, in layers, or centre filled (Fig. 5.15(a)) (for example liquid centres or chocolate paste around hard-boiled sweets). The food is then cooled in a cooling tunnel. When it has hardened sufficiently, individual sweets are ejected and the moulds restart the cycle (Fig. 5.15(b)) (Verity, 1991). Details of chocolate moulding are given by Perreau (1989).

The three main types of equipment differ in the method of ejection, and the material used for the mould:

- metal moulds fitted with ejector pins are used for hard confectionery (for example butterscotch)
- flexible polyvinyl chloride moulds, which eject the food by mechanical deformation, are used for soft confectionery (for example toffee, fudge, jellies, caramel, fondant and chocolate)
- polytetrafluoroethylene-coated aluminium moulds, with compressed-air ejection, are used for jellies, gums, fondant and crèmes.

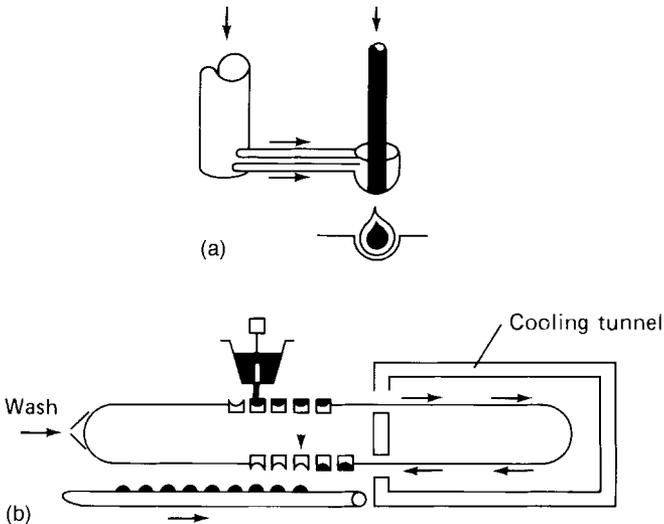


Fig. 5.15 (a) Depositing centre-filled confectionery; (b) confectionery moulding: an air demoulding depositor.
(Courtesy of Baker Perkins Ltd.)

Each type of equipment is automatically controlled. Other types of forming equipment extrude sugar confectionery (Chapter 14) and shape it using a series of rollers, to produce a sugar 'rope'. Individual sweets are then cut from the rope and shaped by dies.

Microprocessor-controlled depositors are used to form cake mixes and high-viscosity liquids for confectionery products into a wide variety of shapes. The memory can hold the sizes, shapes and weights of up to 99 different products, which are called up by the operator using a two-digit product code.

5.3 Acknowledgements

Grateful acknowledgement is made for information supplied by the following: Allen Machinery Systems, Stourbridge, West Midlands DY9 7NB, UK; APV Baker Ltd, Peterborough PE4 7AP, UK; Interfood Ltd, Hemel Hempstead, Hertfordshire HP2 7DU, UK; Robinson's of Derby, Derby DE2 6JL, UK; Machinefabriek C Rijkaart bv, Asperen, Holland; Sandvik Jahn, Huntingdon PE18 7EW, UK; Winkworth Machinery Ltd, Staines, Middlesex TW18 4PX, UK; Tweedy Ltd, Burnley, Lancashire BB12 6JL, UK; Morton Machine Co. Ltd, Motherwell ML1 5SW, UK; Werner & Pfleiderer, Industrielle Backtechnik GmbH, Tamm, Germany; Mono Equipment Ltd, Swansea SA5 4EB, UK; T. Giusti & Son Ltd, London N7 9AW, UK.

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6

Separation and concentration of food components

Foods are complex mixtures of compounds and the extraction or separation of food components is fundamental for the preparation of ingredients to be used in other processes (for example cooking oils from oilseeds or gelatin from connective tissue); or for retrieval of high value compounds, such as enzymes (e.g. papain from papaya for meat tenderisation or rennet from calf stomachs for cheesemaking). Other types of separation methods are used to sort foods by separating them into classes based on size, colour or shape; to clean them by separating contaminating materials (Chapter 3); or to selectively remove water from foods by evaporation (Chapter 13) or by dehydration (Chapter 15).

In this chapter, the unit operations that are used for the physical removal of food components by separation, extraction or concentration are described. There are three main categories:

1. Separation of liquids and solids from slurries, pastes, particulates or flours, where either one or both components may be valuable (for example juices, pectin, enzymes, cooking oil, cream and coffee solubles).
2. Separation of small amounts (less than 2%) of solids from liquids. Here the main purpose is purification of water or clarification of liquids such as wine, beer, juices, etc. and the solids are not valuable.
3. Extraction of small amounts of valuable materials using a solvent.

Each operation is used as an aid to processing and is not intended to preserve food. Changes in nutritional and sensory qualities arise through intentional separation or concentration of food components, but generally the processing conditions do not involve heat and cause little damage to foods. Other methods for separation of food components include sieving, described in Chapter 4, and crystallisation and distillation, described by Brennan *et al.* (1990) and Heldman and Hartel (1997b). Osmotic concentration of fruits and vegetables, by soaking in concentrated solutions of sugar or salt respectively, is a form of dehydration and is discussed further in Chapter 15.

6.1 Centrifugation

There are two main applications of centrifugation: separation of immiscible liquids and separation of solids from liquids. Separation of solid particles from air by centrifugal action in the 'cyclone' separator is described in more detail in Chapter 15 and by Heldman and Hartel (1997b).

6.1.1 Theory

Centrifugal force is generated when materials are rotated; the size of the force depends on the radius and speed of rotation and the density of the centrifuged material. In the separation of immiscible liquids (for example emulsions (Chapter 4)), the denser liquid moves to the bowl wall and the lighter liquid is displaced to an inner annulus (Fig. 6.1). The thickness of the layers is determined by the density of the liquids, the pressure difference across the layers and the speed of rotation. A boundary region between the liquids at a given centrifuge speed forms at a radius r_n where the hydrostatic pressure of the two layers is equal. This is termed the neutral zone and is important in equipment design to determine the position of feed and discharge pipes. It is found using:

$$r_n^2 = \frac{\rho_A r_A^2 - \rho_B r_B^2}{\rho_A - \rho_B} \quad [6.1]$$

where ρ (kg m^{-3}) = density and r (m) = the radius. The subscripts A and B refer to the dense and light liquid layers respectively.

If the purpose is to remove light liquid from a mass of heavier liquid (for example in cream separation from milk), the residence time in the outer layer exceeds that in the

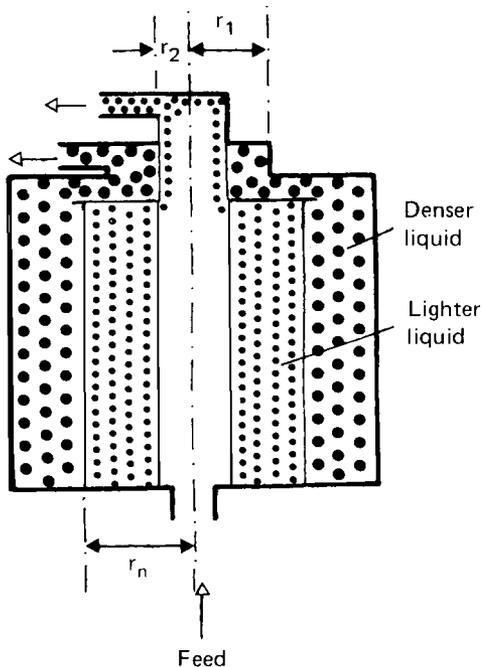


Fig. 6.1 Separation of immiscible liquids: r_1 , radius of dense phase outlet; r_2 , radius of light phase outlet; r_n , radius of neutral zone.

inner layer. This is achieved by using a smaller radius of the outer layer (r_1 in Fig. 6.1) and hence reducing the radius of the neutral zone. Conversely, if a dense liquid is to be separated from a mass of lighter liquid (for example the removal of water from oils), the radius of the outer layer (and the neutral zone) is increased.

Sample problem 6.1

A bowl centrifuge is used to break an oil-in-water emulsion (Chapter 4). Determine the radius of the neutral zone in order to position the feed pipe correctly. (Assume that the density of the continuous phase is 1000 kg m^{-3} and the density of the oil is 870 kg m^{-3} . The outlet radii from the centrifuge are 3 cm and 4.5 cm.)

Solution to Sample problem 6.1

$$\begin{aligned} r_n &= \sum \left[\frac{1000(0.045)^2 - 870(0.03)^2}{1000 - 870} \right] \\ &= \sqrt{\left(\frac{2.025 - 0.783}{130} \right)} \\ &= 0.097 \text{ m} \end{aligned}$$

When particles are removed from liquids in centrifugal clarification, the particles move to the bowl wall under centrifugal force. If liquid flow is streamlined (Chapter 1), the rate of movement is determined by the densities of the particles and liquid, the viscosity of the liquid and the speed of rotation (equation 6.2). Separation under turbulent flow conditions is described by Earle (1983).

$$Q = \frac{D^2 \omega^2 (\rho_s - \rho) V}{18 \mu \ln(r_2/r_1)} \quad \boxed{6.2}$$

where $\omega (= 2\pi N/60) =$ angular velocity, $Q (\text{m}^3 \text{ s}^{-1}) =$ volumetric flowrate, $V (\text{m}^3) =$ operating volume of the centrifuge, $D (\text{m}) =$ diameter of the particle, $\rho_s (\text{kg m}^{-3}) =$ density of particles, $\rho (\text{kg m}^{-3}) =$ density of liquid, $\mu (\text{N s m}^{-2}) =$ viscosity of liquid, $r_2 (\text{m}) =$ radius of centrifuge bowl, $r_1 (\text{m}) =$ radius of liquid, $N (\text{rev s}^{-1}) =$ speed of rotation.

For a given particle diameter, the average residence time of a suspension equals the time taken for a particle to travel through the liquid to the centrifuge wall:

$$t = \frac{V}{Q} \quad \boxed{6.3}$$

where $t (\text{s}) =$ residence time. The flow rate can therefore be adjusted to retain a specific range of particle sizes. Derivations and additional details of these equations are given by Brennan *et al.* (1990) and Earle (1983).

6.1.2 Equipment

Centrifuges are classified into three groups for:

1. separation of immiscible liquids
2. clarification of liquids by removal of small amounts of solids (centrifugal clarifiers)

Sample problem 6.2

Beer with a specific gravity of 1.042 and a viscosity of $1.40 \times 10^{-3} \text{ N s m}^{-2}$ contains 1.5% solids which have a density of 1160 kg m^{-3} . It is clarified at the rate of 240 l h^{-1} in a bowl centrifuge which has an operating volume of 0.09 m^3 and a speed of $10\,000 \text{ min}^{-1}$. The bowl has a diameter of 5.5 cm and is fitted with a 4 cm outlet. Calculate the effect on feed rate of an increase in bowl speed to $15\,000 \text{ rev min}^{-1}$ and the minimum rev particle size that can be removed at the higher speed.

Solution to Sample problem 6.2

From equation (6.2),

$$\text{Initial flow rate } Q_1 = \frac{D^2(2\pi N_1/60)^2(\rho_s - \rho)V}{18\mu \ln(r_w/r)}$$

$$\text{New flow rate } Q_2 = \frac{D^2(2\pi N_2/60)^2(\rho_s - \rho)V}{18\mu \ln(r_w/r)}$$

As all conditions except the bowl speed remain the same,

$$\frac{Q_2}{Q_1} = \frac{(2\pi N_2/60)^2}{(2\pi N_1/60)^2}$$

$$\frac{Q_2}{240/3600} = \frac{(2 \times 3.142 \times 15000/60)^2}{(2 \times 3.142 \times 10000/60)^2}$$

Therefore,

$$\begin{aligned} Q_2 &= 0.15 \text{ l s}^{-1} \\ &= 540 \text{ l h}^{-1} \end{aligned}$$

To find the minimum particle size from equation (6.2),

$$\begin{aligned} D^2 &= Q_2 = \frac{Q_2[18\mu \ln(r_w/r)]}{w^2(\rho_s - \rho)V} \\ &= \frac{Q_2[18\mu \ln(r_w/r)]}{(2\pi N_2/60)^2(\rho_s - \rho)V} \\ &= \frac{0.015(18 \times 1.40 \times 10^{-3} \times \ln(0.0275/0.02))}{(2 \times 3.142 \times (15000/60))^2(1160 - 1042)0.09} \end{aligned}$$

$$\begin{aligned} D &= \sqrt{\left(\frac{2.33 \times 10^{-4}}{2.62 \times 10^7}\right)} \\ &= 6.8 \mu\text{m} \end{aligned}$$

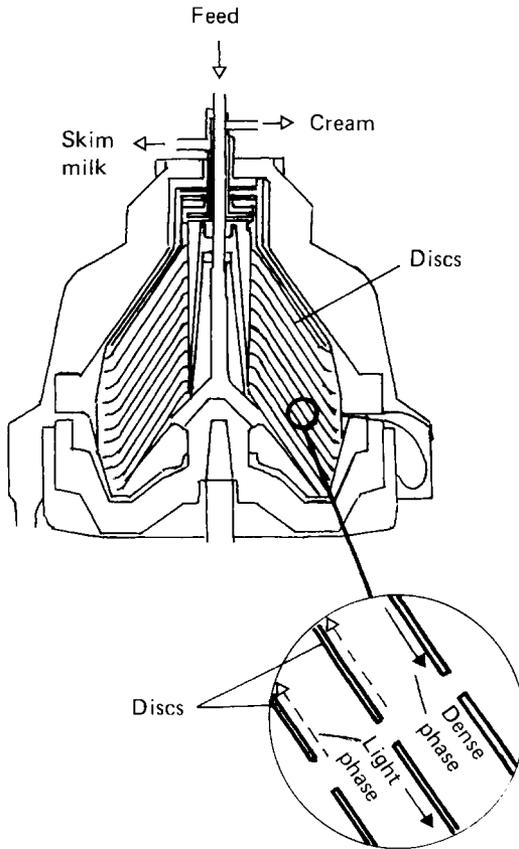


Fig. 6.2 Disc bowl centrifuge.
(Adapted from Hemfort (1983).)

3. removal of solids (desludging or dewatering centrifuges).

Specific applications of centrifuges are described by Hemfort (1984) for the fermentation industries (Chapter 7) and by Hemfort (1983) for the food industry.

Liquid–liquid centrifuges

The simplest type of equipment is the *tubular bowl centrifuge*. It consists of a vertical cylinder (or bowl), typically 0.1 m in diameter and 0.75 m long, which rotates inside a stationary casing at between $15\,000\text{ rev min}^{-1}$ and $50\,000\text{ rev min}^{-1}$ depending on the diameter. Feed liquor is introduced continuously at the base of the bowl and the two liquids are separated and discharged through a circular weir system into stationary outlets (Fig. 6.1).

Better separation is obtained by the thinner layers of liquid formed in the *disc bowl centrifuge* (Fig. 6.2). Here a cylindrical bowl, 0.2–1.2 m in diameter, contains a stack of inverted metal cones which have a fixed clearance of 0.5–1.27 mm and rotate at $2000\text{--}7000\text{ rev min}^{-1}$. They have matching holes which form flow channels for liquid movement. Feed is introduced at the base of the disc stack and the denser fraction moves towards the wall of the bowl, along the underside of the discs. The lighter fraction is

Table 6.1 Applications of centrifuges in food processing

Centrifuge type	Range of particle sizes (μm)	Solids content of feed (% of w/w)	Applications								
			A	B	C	D	E	F	G	H	
Disc bowl											
Clarifier	0.5–500	<5	★	★	★						
Self-cleaning	0.5–500	2–10	★	★	★	★	★				★
Nozzle bowl	0.5–500	5–25		★	★	★	★	★			★
Decanter	5–50 000	3–60		★	★	★	★		★	★	★
Basket	7.5–10 000	5–60							★	★	
Reciprocating conveyor	100–80 000	20–75							★	★	

A, liquid–liquid extraction; B, separation of liquid mixtures; C, clarification of liquids; D, concentration of slurries; E, liquid–solid–liquid extraction; F, dehydration of amorphous materials; G, de-watering of crystalline foods; H, wet classification.

Adapted from Hemfort (1983).

displaced towards the centre along the upper surfaces and both liquid streams are removed continuously by a weir system at the top of the centrifuge in a similar way to the tubular bowl system. Disc bowl centrifuges are used to separate cream from milk and to clarify oils, coffee extracts and juices (Table 6.1). Disc bowl and tubular centrifuges have capacities of up to $150\,000\text{ l h}^{-1}$.

Centrifugal clarifiers

The simplest solid–liquid centrifuge is a *solid bowl clarifier*, which is a rotating cylindrical bowl, 0.6–1.0 m in diameter. Liquor, with a maximum of 3% w/w solids, is fed into the bowl and the solids form a cake on the bowl wall. When this has reached a pre-determined thickness, the bowl is drained and the cake is removed automatically through an opening in the base. Feeds which contain a higher solids content (Table 6.1) are separated using *nozzle centrifuges* or *valve discharge centrifuges*. These are similar to disc bowl types, but the bowls have a biconical shape. In the nozzle type, solids are continuously discharged through small holes at the periphery of the bowl and are collected in a containing vessel. In the valve type the holes are fitted with valves that periodically open for a fraction of a second to discharge the accumulated solids. The advantages of the latter design include less wastage of liquor and the production of drier solids. Both types are able to separate feed liquor into three streams: a light phase, a dense phase and solids. Centrifugal clarifiers are used to treat oils, juices, beer and starches and to recover yeast cells. They have capacities up to $300\,000\text{ l h}^{-1}$.

Desludging, decanting or dewatering centrifuges

Feeds with high solids contents (Table 6.1) are separated using desludging centrifuges, including conveyor bowl, screen conveyor, basket and reciprocating conveyor centrifuges. In the *conveyor bowl centrifuge* the solid bowl rotates up to 25 rev min^{-1} faster than the screw conveyor (Fig. 6.3). This causes the solids to be conveyed to one end of the centrifuge, whereas the liquid fraction moves to the other larger-diameter end. The solids are relatively dry compared with other types of equipment.

The *screen conveyor centrifuge* has a similar design but the bowl is perforated to remove the liquid fraction. The *reciprocating conveyor centrifuge* is used to separate

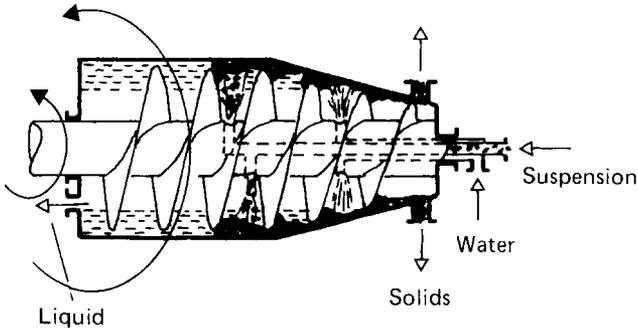


Fig. 6.3 Conveyor bowl centrifuge.
(After Leniger and Beverloo (1975).)

fragile solids (for example crystals from liquor). Feed enters a rotating basket, 0.3–1.2 m in diameter, through a funnel which rotates at the same speed. This gradually accelerates the liquid to the bowl speed and thus minimises shearing forces. Liquid passes through perforations in the bowl wall. When the layer of cake has built up to 5–7.5 cm, it is pushed forwards a few centimetres by a reciprocating arm. This exposes a fresh area of basket to the feed liquor.

The *basket centrifuge* has a perforated metal basket lined with a filtering medium, which rotates at up to 2000 rev min⁻¹ in automatically controlled cycles which last 5–30 min, depending on the feed material. The feed liquor first enters the slowly rotating bowl; the speed is then increased to separate solids and finally the bowl is slowed and the cake is discharged through the base by a blade. Capacities of these dewatering centrifuges are up to 90 000 l h⁻¹ and they are used to recover animal and vegetable proteins, to separate coffee, cocoa and tea slurries and to desludge oils.

6.2 Filtration

Filtration is the removal of insoluble solids from a suspension (or ‘feed slurry’) by passing it through a porous material (or ‘filter medium’). The resulting liquor is termed the ‘filtrate’ and the separated solids are the ‘filter cake’. Filtration is used to clarify liquids by the removal of small amounts of solid particles (for example from wine, beer, oils and syrups).

6.2.1 Theory

When a suspension of particles is passed through a filter, the first particles become trapped in the filter medium and, as a result, reduce the area through which liquid can flow. This increases the resistance to fluid flow and a higher pressure difference is needed to maintain the flow rate of filtrate. The rate of filtration is expressed as follows:

$$\text{Rate of filtration} = \frac{\text{driving force (the pressure difference across the filter)}}{\text{resistance to flow}}$$

Assuming that the filter cake does not become compressed, the resistance to flow through the filter is found using

$$R = \mu r \left(\frac{V_c V}{A + L} \right) \quad [6.4]$$

where R (m^{-2}) = resistance to flow through the filter, μ (N s m^{-2}) = viscosity of the liquid, r (m^{-2}) = specific resistance of the filter cake, V (m^3) = volume of the filtrate, V_c = the fractional volume of filter cake in the feed liquid volume, V, A (m^2) = area of the filter and L = equivalent thickness of the filter and initial cake layer.

For constant rate filtration, the flow rate through the filter is found using:

$$Q = \frac{\mu r V V_c}{A^2 \Delta P} + \frac{\mu r L}{A \Delta P} \quad [6.5]$$

where Q (V/t) ($\text{m}^3 \text{ s}^{-1}$) = flow rate of filtrate, ΔP (Pa) = pressure difference and t (s) = filtration time. This equation is used to calculate the pressure drop required to achieve a desired flow rate or to predict the performance of large scale filters on the basis of data from pilot scale studies.

In constant-pressure filtration, the flow rate gradually decreases as the resistance to flow, caused by the accumulating cake, increases. Equation (6.5) is rewritten with ΔP constant as:

$$\frac{tA}{V} = \frac{\mu r V_c V}{2\Delta P A} + \frac{\mu r L}{\Delta P} \quad [6.6]$$

If $t/(V/A)$ is plotted against V/A , a straight line is obtained (Fig. 6.4). The slope (equation 6.7) and the intercept (equation 6.8) are used to find the specific resistance of the cake and the equivalent cake thickness of the filter medium:

$$\text{Slope} = \mu r V_c / 2\Delta P \quad [6.7]$$

$$\text{Intercept} = \mu r L / \Delta P \quad [6.8]$$

If the filter cake is compressible (that is the specific resistance changes with applied pressure) the term r is modified as follows:

$$r = r'(\Delta P)^s \quad [6.9]$$

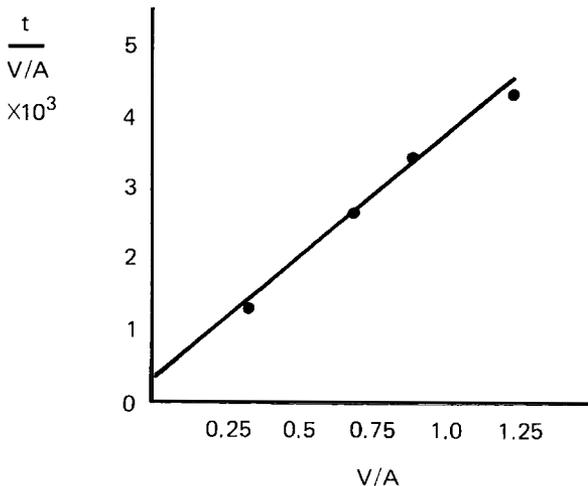


Fig. 6.4 Graph of $t/(V/A)$ versus V/A .

where r' is the specific resistance of the cake under a pressure difference of 101×10^3 Pa and s = the compressibility of the cake. This is then used in equation (6.4). Derivations of the above equations and further details are given by Earle (1983), Jackson and Lamb (1981) and Toledo (1999a).

Sample problem 6.3

Pulp which contains 15% solids is filtered in a plate and frame filter press (Section 6.2.2) with a pressure difference of 290 Pa. The masses of filtrate are shown below for a 1.5 h cycle. Calculate the specific resistance of the cake and the volume of filtrate that would be obtained if the cycle time were reduced to 45 min. (Assume that the cake is incompressible and the viscosity of the filtrate is 1.33×10^{-3} N s m⁻².)

Time (min)	7.5	30.4	50	90
Mass of filtrate (kg)	1800	3800	4900	6800

Solution to Sample problem 6.3

Time (s):	450	1825	3000	5400
V (m ³)	1.8	3.8	4.9	6.8
V/A	0.33	0.69	0.89	1.24
$t/(V/A)$	1364	2645	3371	4355

Plotting $t/(V/A)$ vs (V/A) (Fig. 6.4)

$$\text{slope} = 2666.7$$

$$\text{intercept} = 300$$

(1) From equation (6.7)

$$2666.7 = 1.33 \times 10^{-3} \times r \times 0.15/2 \times 290$$

$$r = 92273 \text{ m}^{-2}$$

(2) From equation (6.6)

$$tA/V = 2666.7 (V/A) + 300$$

For a 45 min (2700 s) cycle

$$2700 = 2666.7(V/0.55)^2 + 300(V/0.55)$$

$$\begin{aligned} \frac{V}{0.55} &= \frac{-300 \pm \sqrt{(90000 + 10800 \times 2666.7)}}{2 \times 2666.7} \\ &= 0.52 \text{ m}^3 \end{aligned}$$

6.2.2 Equipment

Gravity filtration is slow and finds little application in the food industry. Filtration equipment operates either by the application of pressure to the feed side of the filter bed or by the application of a partial vacuum to the opposite side of the filter bed. Centrifugal filtration using a basket centrifuge is described above. Filter aids are usually applied to the filter or mixed with the food to improve the formation of filter cake.

Pressure filters

Two commonly used pressure filters are the batch *plate-and-frame filter press* (Fig. 6.5) and the *shell-and-leaf pressure filter*. In the plate-and-frame design, cloth or paper filters are supported on vertical plates. Feed liquor is pumped into the press and liquid passes through the filter cloths and flows down the grooved surfaces of the plates to drain through an outlet channel in the base of each plate. A layer of cake builds up on the cloths until the space between the plates is filled.

In operation, the pressure is increased to a pre-determined value and the plates are then back-washed with water. The press is dismantled and the cake is removed, ready to begin another cycle. The filter press has relatively low capital costs, high flexibility for different foods, it is reliable and easily maintained. It is widely used for the production of apple juice and cider (for example Jones *et al.*, 1983). However, it is time consuming and highly labour intensive.

The *shell-and-leaf pressure filter* is used to overcome the problems of high labour costs and lack of convenience of plate-and-frame presses. It consists of mesh 'leaves', which are coated in filter medium and supported on a hollow frame which forms the outlet channel for the filtrate. The leaves are stacked horizontally or vertically inside a pressure vessel, and in some designs they rotate at $1-2 \text{ rev min}^{-1}$ to improve the uniformity of cake buildup. Feed liquor is pumped into the shell at a pressure of approximately $400 \times 10^3 \text{ Pa}$. When filtration is completed, the cake is blown or washed from the leaves. This equipment has a higher cost than plate filters and is best suited to routine filtration of liquors which have similar characteristics.

Vacuum filters

Vacuum filters are limited by the cost of vacuum generation to a pressure difference of about $100 \times 10^3 \text{ Pa}$. However, cake is removed at atmospheric pressure and these types of

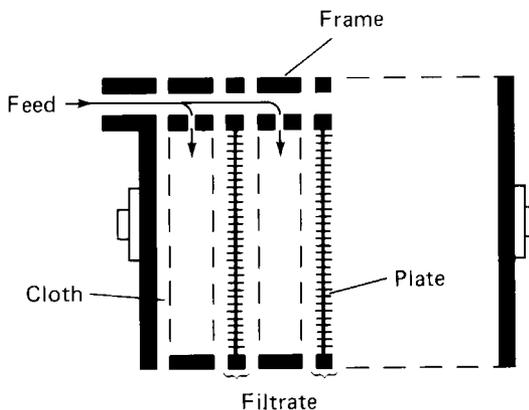


Fig. 6.5 Plate-and-frame filter press.

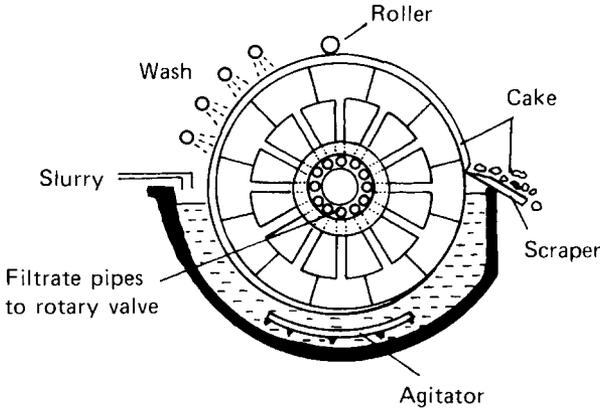


Fig. 6.6 Rotary drum filter.
(After Leniger and Beverloo (1975).)

filter are therefore able to operate continuously. (Pressure filters have batch operation because the pressure must be reduced for cake removal.) Two common types of vacuum filter are the rotary drum filter and rotary disc filter.

A *rotary drum filter* consists of a horizontal cylinder which has the surface divided into a series of shallow compartments, each covered in filter cloth and connected to a central vacuum pump (Fig. 6.6). As the drum rotates, it dips into a bath of liquor and filtrate flows through the filter and out through channels in the drum. When a compartment leaves the bath, the filter cake is sucked free of liquor, washed with sprays and the vacuum is released. Compressed air is blown from beneath the cloth to loosen the cake, which is removed by a scraper before the individual compartment restarts the cycle.

Rotary vacuum disc filters consist of a series of vertical discs which rotate slowly in a bath of liquor in a similar cycle to drum filters. Each disc is divided into portions which have outlets to a central shaft. The discs are fitted with scrapers to remove the cake continuously. These types of filter are compact and have low labour costs and high capacity. However, they have high capital costs and produce cake which has a moderately high moisture content.

6.3 Expression

6.3.1 Theory

The main applications of expression are in the extraction of components plant materials either for direct consumption (for example fruit juices) or for use in subsequent processing (for example sugar, grape juice for wine and vegetable oils). These materials are located within the cell structure of the plants and it is necessary to disrupt the cells in order to release them. This is achieved either in a single-stage, which both ruptures the cells and expresses the liquid, or in two stages (size reduction to produce a pulp or flour, followed by separation in a press). In general the single-stage operation is more economical, permits higher throughputs and has lower capital and operating costs, but for some products that are especially hard (for example oil bearing nuts) a two-stage expression is more effective. Better extraction is achieved by heating oilseeds or flours to reduce the oil viscosity, release oil from intact cells and remove moisture. There is an optimum moisture content for each type of oil seed to obtain a maximum yield of oil.

In fruit processing, the press should remove the maximum quantity of juice, without substantial quantities of solids, or phenolic compounds from the skins which cause bitterness and browning. This is achieved using lower pressures and fewer pressings. It is also necessary to increase the pressure slowly to avoid the formation of a dense impenetrable press cake, as the solid material is easily deformed and blocks the press.

The factors that influence the juice yield from a press include:

- maturity and growth conditions of the raw material
- extent of cell disruption
- thickness of the pressed solids and their resistance to deformation
- rate of increase in pressure, the time of pressing and the maximum pressure applied
- temperatures of solids and liquid and the viscosity of the expressed liquid.

6.3.2 Equipment

Batch presses

Common types of equipment for expressing juice or oils are the *tank press* and the *cage press*.

The tank press is used for fruit juice production and consists of a horizontal cylinder which is divided internally by a membrane. During an automatically controlled pressing cycle of 1.5 h, fruit pulp is fed into one side of the membrane and compressed air is applied to the opposite side (Fig. 6.7). Juice flows out through channels and, when pressing is completed, the tank is rotated to loosen and discharge the press residue. High yields of good-quality juice are obtained by the gentle increase in pressure at capacities ranging from 3600 kg to 25 000 kg (Vine, 1987).

In the cage press, up to 2 t of fruit pulp or oilseed flour is placed into a vertical perforated or slatted cage, either loose or in cloth bags depending on the nature of the material. In larger presses, ribbed layer plates are used to reduce the thickness of the pulp or flour bed. The pressure is gradually increased on the top plate by an hydraulic system or motor-driven screw thread and liquid is collected at the base of the press. The equipment allows close control over the pressure exerted on the pulp/flour and may operate semi-automatically to reduce labour costs.

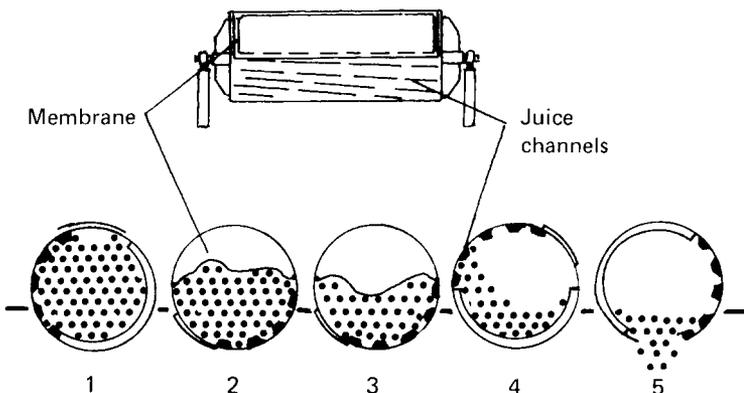


Fig. 6.7 Tank press: 1, tank filled; 2, membrane partly inflated; 3, membrane further inflated; 4, loosening residue; 5, discharge.

(After Vine (1987).)

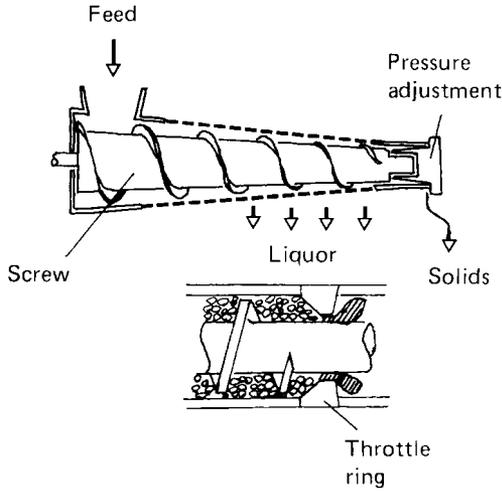


Fig. 6.8 Screw press, showing throttle ring used for oilseed pressing.
(After Brennan *et al.* (1990) and Stein (1984).)

Continuous presses

There are several types of continuous press used commercially: the belt press for fruit processing, the screw expeller for both fruit processing and oil extraction (a similar design is used for extrusion (Chapter 14)), and the roller press for sugar cane processing.

Belt presses consist of a continuous belt, made from canvas-plastic composite material, which passes under tension over two hollow stainless steel cylinders, one of which is perforated. Pulped fruit is fed onto the inside of the belt and is pressed between the belt and the perforated cylinder. Juice flows through the perforations and the press cake continues around the belt and is removed by a scraper or auger. They produce high yields of good-quality juice but have high capital costs and difficulty in maintenance and cleaning.

The *screw expeller* consists of a robust horizontal barrel containing a stainless steel helical screw (Fig. 6.8). The pitch of the screw flights gradually decreases towards the discharge end, to increase the pressure on the material as it is carried through the barrel. The final section of the barrel is perforated to allow expressed liquid to escape. Press cake is discharged through the barrel outlet and the pressure in the barrel is regulated by adjusting the diameter of the discharge port. Frictional heat reduces the viscosity of the oil and some types of expellers have supplementary heaters fitted to the barrel to improve yields. In juice extraction the barrel is cooled to reduce the friction heat, generated by the movement of food, which may have an undesirable effect on flavour and aroma. Capacities range from 40 kg h^{-1} to 8000 kg h^{-1} . The oil cake has 5–18% (w/w) residual oil, depending on the type of oil-seed and the operating conditions (Barker, 1987). A modified screw press is described by Stein (1984), (Fig. 6.8), in which high shearing forces act on the seeds as they are forced through a series of throttle rings located in the barrel.

In the *roller press*, pulp or sugar cane is fed between heavy fluted metal rollers and liquid flows along the grooves to a collection pan.

6.4 Extraction using solvents

Unit operations that involve separation of specific components of foods are important in a number of applications, including production of:

- cooking oils or speciality oils from nuts and seeds
- flavours and essential oils (e.g. black pepper, cardamom, clove, ginger, hops, parsley, vanilla, etc.)
- coffee
- sugar
- removal of caffeine from coffee and tea.

Once the solvent has been removed from the extracted foods, some may be used directly (for example cooking oils) or they may be further processed by concentration (Section 6.5 and Chapter 13) and/or dehydration (Chapter 15). Many extraction operations operate close to ambient temperature, but even when elevated temperatures are used to increase the rate of extraction, there is little damage caused by heat and the product quality is not significantly affected.

The main types of solvents used for extraction are water, organic solvents or supercritical carbon dioxide. These are described below.

6.4.1 Theory

Solid-liquid extraction involves the removal of a desired component (the solute) from a food using a liquid (the solvent) which is able to dissolve the solute. This involves mixing the food and solvent together, either in a single stage or in multiple stages, holding for a pre-determined time and then separating the solvent. During the holding period there is mass transfer of solutes from the food material to the solvent, which occurs in three stages:

1. the solute dissolves in the solvent
2. the solution moves through the particle of food to its surface
3. the solution becomes dispersed in the bulk of the solvent.

During extraction, the holding time should therefore be sufficient for the solvent to dissolve sufficient solute and for the changes in composition to approach an equilibrium. The time required depends on the solubility of a given solute in the solvent selected and also on the following factors:

- *The temperature of extraction.* Higher temperatures increase both the rate at which solutes dissolve in the solvent and the rate of diffusion into the bulk of the solvent. The temperature of most extraction operations is limited to less than 100°C by economic considerations, extraction of undesirable components at higher temperatures or heat damage to food components.
- *The surface area of solids exposed to the solvent.* The rate of mass transfer is directly proportional to the surface area, so reductions in particle size (giving an increase in surface area) increase the rate of extraction up to certain limits.
- *The viscosity of the solvent.* This should be sufficiently low to enable the solvent to penetrate easily the bed of solid particles.
- *The flowrate of the solvent.* Higher flowrates reduce the boundary layer of concentrated solute at the surface of particles and thus increase the rate of extraction.

Table 6.2 Solvents used to extract food components

Food	Solvent	Final solute concentration (%)	Temperature (°C)
Decaffeinated coffee	Supercritical carbon dioxide, water or methylene chloride	N/A	30–50 (CO ₂)
Fish livers, meat byproducts	Acetone or ethyl ether	N/A	30–50
Hop extract	Supercritical carbon dioxide	N/A	<100–180
Instant coffee	Water	25–30	70–90
Instant tea	Water	2.5–5	N/A
Olive oil	Carbon disulphide	N/A	
Seed, bean and nut oils (e.g. from soybeans, groundnuts, cottonseed, sunflower seed, etc.)	Hexane, heptane or cyclohexane	N/A	63–70 (hexane) 90–99 (heptane) 71–85 (cyclohexane)
Sugar beet	Water	approx. 15	55–85

Adapted from data of Brennan *et al.* (1990) and Clarke (1990).

Examples of mass transfer are described in Chapter 1 and further details are given in Brennan *et al.* (1990) and Toledo (1999b).

Solvents

The types of solvent used commercially to extract food components are shown in Table 6.2. Extraction using water (leaching) has obvious advantages of low cost and safety and is used to extract sugar, coffee and tea. Oils and fats require an organic solvent and as these are highly flammable, great care is needed in both operating procedures and to ensure that equipment is gas-tight and electrical apparatus is spark-proof.

Supercritical carbon dioxide has found increasingly widespread application for removing caffeine from coffee or tea and for producing hop extracts for brewing (Gardner, 1982). It has also been used to extract and concentrate flavour compounds from fruits and spices (including pepper, marjoram, nutmeg, cardamom, cloves and ginger), and speciality oils from citrus and a variety of nuts and seeds. The combination of supercritical CO₂ and extrusion to produce a new range of breakfast cereals, pasta products and confectionery is described by Rizvi *et al.* (1995). Gaehrs (1990) has reviewed the economics of extraction and applications to different products and the topic is comprehensively reviewed by Steytler (1996).

The term supercritical arises from the critical temperature and critical pressure lines on a pressure–temperature diagram (Fig. 6.9). The supercritical region for carbon dioxide is when it is above the critical pressure line and to the right of the critical temperature line (31°C) (Brogle, 1982). As a solvent it acts as a liquid but has a low viscosity and diffuses easily like a gas. It has the advantages of being highly volatile and so is easily separated from solute without leaving any residues in the food. It is also non-flammable, non-toxic, bacteriostatic and low cost. It is used under conditions that are close to the critical point (near-critical fluid or NCF) for de-odourising applications or for highly soluble solutes. For more complete extraction or for applications that involve less soluble solutes, it is used at higher temperatures and pressures (Rizvi *et al.*, 1986). The upper limit for the operating temperature is the heat sensitivity of the food components and the upper limit for pressure (about 40 MPa) is the cost of pressurised equipment.

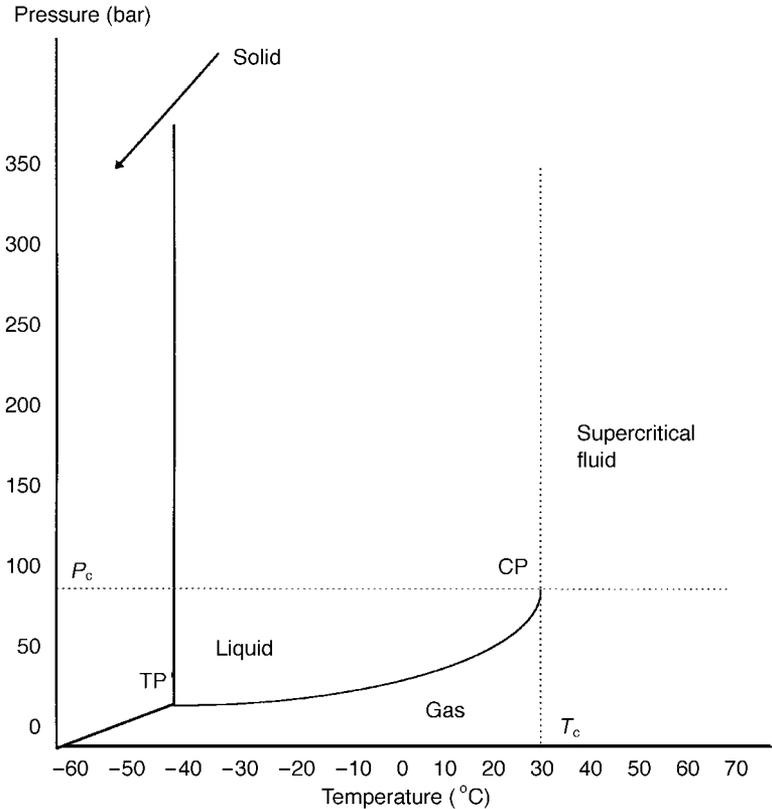


Fig. 6.9 Pressure–temperature diagram for carbon dioxide. TP = triple point, CP = critical point, T_c = critical temperature (31.06°C), P_c = critical pressure (73.8 bar). (Adapted from Brennan *et al.* (1990).)

6.4.2 Equipment

Extractors are either single-stage or multi-stage static tanks or continuous extractors. The components of a typical extraction unit that uses near-critical CO₂ solvent are shown in Fig. 6.10.

The essential components are an extraction vessel, a separation vessel, a condenser and a pump. In supercritical CO₂ extraction, CO₂ is stored as a near-critical liquid in the condenser and then pumped to the extraction vessel through a heat exchanger by a high pressure pump. The state of the CO₂ in the extractor is determined by the pressure, controlled by pressure relief valve, and the temperature, thermostatically controlled by liquid recirculating through a jacket surrounding the vessel. The material to be extracted is purged with gaseous CO₂ to remove air and then liquid CO₂ is pumped in at a rate that permits a sufficient residence time for equilibrium conditions to be established. The solution is then passed to the separation vessel in which conditions are adjusted to minimise the solubility of the extracted components (often by decompression). The CO₂ is then returned to the cooled condenser for re-use and the extract is removed from the separation vessel.

Single-stage extractors

These are closed tanks, fitted with a mesh base to support the solid particles of food. Heated solvent percolates down through the particles and is collected below the mesh

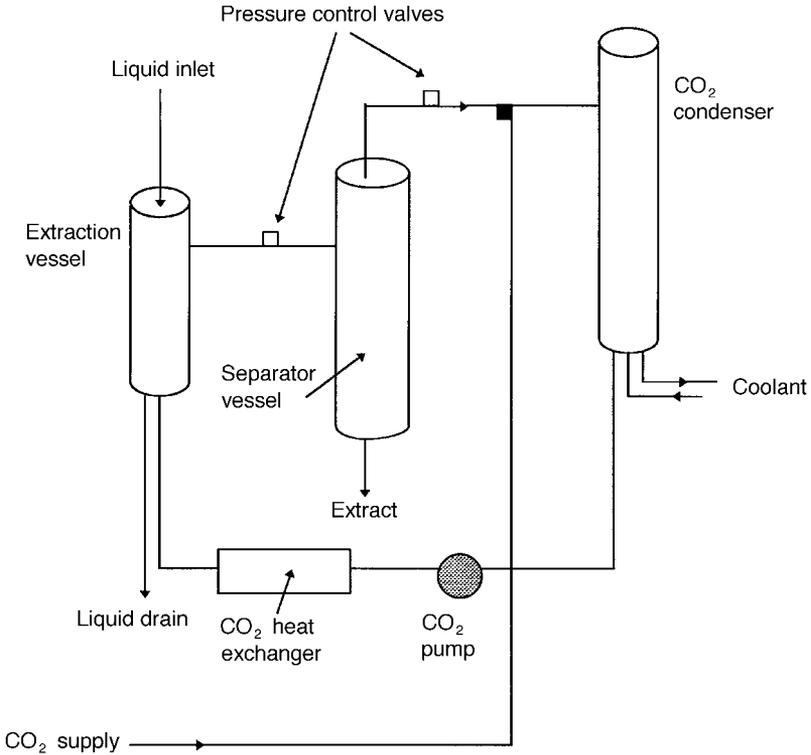


Fig. 6.10 Layout of a CO₂ extraction plant.
(Adapted from Steytler (1996).)

base, with or without recirculation. They are used to extract oils or to produce coffee or tea extracts. Instant coffee production is described in detail by Clarke (1990). Although they have low capital and operating costs, single-stage extractors produce relatively dilute solutions which may require expensive solvent recovery systems for organic solvents or pollution control measures when water is used as the solvent.

Multi-stage extractors

These comprise a series of up to 15 tanks, each similar to single extractors, linked together so that solvent emerging from the base of one extractor is pumped counter-currently to the next in the series. These are used to produce oils, tea and coffee extracts and to extract sugar from beet.

Continuous extractors

There are a large number of designs of extractor, each of which may operate counter-currently and/or co-currently. For example, one design is an enclosed tank containing two vertical bucket elevators (Chapter 26) made from perforated buckets and linked to form a continuous ring. Fresh material is loaded into the descending buckets of one elevator and solvent is pumped in at the top to extract solutes co-currently. As the buckets then move upwards, fresh solvent is introduced at the top of the second elevator to extract solutes counter-currently. The solution collects at the base and is pumped to the top of the first elevator to extract more solute, or it is separated for further processing. Other designs of equipment employ perforated screw conveyors instead of bucket elevators.

Other designs use a rotating carousel in which segments with perforated bases contain the feed material. Solvent is sprayed onto each segment, collected at the base and pumped to the preceding segment to produce counter-current extraction. These and centrifugal separators (Section 6.1.2) are used to extract oils, coffee, sugar beet, and in the preparation of protein isolates. Further details of their operation are given by Brennan *et al.* (1990).

6.5 Membrane concentration (hyperfiltration and ultrafiltration)

Reverse osmosis (RO) (or 'hyperfiltration') and ultrafiltration (UF) are both unit operations in which water and some solutes in a solution are selectively removed through a semi-permeable membrane. They are similar in that the driving force for transport across the membrane is the pressure applied to the feed liquid. However, reverse osmosis is used to separate water from low-molecular-weight solutes (for example salts, monosaccharides and aroma compounds), which have a high osmotic pressure (Table 6.3). A high pressure, five to ten times that used in UF ($4000\text{--}8000 \times 10^3$ Pa), is therefore necessary to overcome this (hence the term *reverse osmosis*).

The largest commercial food application of reverse osmosis is the concentration of whey from cheese manufacture, either as a pre-concentration stage prior to drying or for use in the manufacture of ice cream. Reverse osmosis is also used to:

- concentrate and purify fruit juices (Robe, 1983), enzymes, fermentation liquors and vegetable oils
- to concentrate wheat starch, citric acid, egg white, milk, coffee, syrups, natural extracts and flavours
- to clarify wine and beer
- to demineralise and purify water from boreholes or rivers or by desalination of sea water.

In the last application, monovalent and polyvalent ions, particles, bacteria and organic materials with a molecular weight greater than 300 are all removed by up to 99.9% to give high-purity process water for beverage manufacture and other applications.

Other applications include 'dealcoholisation' to produce low-alcohol beers, cider and wines, and recovery of proteins or other solids from distillation residues, dilute juices, waste water from corn milling or other process washwaters. Membrane pre-concentration is also used to prepare coffee extracts and liquid egg for drying and to pre-concentrate

Table 6.3 Osmotic pressures of selected solutions

Solution	Concentration	Osmotic pressure (Pa $\times 10^5$)
Apple juice	15° Brix	2.04
Citrus juice	10° Brix	1.48
Coffee extract	28% TS	3.40
Lactose	1% w/v	0.37
Milk	–	0.69
Salt solution	15% TS	13.8
Sucrose solution	44° Brix	6.9
Sugar syrup	20° Brix	3.41
Tomato paste	33° Brix	6.9
Whey	–	0.69

TS = total solids, w/v = weight per volume.
Adapted from Lewis (1996a).

juices and dairy products before evaporation, so improving the economy of evaporators. Concentrating fluids by removal of water at low temperatures in the dairy, fruit juice and sugar processing industries competes with vacuum evaporation (Chapter 13) and freeze concentration (Chapter 22). The advantages of membrane concentration over concentration by evaporation are:

- the food is not heated, and there is therefore negligible loss of volatiles or changes to nutritional or eating quality
- in contrast with boiling, membrane concentration does not involve a change in phase and therefore uses energy more efficiently (Table 6.4)
- simple installation with lower labour and operating costs
- no requirement for steam boilers.

The main limitations of membrane concentration are:

- variation in the product flow rate when changes occur in the concentration of feed liquor
- higher capital costs than evaporation
- a maximum concentration to 30% total solids
- fouling of the membranes (deposition of polymers), which reduces the operating time between membrane cleaning.

Different types of membrane reject solutes with specific ranges of molecular weight (Fig. 6.11). These molecular weight 'cutoff' points are used to characterise membranes. For reverse osmosis membranes, the cutoff points range from molecular weights of 100 Da at $4000\text{--}7000 \times 10^3$ Pa to 500 Da at $2500\text{--}4000 \times 10^3$ Pa.

Table 6.4 Comparison of reverse osmosis and evaporation of whey

Parameter	Reverse osmosis	Evaporation
Steam consumption	0	250–550 kg per 1000 l water removed
Electricity consumption	10 kW h per 1000 l water removed (continuous); 20 kW h per 1000 l water removed (batch)	Approximately 5 kW h per 1000 l water removed
Energy use (kW h)	3.6 (6–12% solids) 8.8 (6–18% solids) 9.6 (6–20% solids)	One effect 387 (6–50% solids) Two effects 90 (6–50% solids) Seven effects 60 (6–50% solids) MVR* 44
Labour	4 h day ⁻¹	Normally two operators during whole operation (boiler house and evaporator)
Cooling-water consumption	0–29 300 kJ per 1000 l water removed (continuous); 0–58 600 kJ per 1000 l water removed (batch)	$(5.2\text{--}1.2) \times 10^6$ kJ per 1000 l water removed
Economical plant size	6000 l day ⁻¹ day or more, no upper limit	80 000–100 000 l day ⁻¹
Consideration in final product	Maximum 30% total solids. Capacity varies with concentration	Up to 60% total solids

* MVR, mechanical vapour recompression.

Adapted from Madsen (1974).

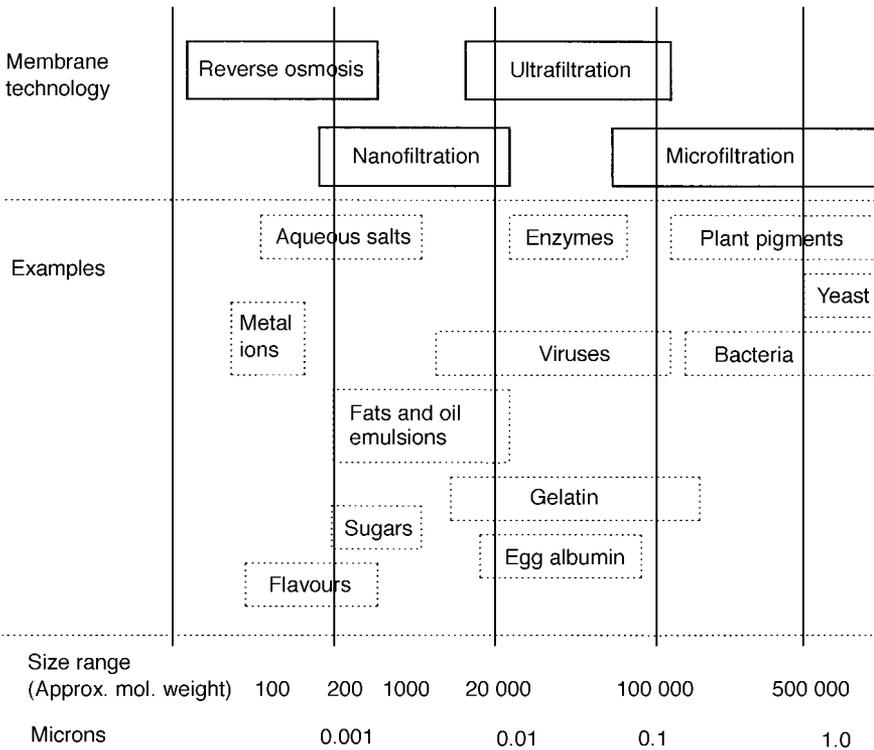


Fig. 6.11 Size separation capabilities of different membrane systems.
(From Anon. (1997).)

The term *nanofiltration* (NF) (or ‘loose reverse osmosis’) is used when membranes remove materials having molecular weights in the order of 300–1000 Da (Rosenberg, 1995). This compares to a molecular weight range of 2000–300 000 for ultrafiltration membranes, although above 30 000 there is overlap with microfiltration (Fig. 6.11). NF is capable of removing ions that contribute significantly to the osmotic pressure and thus allows operation at pressures that are lower than those needed for RO.

UF membranes have a higher porosity and retain only large molecules (for example proteins or colloids) which have a lower osmotic pressure. Smaller solutes are transported across the membrane with the water. Ultrafiltration therefore operates at lower pressures ($50\text{--}1000 \times 10^3$ Pa). The most common commercial application of ultrafiltration is in the dairy industry to concentrate milk prior to the manufacture of dairy products, to concentrate whey to 20% solids or selectively to remove lactose and salts. In cheese manufacture, ultrafiltration has advantages in producing a higher product yield and nutritional value, simpler standardisation of the solids content, lower rennet consumption and easier processing. Other applications include:

- concentration of sucrose and tomato paste
- treatment of still effluents in the brewing and distilling industries
- separation and concentration of enzymes, other proteins or pectin
- removal of protein hazes from honey and syrups
- treatment of process water to remove bacteria and contaminants (greater than $0.003 \mu\text{m}$ in diameter) (Mackintosh, 1983)

- pre-treatment for reverse osmosis membranes to prevent fouling by suspended organic materials and colloidal materials.

An extension of UF, in which water is added back to the extract during the concentration process is known as *diafiltration*. This is useful in selectively removing lower molecular weight materials from a mixture, and is described in detail by Lewis (1996b). It offers a useful alternative process to ion exchange or electrodialysis (see below) for removal of anions, cations, sugars, alcohol or antinutritional compounds.

Microfiltration (MF) is similar to UF in using lower pressures than RO, but is distinguished by the larger range of particle sizes that are separated (0.01–2 μm) (Fig. 6.11). Whereas UF is used to separate macromolecules, MF separates dispersed particles such as colloids, fat globules or cells, and may therefore be thought of as falling between UF and conventional filtration (Grandison and Finnigan, 1996). It was developed before other membrane processes but has advanced more slowly due to difficulties in microporous membrane design which trapped particles and blocked the material. More recent developments in membrane materials have partially overcome this problem to permit continuous processing of larger volumes of liquids with higher concentrations of suspended solids. An example of the applications of UF, MF and DF for the fractionation of milk proteins is shown in Fig. 6.12. These processes enable new possibilities to tailor the functional properties of milk proteins (e.g. water holding capacity, fat binding, emulsification characteristics, whippability and heat stability) for specific applications as food ingredients (Rosenberg, 1995).

Ion-exchange and *electrodialysis* are both separation methods that remove electrically charged ions and molecules from liquids. In ion-exchange, solutes such as metal ions, proteins, amino acids and sugars are transferred from a feed material and retained on a solid ion-exchange material by a process of electrostatic adsorption (i.e. attraction between the charge on the solute and an opposite charge on the ion-exchanger). They can then be separated by washing off the ion-exchanger. The ion-exchanger is either a cation exchanger (having a fixed negative charge) or an anion exchanger (having a fixed positive charge). They are constructed using a porous matrix made from polyacrylamides, polystyrene, dextrans or silica. The applications in food processing include decolourisation of sugar syrups, protein recovery from whey or blood, water softening and demineralisation and separation of valuable materials such as purified enzymes (Grandison, 1996).

Electrodialysis (ED) is used to separate electrolytes from non-electrolytes and to exchange ions between solutions. A direct current is passed through a solution and ions or molecules migrate due to their electrical charge towards an anode or a cathode. Separation is based on ion-selective membranes (sheets of cation- and anion-exchange materials) which act as barriers to either anions or cations. Therefore anions that migrate towards the anode pass through anion membranes but are rejected by cation membranes and vice versa. The membranes are arranged alternately to form ion-diluting cells and ion-concentrating cells. In an example described by Grandison (1996), cheese whey is circulated through ion-diluting cells and brine is circulated through ion-concentrating cells. Mineral ions leave the whey and become concentrated in the brine, thus demineralising the whey. This is a major application of ED and demineralised whey is used in infant feeds, drinks, salad dressing, confectionery coatings, ice cream mixes and bakery. It can also be used to remove potassium and tartaric acid from wines to prevent precipitate formation, to desalinate pickling brines and to de-acidify fruit juices to reduce their sourness products (Grandison, 1996).

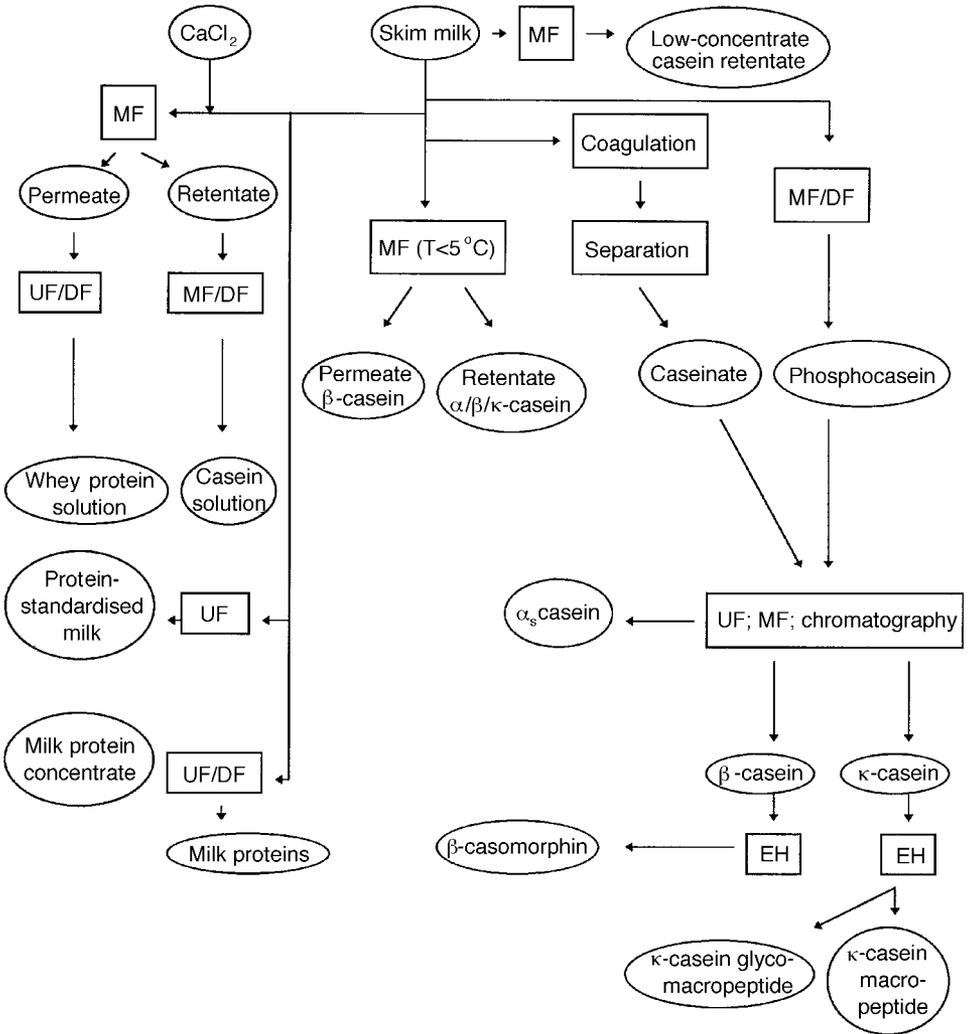


Fig. 6.12 Fractionation of milk proteins using UF, MF and DF. (EH = enzyme hydrolysis, T = temperature.)
(From Rosenberg (1995).)

Pervaporation is an emerging membrane separation technique, in which a liquid feed mixture is separated by partial vaporisation through a non-porous, selectively permeable membrane. It produces a vapour permeate and a liquid retentate. Partial vaporisation is achieved by reducing the pressure on the permeate side of the membrane (vacuum pervaporation) or less commonly, sweeping an inert gas over the permeate side (sweep gas pervaporation). There are two types of membrane, which are used in two distinct applications: hydrophilic polymers (e.g. poly (vinyl alcohol) or cellulose acetate) preferentially permit water permeation, whereas hydrophobic polymers (e.g. poly (dimethylsiloxane) or poly (trimethylsilylpropyne)) preferentially permit permeation of organic materials. Vacuum pervaporation at ambient temperatures using hydrophilic membranes is used to dealcoholise wines and beers, whereas hydrophobic membranes are used to concentrate aroma compounds, such as alcohols, aldehydes and esters, to up to

one hundred times the concentration in the feed material. The concentrate is then added back to a food after processing (e.g. after evaporation, Chapter 13) to improve its sensory characteristics. A review of these and other applications of pervaporation is given by Karlsson and Tragardh (1996).

6.5.1 Theory

In both reverse osmosis and ultrafiltration the flow rates through the membrane depend on the resistance of the membrane material, the resistance of boundary layers of liquid on each side of the membrane (Chapter 1), and the extent of fouling. Movement of molecules through reverse osmosis membranes is by diffusion and not by liquid flow. The molecules dissolve at one face of the membrane, are transported through it and then removed from the other face. The flow rate of liquid (the 'transport rate' or 'flux') is determined by the solubility and diffusivity of the molecules in the membrane material, and by the difference between the osmotic pressure of the liquid and the applied pressure. The pressure difference across the membrane (the trans-membrane pressure) is found using:

$$P = \frac{P_f + P_r}{2} - P_p \quad \boxed{6.10}$$

where P (Pa) = trans-membrane pressure, P_f (Pa) = pressure of the feed (inlet), P_r (Pa) = pressure of the retentate (outlet) (high molecular weight fraction) and P_p (Pa) = pressure of the permeate (low molecular weight fraction).

Water flux increases with an increase in applied pressure, increased permeability of the membrane and lower solute concentration in the feed stream.

It is calculated using:

$$J = kA(\Delta P - \Delta \Pi) \quad \boxed{6.11}$$

where J (kg h^{-1}) = flux, K ($\text{kg m}^{-2} \text{h}^{-1} \text{Pa}^{-1}$) = mass transfer coefficient, A (m^2) = area of the membrane, ΔP (Pa) = applied pressure and $\Delta \Pi$ (Pa) = change in osmotic pressure.

Osmotic pressure is found for dilute solutions using:

$$\Pi = MRT \quad \boxed{6.12}$$

where T ($^{\circ}\text{K}$) (where $^{\circ}\text{K} = ^{\circ}\text{C} + 273$) = absolute temperature, R ($\text{Pa m}^{-3} \text{mol}^{-1} \text{K}^{-1}$) = universal gas constant, M (mol m^{-3}) = molar concentration and Π (Pa) = osmotic pressure.

Many foods have high osmotic pressures (for example $(6-10) \times 10^5$ Pa for fresh fruit juice), and a high applied pressure is therefore needed. Solutes that are 'rejected' (retained) by the membrane either have a lower solubility than water in the membrane material or diffuse more slowly through the membrane. The rate of rejection is 100% (all solutes) for RO membranes.

The important factors in determining the performance of a membrane are its thickness, chemical composition and molecular structure. The pores of ultrafiltration membranes are considerably larger ($0.01-100 \mu\text{m}$), and water and small solutes flow through the membrane under hydraulic (streamline, viscous) flow (Chapter 1). Larger solutes become concentrated at the membrane surface. The rate of rejection for UF membranes is 95-100% of high molecular weight solutes and 0-10% of low molecular weight solutes (virtually free passage). The flux is therefore controlled by the applied pressure, and the solute concentrations in the bulk of the liquid and at the membrane surface:

$$J = KA \ln\left(\frac{c_1}{c_2}\right)$$

6.13

where c_1 = concentration of solutes at the membrane and c_2 = concentration of solutes in the liquid.

Other factors that influence the flux include the liquid velocity, viscosity and temperature. A high flow rate is necessary to reduce the formation of a layer of polymer gel at the membrane. In batch operation the liquid is recirculated until the desired concentration is achieved, whereas in continuous production an equilibrium is established, where the feed rate equals the sum of the permeate and concentrate flow rates. The ratio of this sum determines the degree of concentration achieved. Theoretical aspects of membrane filtration are discussed in more detail by Toledo (1999a), Lewis (1996a), Lewis (1996b) and Heldman and Hartel (1997a).

Sample problem 6.4

Fruit juice containing 9% w/w solids is pre-concentrated at 35°C by reverse osmosis, prior to concentration in an evaporator. If the operating pressure is 4000 kPa and the mass transfer coefficient is $6.3 \times 10^{-3} \text{ kg m}^{-2} \text{ h}^{-1} \text{ kPa}^{-1}$, calculate the area of membrane required to remove 5 t of permeate in an 8 h shift. (Assume that sucrose forms the majority of the solids in the juice and the universal gas constant is $8.314 \text{ kPa m}^{-3} \text{ mol}^{-1} \text{ K}^{-1}$.)

Solution to Sample problem 6.4

$$\text{Molar concentration } (M) = \frac{\text{concentration}(\text{g l}^{-1})}{\text{molecular weight}}$$

$$\text{g l}^{-1} \equiv \text{kg m}^{-3} = 90/342 = 0.264 \text{ mol m}^{-3}$$

From equation (6.12),

$$\begin{aligned} \Pi &= 0.264 \times 8.314(35 + 273) \\ &= 676 \text{ kPa} \end{aligned}$$

Therefore,

$$\begin{aligned} \text{required flux} &= \frac{5000}{8} \\ &= 625 \text{ kg h}^{-1} \end{aligned}$$

From equation (6.11)

$$6.25 = 6.3 \times 10^{-3} A(4000 - 676)$$

Thus,

$$A = 29.9 \text{ m}^2 = 30 \text{ m}^2$$

6.5.2 Equipment

The molecular structure of reverse osmosis membranes is the main factor that controls the rate of diffusion of solutes. The materials should have a high water permeability and a high solute rejection and durability. 'Ultrathin' membranes (0.05–0.1 μm thick) were made initially from cellulose acetate, mixed cellulose esters (acetate-propionate-butyrate), polyacrylonitrile, polyamides or polyurethanes (Michaels, 1974). They have the required permeability, high stability and mechanical strength to resist the high operating pressures. *Loeb* membranes are heterogeneous membranes which consist of a thin layer of membrane (for example 0.1 μm thick cellulose ester) on a thicker (5–10 mm) layer of porous support material. However, these materials were limited to operating temperatures below 30°C and a pH range of 3–6, and were followed by newer materials made from polyamides and polysulphones and inorganic membranes made from sintered or ceramic materials (Table 6.5). These are able to withstand higher temperatures (e.g. 80°C) and a wider pH range (e.g. pH 3–11).

The main requirement of an ultrafiltration membrane is the ability to form and retain a 'microporous' structure during manufacture and operation. Rigid ceramic or glassy polymers, which are thicker than reverse osmosis membranes (0.1–0.5 μm), are used. They are mechanically strong, durable and resistant to abrasion, heat and hydrolysis or oxidation in water. They do not creep, soften or collapse under pressure. Suitable materials are described in Table 6.5. The pore size in the inner skin determines the size of molecules which can pass through the membrane; larger molecules are retained on the inside of the membrane. MF membranes are similar to UF membranes, having two parts: a macroporous support material and a microporous coating on the surface. The macroporous support materials are produced from sintered materials such as alumina, carbon, stainless steel and nickel, and have a pore diameter of 10 μm or more to allow the permeate to drain away freely. Inorganic materials such as glass and compounds of

Table 6.5 Advantages and limitations of different types of membrane for RO and UF

Type of membrane	Advantages	Limitations
Cellulose acetate	High permeate flux Good salt rejection Easy to manufacture	Break down at high temperatures pH sensitive (can only operate between pH 3–6) Broken down by chlorine, causing problems with cleaning and sanitation
Polymers (for example polysulphones, polyamides, poly-vinyl chloride, polystyrene, polycarbonates, polyethers)	Polyamides have better pH resistance than cellulose acetate Polysulphones have greater temperature resistance (up to 75°C), wider pH range (1–13) and better chlorine resistance (up to 50 $\mu\text{g kg}^{-1}$). Easy to fabricate Wide range of pore sizes	Do not withstand high pressures and restricted to ultrafiltration Polyamides more sensitive to chlorine than cellulose acetate
Composite or ceramic membranes (for example porous carbon, zirconium oxide, alumina)	Inert Very wide range of operating temperatures and pH Resistant to chlorine and easily cleaned	Expensive

Adapted from the data of Heldman and Hartel (1997a).

aluminium, zirconium and titanium are used for microporous component of membranes. These have good structural strength and resistance to higher temperatures and damage from chemicals or abrasion.

All types of membranes should be supported to resist the high pressures and the membrane plus support material are termed a 'module'. The design criteria for modules should include:

- provision of a large surface area in a compact volume
- configuration of the membrane to permit suitable turbulence, pressure losses, flow rates and energy requirements
- no dead spaces and capability for cleaning-in-place (CIP) on both the concentrate and permeate sides
- easy accessibility for cleaning and membrane replacement (Lewis, 1996a).

The two main configurations of membranes are the *tubular* and *flat plate* designs. Tubular membranes are held in cylindrical tubes mounted on a frame with associated pipework and controls. The two main types are the *hollow fibre* and *wide tube* designs. Hollow fibre systems (Fig. 6.13) have 50–1000 fibres, one metre long and 0.001–1.2 mm in diameter, with membranes of about 250 μm thick. The fibres are attached at each end to a tube sheet to ensure that the feed is uniformly distributed to all tubes. These systems have a large surface area to volume ratio and a small holdup volume. They are used for RO applications such as desalination, but in UF applications the low applied pressure and laminar flow limits this system to low viscosity liquids that do not contain particles. They are also more expensive because an entire cartridge must be replaced if one or more fibres burst. However, they are easy to clean and do not block easily.

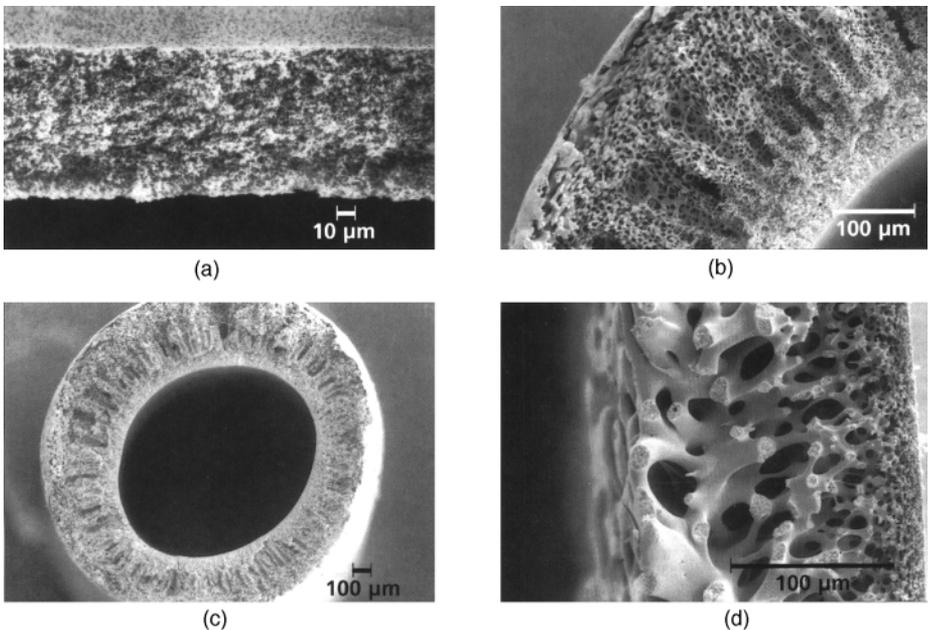


Fig. 6.13 Membrane structures: (a) asymmetrical membrane cross-section; (b) symmetrical membrane cross-section; (c) hollow-fibre asymmetrical membrane cross-section; (d) flat sheet asymmetrical membrane cross-section.

(Courtesy of Environmental Technology Best Practice Programme.)

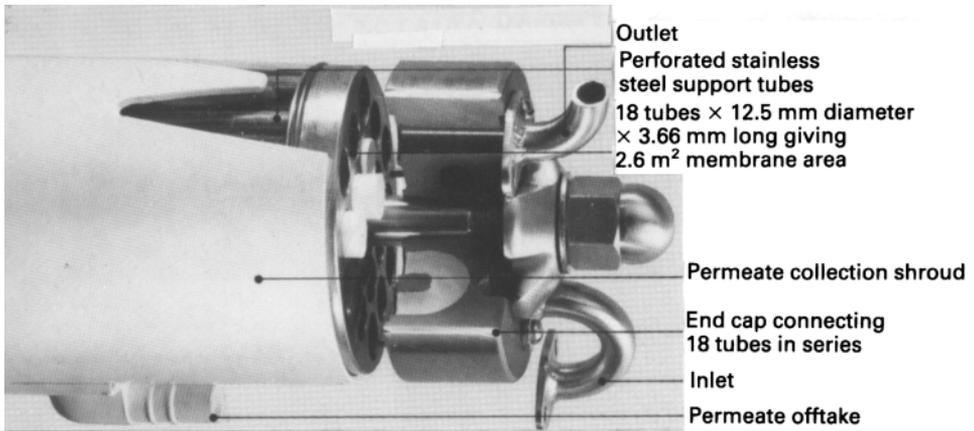


Fig. 6.14 Tubular membrane.
(Courtesy of Patterson Candy International Ltd.)

In the *wide tube* design (Fig. 6.14) a number of perforated stainless steel tubes are fabricated as a shell and tube heat exchanger (see Chapter 13) and each tube is lined with a membrane. The tubes support the membrane against the relatively high applied pressure. Special end caps connect up to 20 tubes, each 1.2–3.6 m long and 12–25 mm in diameter, in series or in parallel, depending on the application. These systems operate under turbulent flow conditions with higher flow rates and can therefore handle more viscous liquids and small particulates. They are less susceptible to fouling and are suitable for CIP, although the higher flow rates mean that pumping costs are correspondingly higher than hollow fibre systems.

Flat plate systems can be either plate-and-frame types or spiral-wound cartridges. The plate-and-frame design is similar to a plate filter press (Fig. 6.5) or plate heat exchanger (Chapter 11), having membranes stacked together with intermediate spacers and collection plates to remove permeate. Flow can be either laminar or turbulent and feed can be passed over plates in either series or parallel. The design allows a high surface area to be fitted into a compact space and individual membranes can be replaced easily (Lewis, 1996a).

In the spiral-wound system (Fig. 6.15), alternating layers of polysulphone membranes and polyethylene supports are wrapped around a hollow central tube and are separated by a channel spacer mesh and drains. The cartridge is approximately 12 cm in diameter and 1 m long. Feed liquor enters the cartridge and flows tangentially through the membrane. Permeate flows into channels and then to the central tube, and the concentrate flows out of the other end of the cartridge. Separator screens cause turbulent flow to maximise the flux, and this, together with low volume of liquid in relation to the large membrane area, reduce the need for large pumps. These systems are relatively low cost and are gaining in popularity.

A typical reverse osmosis plant operates with a flux of 450 l h^{-1} at $4000 \times 10^3 \text{ Pa}$ up to a flux of $1200\text{--}2400 \text{ l h}^{-1}$ at $8000 \times 10^3 \text{ Pa}$. A fourfold concentration of whey typically would have production rates of $80\text{--}90 \text{ t day}^{-1}$. A comparison of ‘once-through’ and multi-stage recycling of liquid through banks of membranes is described by Pepper and Orchard (1982) and Lewis (1996a). For ultrafiltration plant, typical operating pressures are $70\text{--}1000 \times 10^3 \text{ Pa}$, at flux rates of up to 40 l min^{-1} per tube.

Microfiltration membranes have high permeate fluxes initially, but become fouled more rapidly than RO or UF membranes. They are therefore ‘backflushed’ (a quantity of

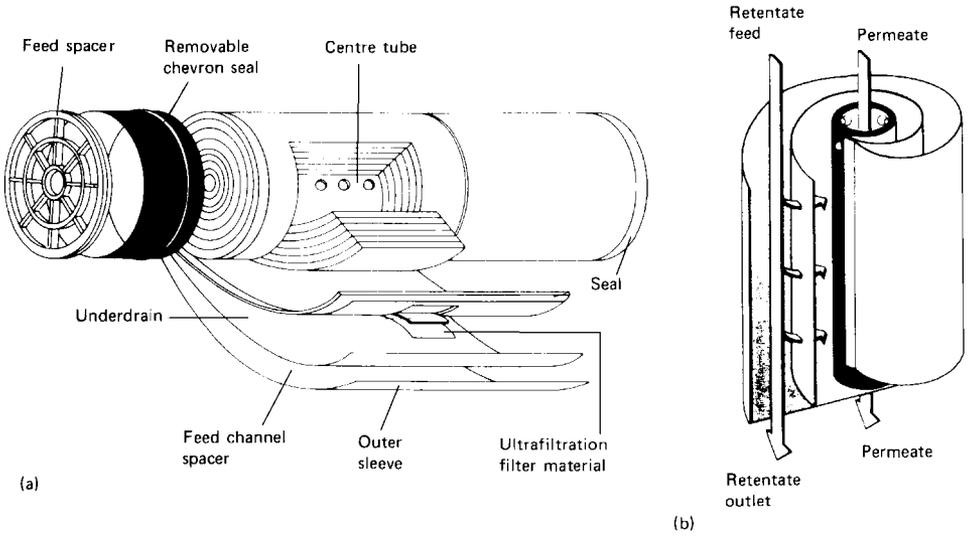


Fig. 6.15 Spiral cartridge membrane: (a) components; (b) schematic flow diagram. (Courtesy of Millipore Ltd.)

permeate is forced back through the membrane) to remove particles from the membrane surface. Other methods of maintaining flux levels are described by Grandison and Finnigan (1996).

6.6 Effect on foods

The unit operations described in this chapter are intended to remove components of the food and they are used to alter or improve the sensory properties of the resulting products (for example clarification of juices, separation of cream). The effects on nutritional value are more difficult to assess in most operations and are usually incidental to the main purpose of altering eating qualities. However, with the exception of some types of solvent

Table 6.6 Loss of nutrients during membrane concentration of milk

Nutrient	Loss (%)	
	Reverse osmosis	Ultrafiltration
Protein	0	5
Fat	0	0
Carbohydrate	0	43
Energy	0	13
Thiamin	0	38
Riboflavin	0	39
Nicotinic acid	8	41
Vitamin B ₆	3	36
Vitamin B ₁₂	0	2
Vitamin C	–	87
Folic acid	0	5
Pantothenic acid	0	32
Biotin	0	37

From Glover (1971).

extraction, these operations take place at ambient temperatures and loss of heat sensitive nutrients is not significant. The main losses occur as a result of the physical removal of food components.

In contrast to concentration by boiling (Chapter 13), reverse osmosis and ultrafiltration membranes concentrate foods without heat to produce good retention of sensory and nutritional qualities. For example in whey the functional properties (emulsifying ability, foaming ability and solubility) of proteins are retained, and different products which have specified ranges of protein and lactose content can be produced for use in fortified jams, low-calorie mayonnaise, dips, sauces and skinless sausages, and as alternatives to egg albumin (Smallwood, 1986). Concentrated orange juice prepared by reverse osmosis was found to be no different to a control after 43 months, whereas juice prepared by vacuum-evaporation was inferior to the control (Papanicolaou *et al.*, 1984). Both types of membrane retain proteins, fats and larger carbohydrates, but the larger pore size of ultrafiltration membranes allows sugars, vitamins and amino acids to be lost (Table 6.6).

6.7 Acknowledgements

Grateful acknowledgement is made of information supplied by the following: Simon-Rosedowns Ltd, Hull HU2 0AD, UK; Westfalia Separator AG, D-4740 Oelde, Germany; Paterson Candy International Ltd, Whitchurch, Hampshire, UK; Millipore UK Ltd, Harrow, Middlesex HA1 2YH, UK; Alfa Laval Co. Ltd, Brentford, Middlesex TW8 9BT, UK; Pall Europe Ltd, Portsmouth, PO1 3PD, UK; Filtration Services Ltd, Macclesfield, Cheshire SK11 6LF, UK; Environmental Technology Best Practice Programme, UK Government.

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Fermentation and enzyme technology

Fermented foods are among the oldest processed foods and have formed a traditional part of the diet in almost all countries for millennia. Today they continue to form major sectors of the food processing industry, including baked products, alcoholic drinks, yoghurt, cheese and soy products among many others. During food fermentations, the controlled action of selected micro-organisms is used to alter the texture of foods, preserve foods by production of acids or alcohol, or to produce subtle flavours and aromas which increase the quality and value of raw materials. Today the preservative effect is supplemented by other unit operations (for example pasteurisation, chilling or modified atmosphere packaging (Chapters 11, 19 and 20). The main advantages of fermentation as a method of food processing are:

- the use of mild conditions of pH and temperature which maintain (and often improve) the nutritional properties and sensory characteristics of the food
- the production of foods which have flavours or textures that cannot be achieved by other methods
- low energy consumption due to the mild operating conditions
- relatively low capital and operating costs
- relatively simple technologies.

A more recent development is the separation and purification of enzymes from microbial cells, or from animal or plant sources for use in food processing. The enzymes are either added to foods as concentrated solutions or powders, or immobilised on support materials in a 'reactor' where they are re-used for extended periods. They are used to bring about specific reactions under mild conditions of temperature and pH and have found very wide applications in the food industry, for example, in the production of bakery products, fruit juices, glucose syrups and cheese.

The main advantages of technical enzymes are:

- they cause highly specific and controlled changes to foods
- there is minimal loss of nutritional quality at the moderate temperatures employed
- lower energy consumption than corresponding chemical reactions

- the production of new foods, not achievable by other methods.

In this chapter, commercially important food fermentations and technical enzymes are described. The use of enzymes in food analysis is rapidly expanding and is discussed in detail by Guilbault (1984) and Allen (1990). The effects of naturally occurring enzymes on food quality are discussed in other chapters where their action relates specifically to the unit operation under consideration.

7.1 Fermentation

7.1.1 Theory

The main factors that control the growth and activity of micro-organisms in food fermentations are:

- availability of carbon and nitrogen sources, and any specific nutrients required by individual micro-organisms
- substrate pH
- moisture content
- incubation temperature
- redox potential
- stage of growth of micro-organisms
- presence of other competing micro-organisms.

These factors are discussed in greater detail in microbiological texts (for example Jay (1978) and Stanbury and Whitaker (1984)).

Batch culture

In batch culture the growth of micro-organisms can be described by a number of phases (Fig. 7.1). Cell growth during the logarithmic (or exponential) phase is at a constant rate which is shown by:

$$\ln C_b = \ln c_0 + \mu t \quad \boxed{7.1}$$

where c_0 = original cell concentration, c_b = cell concentration after time t , (biomass produced), μ (h^{-1}) = specific growth rate and t (h) = time of fermentation. Graphically, the natural logarithm (ln) of cell concentration versus time produces a straight line, the slope of which is the specific growth rate. The highest growth rate (μ_{max}) occurs in the logarithmic phase (Fig. 7.1).

The rate of cell growth eventually declines owing to exhaustion of nutrients and/or accumulation of metabolic products in the growth medium. If different initial substrate concentrations are plotted against cell concentration in the stationary phase, it is found that an increase in substrate concentration results in a proportional increase in cell yield (AB in Fig. 7.2). This indicates substrate limitation of cell growth, which is described by:

$$c_b = Y(S_0 - S_r) \quad \boxed{7.2}$$

where c_b = concentration of biomass, Y (dimensionless group – Appendix D) = yield factor, S_0 (mg l^{-1}) = original substrate concentration, S_r (mg l^{-1}) = residual substrate concentration. The portion of the curve BC in Fig. 7.2 shows inhibition of cell growth by products of metabolism.

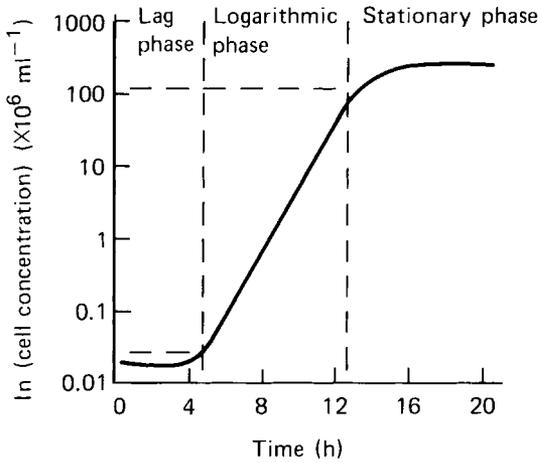


Fig. 7.1 Phases in the growth of micro-organisms.

The reduction in growth rate is related to the residual substrate concentration by Monod's equation:

$$\mu = \frac{\mu_{\max} S_r}{(K_s + S_r)} \quad (7.3)$$

where μ_{\max} (h^{-1}) = maximum specific growth rate, K_s (mg l^{-1}) = substrate utilisation constant. K_s is a measure of the affinity of a micro-organism for a particular substrate (a high affinity produces a low value of K_s).

The rate of production of primary metabolic products (for example ethanol, amino acids and citric acid) is determined by the rate of cell growth, and is found using:

$$q_p = Y_{p/s} \mu \quad (7.4)$$

where q_p = specific rate of product formation, and $Y_{p/s}$ = yield of product related to amount of substrate consumed.

The specific rate of product formation for primary products varies with the specific growth rate of cells. The rate of production of secondary products (those produced from primary products (for example aromatic compounds and fatty acids)), which are produced

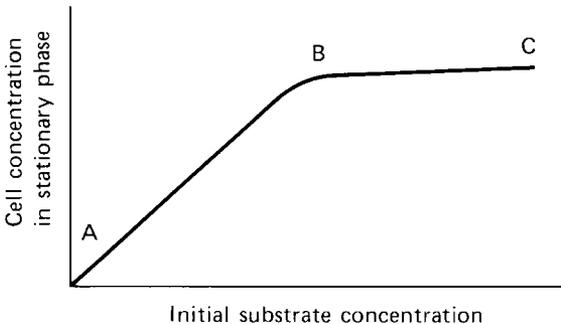


Fig. 7.2 Effect of initial substrate concentration on cell concentration at the end of the logarithmic phase of growth.

(After Stanbury and Whitaker (1984).)

in the stationary growth phase, does not vary in this way and may remain constant or change in more complex ways.

The productivity of a culture is the amount of biomass produced in unit time (usually per hour) and is found using:

$$P_b = \frac{(c_{\max} - c_0)}{t_1 - t_2} \quad \boxed{7.5}$$

where P_b ($\text{g l}^{-1} \text{h}^{-1}$) = productivity, c_{\max} = maximum cell concentration during the fermentation, c_0 = initial cell concentration, t_1 (h) = duration of growth at the maximum specific growth rate, t_2 (h) = duration of the fermentation when cells are not growing at the maximum specific growth rate and including the time spent in culture preparation and harvesting.

Sample problem 7.1

An inoculum containing 3.0×10^4 cells ml^{-1} of *Saccharomyces cerevisiae* is grown on glucose in a batch culture for 20 h. Cell concentrations are measured at 4 h intervals and the results are plotted in Fig. 7.1. The total time taken for culture preparation and harvest is 1.5 h. Calculate the maximum specific growth rate and the productivity of the culture.

Solution to Sample problem 7.1

From equation (7.1) for the logarithmic phase,

$$\ln 2 \times 10^8 = \ln 3 \times 10^4 + \mu_{\max} 8.5$$

Therefore,

$$\begin{aligned} \mu_{\max} &= \frac{\ln 2 \times 10^8 - \ln 3 \times 10^4}{8.5} \\ &= 0.95 \text{ h}^{-1} \end{aligned}$$

From equation (7.5),

$$\begin{aligned} P_b &= \frac{2 \times 10^8 - 3 \times 10^4}{8.5 + [(20 - 8.5) + 1.5]} \\ &= 9.3 \times 10^6 \text{ cells h}^{-1} \end{aligned}$$

Continuous culture

Cultures in which cell growth is limited by the substrate in batch operation have a higher productivity if the substrate is added continuously to the fermenter, and biomass or products are continuously removed at the same rate. Under these conditions the cells remain in the logarithmic phase of growth. The rate at which substrate is added under such 'steady state' conditions is found using:

$$D = \frac{F}{V} \quad \boxed{7.6}$$

where D (h^{-1}) = dilution rate, F (l h^{-1}) = substrate flow rate and V (l) = volume of the fermenter.

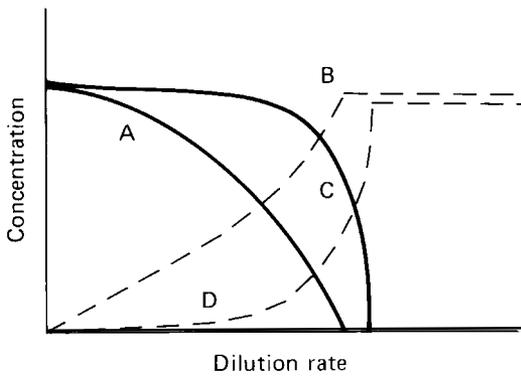


Fig. 7.3 Effect of dilution rate in continuous culture on steady-state cell concentration (—) and residual substrate concentration (- -) for limiting substrate compared with initial substrate concentration: curves A and B, micro-organisms with a low K value; curves C and D, micro-organisms with a high K value.

The steady-state cell concentration and residual substrate concentration respectively are found using:

$$\bar{c} = Y(S_0 - \bar{S}) \quad [7.7]$$

$$\bar{s} = \frac{K_s D}{\mu_{\max} - d} \quad [7.8]$$

where \bar{c} = steady-state cell concentration, Y = yield factor, S = steady-state residual substrate concentration, K_s (mg l^{-1}) = substrate utilisation constant.

The maximum dilution rate that can be used in a given culture is controlled by μ_{\max} and is influenced by the substrate utilisation constant and yield factor (Fig. 7.3).

The productivity of a continuous culture is found using:

$$P_c = D\bar{c} \left(1 - \frac{t_3}{t_4} \right) \quad [7.9]$$

where P_c = productivity of continuous culture, t_3 (h) = time before steady-state conditions are established, t_4 (h) = duration of steady-state conditions.

Further details of the above equations are given by Frazier and Westhoff (1978), Stanbury and Whitaker (1984), Jay (1978) and other microbiological texts.

7.1.2 Types of food fermentations

Micro-organisms that produce a single main by-product are termed *homofermentative* whereas those that produce mixed products are *heterofermentative*. Fermentations can be classified into those in which the main products are organic acids and those in which ethanol and carbon dioxide are the primary products. Lactic acid and ethanolic fermentations are among the most important commercial fermentations and details of the metabolic pathways that are used to produce these products are readily available (for example Stanier *et al.*, 1976). Many fermentations involve complex mixtures of micro-organisms or sequences of microbial populations which develop as changes take place in the pH, redox potential or substrate availability. These are described below.

Sample problem 7.2

Brewers' yeast is grown continuously in a fermenter with an operating volume of 12 m^3 . The residence time is 20 h and the yeast has a doubling time of 3.2 h. A 2% inoculum, which contains 5% yeast cells is mixed with the substrate. Calculate the mass of yeast harvested from the fermenter per hour. (Assume that the density of the broth is 1010 kg m^{-3} .)

Solution to Sample problem 7.2

$$\begin{aligned}\text{Flow-rate} &= \frac{\text{volume of fermenter}}{\text{residence time}} \\ &= \frac{12}{20} \\ &= 0.6 \text{ m}^3 \text{ h}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Mass flow rate} &= 0.6 \times 1010 \\ &= 606 \text{ kg h}^{-1}\end{aligned}$$

$$\begin{aligned}\text{Initial yeast concentration} &= \frac{\text{concentration in the inoculum}}{\text{dilution of inoculum}} \\ &= \frac{5/100}{100/2} \\ &= 0.001 \text{ kg kg}^{-1}\end{aligned}$$

The doubling time is 3.2 h. Therefore in 20 h there are $20/3.2 = 6.25$ doubling times. As 1 kg of yeast grows to 2 kg in 3.2 h, 1 kg grows to $1 \times 2^{6.25} = 76 \text{ kg}$ in 20 h. Therefore,

$$\begin{aligned}\text{mass of product} &= \text{initial concentration} \times \text{growth} \times \text{mass flow-rate} \\ &= 0.001 \times 76 \times 606 \\ &= 46 \text{ kg h}^{-1}\end{aligned}$$

Lactic acid fermentations

A selection of common lactic acid fermentations is shown in Table 7.1. The sequence of lactic acid bacteria in a fermentation is determined mainly by their acid tolerance. For example in milk, *Streptococcus liquifaciens*, *Lactococcus* (formerly *Streptococcus*) *lactis* or the closely related *Streptococcus cremoris* are inhibited when the lactic acid content reaches 0.7–1.0%. They are then outgrown by more acid-tolerant species including *Lactobacillus casei* (1.5–2.0% acid) and *Lactobacillus bulgaricus* (2.5–3.0% acid). Similarly, in vegetable fermentations, *Lactobacilli* spp. are stronger acid producers than *Streptococci* spp. Of the four main groups of lactic acid bacteria, *Streptococcus* spp. and *Pediococcus* spp. are homolactic, *Leuconostoc* spp. are heterolactic and *Lactobacillus* spp. vary according to the strain.

In some fermentations, particularly those that involve low-acid substrates (for example milk and meat), a starter culture is added to rapidly generate large numbers of the desired

Table 7.1 Examples of lactic acid fermentations

Food	Micro-organisms	Incubation conditions		
		Temperature (°C)	Time	Other
Cassava	<i>Corynebacterium</i> species <i>Geotrichum</i> species	Ambient	96 h	
Fish	<i>Bacillus pumilus</i> ^a <i>Bacillus licheniformis</i> ^a	Ambient	3–12 months	Fish to salt ratio between 3 to 1 and 5 to 1
Maize	<i>Corynebacterium</i> species <i>Aerobacter</i> species <i>S. cerevisiae</i> <i>Lactobacillus</i> species <i>Candida mycoderma</i>	Ambient	24–72 h	
Meat	<i>Pediococcus cervisiae</i> ^a <i>Lactobacillus plantarum</i> <i>Lactobacillus curvatus</i>	15–26	24 h	85–90% relative humidity
Milk (stirred yoghurt)	<i>Streptococcus thermophilus</i> ^a <i>L. bulgaricus</i> ^a	40–45	2–3 h	
Cheese				
Cottage	<i>Streptococcus diacetylactis</i> ^a	22	14–16	
Camembert and Brie	<i>S. cremoris</i> ^a <i>S. lactis</i> ^a <i>Penicillium caseicolum</i> ^a	32	^b	
Cheddar	<i>S. cremoris</i> ^a <i>S. lactis</i> ^a <i>S. diacetylactis</i> ^a <i>Lactobacilli</i> ^a	32	^b	
Vegetables (cucumber and cabbage)	<i>Lactobacillus mesenteroides</i> <i>Lactobacillus brevis</i> <i>Penicillium cerevisiae</i> <i>L. plantarum</i>	Ambient	48–260 h	2.5–6% salt

^a Prepared inocula used.

^b Fermentation of cheeses continues for 1–12 months during ripening.

micro-organism, and thus reduce fermentation times and inhibit growth of pathogens and spoilage bacteria. In other fermentations, the natural flora are sufficient to reduce the pH rapidly and to prevent the growth of undesirable micro-organisms.

Developments in biotechnology have produced lactic acid bacteria that also have stabilising and viscosity-forming properties (Mogensen, 1991). These are used in a wide variety of fermented milks, dressings and breads to reduce or avoid the use of synthetic stabilisers and emulsifiers. Other lactic acid bacteria, including *Leuconostoc* spp., *Lactobacillus* spp. and *Pediococcus* spp. produce a range of bacteriocins.¹ An example is *Pediococcus acidilactici*, which when used in fermented meat, has the potential to inhibit spoilage bacteria and thus reduce the need for nitrate addition. A similar benefit has been found in the production of European cheeses using starter cultures of *Lactococcus lactis* which produces the bacteriocin, nisin. This prevents growth of *Clostridium tyrobutyricum*

1. Naturally produced peptides that inhibit other micro-organisms, similar in effect to antibiotics.

and thus prevents off-flavour development and 'blowing' of Swiss-type cheese during ripening. Nisin is effective against *Listeria monocytogenes* and, although it has been added to cultures in the past, its production by *Lactococcus lactis* is a cheaper and more effective method of removing this potentially dangerous food poisoning micro-organism from cheese. *Lactococcus lactis* is permitted for use in more than 45 countries and has also found application to inhibit the growth of *Cl. botulinum* in processed cheese, other dairy products, processed vegetables, soups, sauces and beer (Roller *et al.*, 1991). Natural production of nisin may also be used to reduce or avoid chemical preservatives such as nitrate, sorbic acid and benzoic acid (Mogensen, 1991) and to control the quality of wines (Daeschel *et al.*, 1991). Other applications of nisin have been reviewed by De Vuyst and Vandamme (1994) and other inhibitory metabolites of lactic acid bacteria are described by Breidt and Fleming (1997) in their application to minimally processed fruits and vegetables.

Meat and fish products

Pieces of meat are fermented by *Bacillus* spp. and *Staphylococcus* spp. and dried in many parts of Africa as traditional foods. The fermentation causes flavour development and softening due to proteolysis, and preservation is by drying. Dirar (1993a) also describes a fermented fat in Sudan which he notes as being 'possibly the most foul-smelling fermented food in the country, second only to sigda' (presscake fermented after sesame-seed oil extraction).

Fermented sausages (for example salami, pepperoni, medwurst and bologna) are produced from a mixture of finely chopped meats, spice mixtures, curing salts (sodium nitrite/nitrate), salt and sugar. The meat is filled into sausage casings, fermented and then pasteurised at 65–68°C for 4–8 h, dried and stored at 4–7°C. The technology of production is described in detail by Pederson (1971).

Preservation is due to:

- the antimicrobial action of nitrite-spice mixtures and to a lesser extent from added salt
- 0.84–1.2% lactic acid from the fermentation
- heat during pasteurisation and/or smoking (and antimicrobial components in smoke when the product is smoked)
- reduction in water activity due to salt and drying
- low storage temperature.

In Southeast Asia, small fish, shrimp or waste fish are mixed with dry salt and fermented by bacteria including *L. mesenteroides*, *P. cerevisiae* and *L. plantarum* to produce a range of sauces and pastes. Proteins in the fish are broken down by the combined action of bacterial enzymes, acidic conditions and autolytic action of the natural fish enzymes. Dirar (1993a) describes the production of similar fermented fish pastes and fermented mullet in Sudan and North Africa.

Vegetables

Cucumbers, olives and other vegetables are submerged in 2–6% w/w brine, which inhibits the growth of putrefactive spoilage bacteria. Air is excluded and a naturally occurring sequence of lactic acid bacteria grow in the anaerobic conditions to produce approximately 1% w/w lactic acid. The relative importance of each species depends on the initial cell numbers on the vegetable, the salt content and the pH (Fleming, 1982). In some countries, the fermentation of cucumbers is controlled by the addition of acetic acid to prevent growth of spoilage micro-organisms. The brine is then inoculated with either *L. plantarum* alone or a mixed culture with *P. cerevisiae*. Nitrogen gas is continuously

purged through the vessel to remove carbon dioxide and to prevent splitting of the cucumbers.

Other methods of pickling involve different salt concentrations: for example in 'dry salting' to make sauerkraut from cabbage, alternate layers of vegetable and granular salt are packed into tanks. Juice is extracted from leaves by the salt to form a brine, and the fermentation follows a similar sequence to that described for cucumber pickles (Pederson, 1971). In each case preservation is achieved by the combination of acid, salt and in some cases pasteurisation.

Maize, cassava and sorghum

In tropical countries, cereals and root crops are fermented to a range of beverages and staple foods. These are reviewed by Odufa (1985) and Stanton (1985). Fermented maize flour is a staple food in many African countries. Maize kernels are soaked for 1–3 days, milled and formed into a dough. Initially *Corynebacterium* spp. hydrolyse starch and initiate lactic acid production. *Aerobacter* spp. increase the rate of acid production and *S. cerevisiae* contributes to the flavour of the product. As the acidity increases, *Lactobacillus* spp. predominate and continue acid production. Finally *Candida mycoderma* outgrows *S. cerevisiae* and contributes to the final flavour of the fermented dough. It is cooked to form a thick porridge within 1–2 days. The fermentation is therefore used to impart flavour and have a temporary preservative effect.

Cassava is grated and the pressed pulp is fermented by *Corynebacterium* spp., as for maize, to produce lactic and formic acids and to reduce the pH from 5.9 to 4.0. The increased acidity promotes the growth of *Geotrichum* spp., and detoxifies the cassava by releasing gaseous hydrogen cyanide by hydrolysis of the cyanogenic glycosides present in the cassava. Aldehydes and esters produced by *Geotrichum* spp. give the characteristic aroma and taste to the product. The fermented cassava is dried to a granular flour with a shelf life of several months. The fermentation therefore alters the eating quality, and preservation is achieved by drying. Details are given by Abe and Lindsay (1979) and Akinrele (1964). The detailed production of porridges, dried granules, flakes and breads from sorghum, millet and cassava is described by Dirar (1993b).

Milk products

There are a large number of cultured milk products produced throughout the world (for example yoghurt, cheese, Kefir, Koumiss, buttermilk, sour cream and Leben). Differences in flavour are due to differences in the concentration of lactic acid, volatile aldehydes, ketones, organic acids and diacetyl (acetyl methyl carbinol). The last is produced by fermentation of citrate in milk, and gives the characteristic 'buttery' aroma to dairy products. Changes in texture are due to lactic acid, which causes a reduction in electrical charge on the casein micelles. They coagulate at the isoelectric point to form characteristic flocs. These changes are described in detail by Fox (1987) and Schmidt (1992). Modifications to the starter culture, incubation conditions and subsequent processing conditions are used to control the size and texture of the coagulated protein flocs and hence produce the many different textures encountered. Preservation is achieved by chilling and increased acidity (yoghurt and cultured milks) or reduced water activity (cheese).

Yoghurt

In mechanised production, skimmed milk is mixed with dried skimmed milk and heated at 82–93°C for 30–60 min to destroy contaminating micro-organisms and to destabilise

K-casein. It is inoculated with a mixed culture of initially *S. thermophilus* and *L. bulgaricus*. Initially *S. thermophilus* grows rapidly to produce diacetyl and lactic, acetic and formic acids. *L. bulgaricus* possesses weak protease activity which releases peptides from the milk proteins. These stimulate the growth of *S. thermophilus*. The increased acidity then slows the growth of *S. thermophilus* and promotes *L. bulgaricus*, which is stimulated by formate produced in the initial stage. *L. bulgaricus* produces most of the lactic acid and also acetaldehyde which, together with diacetyl, gives the characteristic flavour and aroma in yoghurt. Details of the production are described by Davis (1975) and Tamime and Robinson (1999).

Cheese

More than 400 types of cheese are produced throughout the world, created by differences in fermentation, pressing and ripening conditions, described in detail by Kosikowski (1978) and Campbell-Platt (1987). The fermentation of cottage cheese is stopped once casein precipitation has occurred and the flocs are removed along with some of the whey, but most other cheeses are pressed and allowed to ripen for several weeks or months. In the manufacture of cheddar cheese, *S. lactis* is added to milk and fermented for 30 min. Rennet (Section 7.2.2) is added and the culture is incubated for 1.5–2 h until the curd is firm enough to cut into small cubes. It is then heated to 38°C to shrink the curd and to expel whey. The curd is recut and drained several times, milled, salted and placed in hoops (press frames). It is pressed to remove air and excess whey, and the cheese is then ripened in a cool room for several months. Enzymes from both the micro-organisms and the cheese (including proteases, peptidases, lipase, decarboxylase and deaminases) produce compounds which give characteristic aroma and flavour. The time and temperature of ripening determine whether the cheddar has a mild, medium or strong flavour. Details of the production of cheese are given by Fox (1993) and Banks (1992).

Alcoholic and mixed alcohol–acid fermentations

Table 7.2 describes the conditions used in selected ethanolic and mixed acid–ethanol fermentations.

Bread

The fermentation and baking of cereal flours alter the texture and flavour of the flour and make it palatable as a staple food. Fermentation has no preservative effect and the main function is to produce carbon dioxide to leaven and condition the dough. Yeast and other micro-organisms (e.g. *Lactobacillus* spp.) present in the dough also contribute to the flavour of the bread. Carbon dioxide is retained within the loaf when the gluten structure is set by heat above 74°C. The heat treatment and reduction in water activity preserve the bread. Details of production and different types of bread are described by Matz (1972).

The two main commercial methods of dough preparation are the bulk fermentation process and the Chorleywood bread process, which are described in detail by Chamberlain *et al.* (1965) and Oura *et al.* (1982). A more recent development is a continuous liquid fermentation system for doughs (Fig. 7.4). Here, the growth of yeast and *Lactobacillus* spp. are separated and optimised. Yeast is mixed with flour and water and stored until it is needed. It is then activated by addition of dextrose and added to the dough mixer. Similarly a flour and water mixture is seeded with *Lactobacillus* culture and, when the pH has dropped to around 3.8, 10% of the liquor is pumped to a storage vessel, ready for up to several weeks for use in the mixer. As it is used, it is replaced by fresh flour/water to allow the fermentation to continue. The computer-controlled process

Table 7.2 Alcohol and mixed alcohol–acid fermentations

Food	Micro-organisms	Incubation conditions		
		Temperature (°C)	Time	Other
<i>Alcohol</i>				
Beer				
Ale	<i>S. cerevisiae</i> ^a (‘top-yeast’)	20	120–240 h	
Lager	<i>Saccharomyces carlesbergensis</i> ^a (‘bottom yeast’)	12–15	120–240 h	
Millet Bread	<i>Saccharomycopsis fibuliger</i>	Ambient	120 h	
Wine	<i>S. cerevisiae</i> ^a	26	0.5–1h	
Agave (cactus)	<i>Saccharomyces carbajali</i>	30	200 h	
Bordeaux	<i>Sacchoromyces oviformis</i> ^a <i>Sacchoromyces chevalieri</i> <i>Kloeckera apiculata</i>	25	360 h	
Other grape	<i>S. cerevisiae</i> var. <i>ellipsoideus</i> ^a	25–30	100–360 h	
Palm	<i>Zymomonas</i> species	Ambient	4–12 h	
Rice	<i>Saccharomyces sake</i>	30	–	
<i>Mixed alcohol–acid</i>				
Coffee	<i>Leuconostoc</i> species <i>Lactobacillus</i> species <i>Bacillus</i> species <i>Erwinia</i> species <i>Aspergillus</i> species <i>Fusarium</i> species	Ambient	20–100 h	
Cocoa	Yeasts (see text) <i>L. plantarum</i> <i>Lactobacillus mali</i> <i>Lactobacillus fermentum</i> <i>Lactobacillus collinoides</i> <i>Acetobacter rancens</i> <i>Acetobacter aceti</i> <i>Acetobacter oxydans</i>	Ambient	144 h	
Soy sauce				
First stage	<i>Aspergillus soyae</i> <i>Mucor</i> species <i>Rhizopus</i> species	30	48–72 h	
Second stage	<i>Pediococcus soyae</i> <i>Saccharomyces rouxii</i>	15–25	3–6 months	15–20% brine
Tempeh	<i>Rhizopus oligosporus</i> ^a	30	24–48 h	
Vinegar	<i>S. cerevisiae</i> ^a <i>A. aceti</i> ^a	30 25	100–240 h 72–168 h 72–120 h	First stage Second stage
Citric acid	<i>Acetobacter niger</i> ^a	27	168 h	Substrate limited

^a Inoculum used.

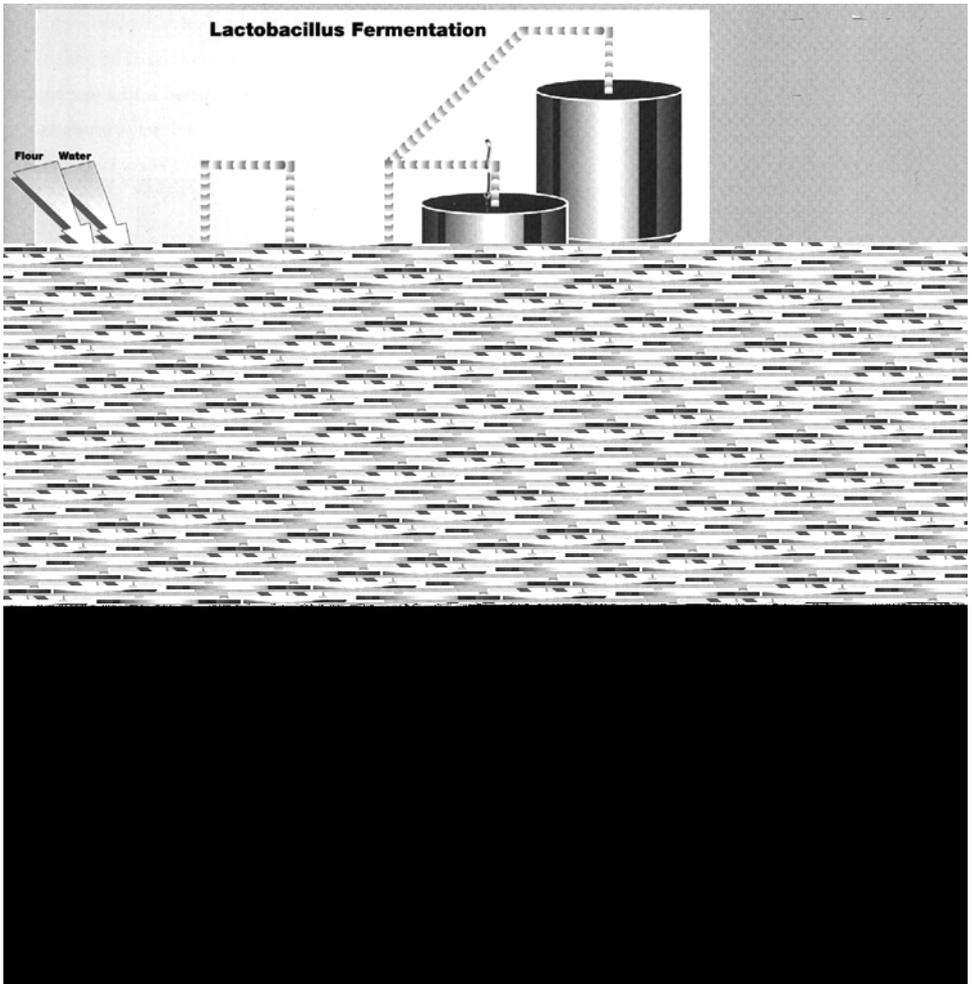


Fig. 7.4 Continuous liquid fermentation system for dough preparation.
(Courtesy of APV Baker Ltd.)

is claimed to greatly improve fermentation efficiency, reduce labour, floor space, eliminate the need for dough-tubs and a fermentation room, and produce more consistent and hygienic doughs.

Alcoholic beverages

Beer wort is produced by boiling malted grains (for example barley) to release maltose and other sugars and, in some beers, by adding hop flowers to produce bitterness. Developments in wort preparation, described by Atkinson (1987) and Hudson (1986), include the use of hop extracts and dextrose syrups to increase product uniformity, and higher-temperature shorter-time boiling to reduce energy consumption. Variation in the composition of the wort, the strain of yeast (*S. cerevisiae*, *S. carlsbergensis*), and the fermentation time and conditions, result in the wide range of beers produced. Other substrates including millet, sorghum and maize are also used where these are the staple crops.

Sugars present in grape juice (or 'must') are fermented to produce 6–14% ethanol in wines. Cells are removed by filtration or centrifugation (Chapter 6) and the wine is aged

to reduce the acidity and to develop a characteristic bouquet. The main acid in most wines is tartaric acid but, in some red wines, malic acid is present in a high concentration. In these, a secondary malo-lactic fermentation by lactic acid bacteria converts malic acid to lactic acid which reduces the acidity and improves the flavour and aroma. Details of grape wine production are given by Amerine *et al.* (1967). Other wines are produced throughout the world from many fruits, tree saps honey and vegetable pods. For example palm sap is fermented by naturally occurring *Zymomonas* spp. to produce palm wine. Lactic acid bacteria produce small amounts of aldehydes and lactic and acetic acids, which give the product a characteristic aroma and flavour. Fermentation times in excess of 12 h produce an over-acidified product and it is therefore consumed on the day of preparation.

Vinegar and other food acids

Ethanol fermentation of wine, cider or malt by yeast is the first of a two-part fermentation in the production of vinegar. In the second stage the ethanol is oxidised by *A. aceti* to acetic acid and a number of flavour compounds. This stage is sensitive to the concentration of dissolved oxygen, and fermenters are carefully designed to ensure that an adequate supply of air is maintained (Beaman, 1967). During maturing of vinegar, reactions between residual ethanol and acetic acid form ethyl acetate, which imparts the characteristic flavour to the product.

Citric acid is widely used as an acidulant in foods. It is produced by fermenting sugar using *Aspergillus niger* in submerged culture, under conditions of substrate limitation (Kapoor *et al.*, 1982). The production of other important food acids, including glutamic acid, gluconic acid, lactic acid, propionic acid and tartaric acid, is described by Pederson (1971).

Cocoa and coffee

Cocoa and coffee berries contain mucilage around the beans, which is removed by fermentation. Cocoa beans are either heaped or placed in slatted fermentation bins ('sweat boxes') and initial fermentation by yeasts (including *S. ellipsoideus*, *Saccharomyces apiculata*, *Hansenula* spp., *Kloeckera* spp., *Debaromyces* spp., *Schizosaccharomyces* spp. and *Candida* spp.), produces ethanol from sugars in the pulp and raises the temperature in the box. Lactic acid bacteria then predominate in the anaerobic conditions. They reduce the pH and further raise the temperature. Pulp is hydrolysed and solubilised during this period and drains away to allow air to penetrate the bean mass. Ethanol is then oxidised to acetic acid by acetic acid bacteria which also cause the temperature to rise to 45–60°C, and destroy the yeast population. The combination of heat and up to 2% w/w acetic acid kills the beans. They are then dried to 7% moisture to preserve the product and roasted to produce the characteristic chocolate flavour and aroma (Carr, 1985). The manufacture of cocoa powder and chocolate are described by Meursing (1987). Coffee berries are soaked, pulped and fermented in slatted tanks where microbial and naturally occurring pectic enzymes solubilise the mucilage. Details of chemical changes during coffee fermentation are described by Arunga (1982).

Soy products

Soy sauce and similar products are made by a two-stage fermentation in which one or more fungal species are grown on a mixture of ground cereals and soy beans. Fungal proteases, α -amylases and invertase act on the soy beans to produce a substrate for the second fermentation stage. The fermenting mixture is transferred to brine and the

temperature is slowly increased. Acid production by *P. soyae* lowers the pH to 5.0, and an alcoholic fermentation by *S. rouxii* takes place. Finally the temperature is gradually returned to 15°C and the characteristic flavour of soy sauce develops over a period of 6 months to 3 years. The process is described in detail by Fukushima (1985). The liquid fraction is separated, clarified, pasteurised and bottled. The final product is preserved by 2.5% ethanol and 18% salt (Pederson, 1971). Details of the biochemistry of flavour and aroma production are described by Yokotsuka (1960), Yong and Wood (1974) and Wood (1982).

In the production of tempeh, soy beans are soaked, deskinning, steamed for 30–120 min and fermented. Enzyme activity by *Rhizopus oligosporus* softens the beans, and mycelial growth binds the bean mass to form a solid cake. The fermentation changes the texture and flavour of soy beans but has no preservative effect. The product is either consumed within a few days or preserved by chilling

7.1.3 Equipment

Solid substrates are incubated in trays or tanks, contained in rooms that have temperature and humidity control. Some meat products are filled into plastic or cellulose casings prior to fermentation. Liquid substrates are incubated in either stainless steel tanks or in cylindrical stirred fermenters (Fig. 7.5). Fermenter design and operation is discussed in detail by Stanbury and Whitaker (1984).

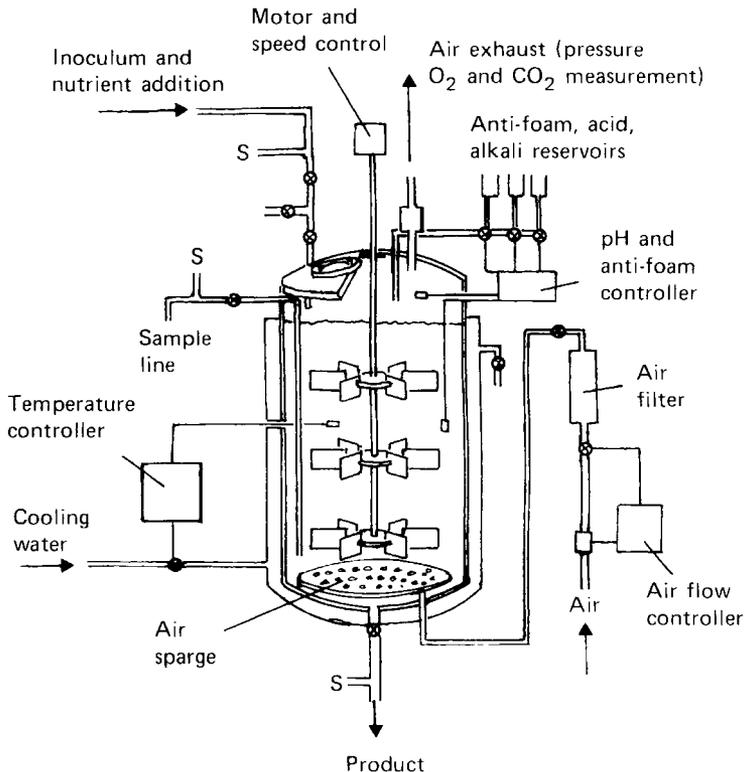


Fig. 7.5 Batch fermenter showing controls and instrumentation: S, steam sterilising points.

7.1.4 Effect on foods

The mild conditions used in food fermentations produce few of the deleterious changes to nutritional quality and sensory characteristics that are found with many other unit operations. Complex changes to proteins and carbohydrates soften the texture of fermented products. Changes in flavour and aroma are also complex and in general poorly documented. Flavour changes include reduction in sweetness and increase in acidity due to fermentation of sugars to organic acids, an increase in saltiness in some foods (pickles, soy sauce, fish and meat products) due to salt addition and reduction in bitterness of some foods due to the action of debittering enzymes. The aroma of fermented foods is due to a large number of volatile chemical components (for example amines, fatty acids, aldehydes, esters and ketones) and products from interactions of these compounds during fermentation and maturation. In bread and cocoa, the subsequent unit operations of baking and roasting produce the characteristic aromas. The colour of many fermented foods is retained owing to the minimal heat treatment and/or a suitable pH range for pigment stability. Changes in colour may also occur owing to formation of brown pigments by proteolytic activity, degradation of chlorophyll and enzymic browning.

Microbial growth causes complex changes to the nutritive value of fermented foods by changing the composition of proteins, fats and carbohydrates, and by the utilisation or secretion of vitamins. Micro-organisms absorb fatty acids, amino acids, sugars and vitamins from the food. However, in many fermentations, micro-organisms also secrete vitamins into the food and improve nutritive value (Table 7.3) (Dworschak, 1982). Micro-organisms also hydrolyse polymeric compounds to produce substrates for cell growth, which may increase the digestibility of proteins and polysaccharides.

7.2 Enzyme technology

Only 1% of the enzymes so far identified are produced commercially and the largest volume (35%) are proteases for use in detergent manufacture. However, advances in biotechnology have had a significant effect on the number and type of new enzymes that are available for use in food processing or production of specialist ingredients. There has also been rapid growth in recent years in the use of enzymes to reduce processing costs, to increase yields of extracts from raw materials, to improve handling of materials, and to improve the shelf life and sensory characteristics of foods (Table 7.4). The main advantages in using enzymes instead of chemical modifications are that enzymic reactions are carried out under mild conditions of temperature and pH, and are highly specific, thus reducing the number of side reactions and by-products. Selection of the precise enzyme for a particular application can be difficult and guidelines on methods to do this are given by West (1988).

Enzymes are active at low concentrations and the rates of reaction are easily controlled by adjustment of incubation conditions. Details of the factors that influence enzyme activity and reaction rates are described by Whitaker (1972). However, the cost of many enzymes is high and, in some products, enzymes must be inactivated or removed after processing which adds to the cost of the product. Like other proteins, enzymes may cause allergic responses in some people, and they are usually coated or immobilised on carrier materials to reduce the risk of inhalation of enzyme dust by operators.

Table 7.3 Changes in vitamin content of selected foods during fermentation

Product	Content per 100g						
	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)	Vitamin C (mg)	Pantothenic acid (mg)	Vitamin B ₆ (mg)	Vitamin B ₁₂ (μ g)
Whole milk	0.04	0.18	0.1	1	0.37	0.042	0.4
Yoghurt	0.04	0.18	0.1	1	–	0.040	–
Cheese (Cheddar)	0.03	0.46	0.1	0	0.50	0.08	1.0
Grapes	0.05	0.03	0.3	4	0.075	0.08	0
Wine (table)	Trace	0.01	0.1	–	–	–	–
Cabbage	0.05	0.07	0.3	51	0.21	0.16	0
Sauerkraut ^a	0.07	0.03	0.2	14	0.09	0.13	0
Cucumber	0.03	0.04	0.2	11	0.25	0.042	0
Dill pickle	Trace	0.02	Trace	6	–	–	–
Soy bean							
(unfermented)	0.22	0.06	0.90	–	–	0.08	–
Tempeh	0.13	0.49	4.39	–	–	0.35	–
Soy sauce	0.88	0.37	6.0	–	–	–	–

^a Loss due to canning and storage.

Adapted from Murata *et al.* (1967), Watt and Merrill (1975) and Orr (1969).

Table 7.4 Enzymes used in food processing

Enzyme	Major source	Operating conditions		Type of culture or application
		pH range	Temperature (°C)	
α -amylases	<i>Aspergillus oryzae</i>	4.0–5.0	50–70	Surf., B, I
	<i>Bacillus subtilis</i>	6.0–7.0	80–90	Sub., B, I
	<i>B.licheniformis</i>	6.0–7.0	95–105	Sub., B, I
Amyloglucosidase	<i>A.niger</i>	3.5–5.0	55–65	B, I
Bromelain	Pineapple (<i>Ananas comosus</i>)	4.0–9.0	20–65	SA
Catalase	Beef liver	6.5–7.5	5–45	–
Cellulases	<i>A.niger</i>			
	<i>Trichoderma viride</i>	3.0–5.0	20–60	Sub./Surf., B
	<i>T.reesei</i>			
Ficin	Fig (<i>Ficus carica</i>)	6.5–7.0	25–60	B, SA
Glucoamylases	<i>A.niger</i>	3.5–5.0	30–60	Sub., B, I
	<i>Rhizopus spp.</i>			
Glucose isomerase	<i>Escherichia spp.</i>			
	<i>Lactobacillus spp.</i>	7.0–7.5	60–70	Sub., I
	<i>Streptococcus spp.</i>			
	<i>Bacillus spp.</i>			
Glucose oxidase	<i>A.niger</i>	4.5–7.0	30–60	Sub., Surf, B
Hemi-cellulases	Fungi	3.5–6.0	30–65	Sub.
Invertase	<i>Kluyveromyces fragilis</i>	4.5–5.5	55	Sub., B, I
	<i>S.cerevisiae</i>			
	<i>K.fragilis</i>	7	40	Sub., B, I
Lactase	<i>Aspergillus spp.</i>	4.5–5.0	50–60	
	<i>Chaetomium spp.</i>			
	<i>Mucor pusillus</i>			
	<i>Lactococcus</i> (formerly <i>Streptococcus</i>) <i>lactis</i>			
	<i>Candida pseudotropicalis</i>			
Lipase	Porcine pancreas	5.5–9.5	20–50	B
Papain	Papaya (<i>Carica papaya</i>)	6.0–8.0	20–75	B, SA
Pectic enzymes	<i>A.niger</i>	2.5–5.5	25–65	Surf./Sub. B
Pepsin		1.5–4.0	40	B
Proteases – Acid	<i>B.subtilis</i>	6.0–8.5	20–55	Sub.
	<i>A.oryzae</i>	4.0–7.5	20–50	Surf.
	<i>Rhizopus spp.</i>			
– Neutral	<i>B.subtilis</i>	7.0–8.0	20–50	
	<i>B.polymyxa</i>			
– Alkaline	<i>Bacillus spp.</i>	9.0–11.0	20–50	
Pullulanase	<i>Aerobacter aerogenes</i>	3.5–5.0	55–65	
Rennet	Bovine (chymosin)	3.5–6.0	40	B
	<i>M.pusillus</i>			
	<i>M.miehei</i>			

Surf = surface culture, sub = submerged culture, B = batch application, SA = surface application, I = immobilised.

7.2.1 Enzyme production from micro-organisms

Microbial enzymes have optimum activity under similar conditions to those that permit optimum cell growth. They are either secreted by the cells into the surrounding medium ('extracellular' production) or retained within the cell ('intracellular' enzymes). Extracellular enzyme production occurs in either the logarithmic phase or the stationary

phase of growth, whereas intracellular enzymes are produced during logarithmic growth but are only released into the medium when cells undergo lysis in the stationary or decline phases (Fig. 7.1). The requirements of commercial enzyme production from micro-organisms are as follows:

- micro-organisms must grow well on an inexpensive substrate
- substrates should be readily available in adequate quantities, with a uniform quality
- micro-organisms should produce a constant high yield of enzyme in a short time
- methods for enzyme recovery should be simple and inexpensive
- the enzyme preparation should be stable.

Enzymes are produced by either surface culture on solid substrates (for example rice hulls, fruit peels, soy bean meal or wheat flour) or by submerged culture using liquid substrates (for example molasses, starch hydrolysate or corn steep liquor). Specific minerals may have to be added to substrates to maximise enzyme production. Submerged cultures have lower handling costs and a lower risk of contamination and are more suited to automation than are solid substrates. In batch methods, the inoculum is added to sterile substrate at 3–10% of the substrate volume and cells are grown under controlled conditions for 30–150 h in capacities ranging from 1000 to 100 000 l. Microprocessors are used to automatically control pH, dissolved oxygen, carbon dioxide and temperature (Armiger and Humphrey, 1979).

The success of commercial enzyme production depends on maximising the activity of the micro-organism and minimising the costs of the substrate and incubation and recovery procedures. Extracellular enzymes are recovered from the fermentation medium by centrifugation, filtration, fractional precipitation, chromatographic separation, electrophoresis, membrane separation, freeze drying or a combination of these methods (Skinner, 1975). Intracellular enzymes are extracted by disruption of cells in a homogeniser or mill. Recovery is more difficult and the yield is lower than for extracellular enzymes, because some enzymes are retained within the cell mass. If required, the specific activity of the enzyme is increased by precipitation using acetone, alcohols or ammonium sulphate or by ultrafiltration (Chapter 6).

7.2.2 Application of enzymes in food processing

Batch operation is widely used when the cost of the enzyme is low. The enzyme is mixed with food, allowed to catalyse the required reaction, and then either retained within the food or inactivated by heat. In continuous operation, enzymes are immobilised on support materials by:

- micro-encapsulation in polymer membranes which retain the enzyme but permit the passage of substrates and products
- electrostatic attachment to ion exchange resins
- adsorption onto colloidal silica and/or cross linking with glutaraldehyde
- covalent bonding to organic polymers
- entrapment in polymer fibres (for example cellulose triacetate or starches)
- co-polymerisation with maleic anhydride
- adsorption onto charcoal, polyacrylamide, or glass (Konecny, 1977).

The main advantages of enzyme immobilisation are that enzymes are re-used, there is continuous processing and closer control of pH and temperature to achieve optimum activity. Immobilisation is at present used when an enzyme is difficult to isolate or expensive to prepare. The main limitations are:

- the higher cost of carriers, equipment and process control
- changes to the pH profiles and reaction kinetics of enzymes
- loss of activity (25–60% loss)
- risk of microbial contamination.

In use, either immobilised enzymes are mixed with a liquid substrate and then removed by centrifugation or filtration and re-used, or the feed liquor is passed over an immobilised bed of enzyme fixed into a reactor. Immobilised enzymes should have the following characteristics:

- short residence times for a reaction
- stability to variations in temperature and other operating conditions over a period of time (for example glucose isomerase is used for 1000 h at 60–65°C)
- suitability for regeneration.

A summary of the food applications of the main enzyme groups is shown in Table 7.5.

Carbohydrases

This group of enzymes hydrolyse polysaccharides or oligosaccharides. The commercially important types are:

- α -amylase
- glucoamylase
- invertase
- lactase
- glucose isomerase.

α -amylases randomly hydrolyse α -(1→4) linkages to liquefy starch and produce maltose. They do not hydrolyse α -(1→6) linkages and therefore leave low-molecular-weight dextrans and oligosaccharides unhydrolysed. The products are used as bland tasting, functional ingredients in dried soups, infant foods and sauces. The enzymes are also used for the limited hydrolysis of starch to produce fat mimetics.² β -amylases are exo-enzymes that remove maltose units from non-reducing ends of amylose chains. In amylopectin, the cleavage stops a few units away from the α -1,6-branches. Products are maltose syrups from barley or soybean starches which have wide applications in, for example, brewing, confectionery and bakery products.

Glucoamylase (or amyloglucosidase) is a saccharifying enzyme which removes successive glucose units from the non-reducing ends of starch molecules by rapid cleavage of the 1,4- α -linkages and slower cleavage of the α -1,6-linkages. Unlike α -amylases, it therefore hydrolyses linear and branched chains to form glucose. The products are sweet tasting, fermentable hydrolysates with special functional properties, which are used in the production of alcohol, ascorbic acid and penicillin. The most commonly used starches are maize, wheat, tapioca and potato (Olsen, 1993).

Commercial fungal amylase preparations, which contain smaller quantities of phosphatase, glucoamylase and protease, saccharify starch to a greater extent than a single amylase does. They produce substantial quantities of maltose without significant quantities of glucose and are used in the following applications:

- to eliminate starch hazes and to reduce the viscosity of fruit juices

Table 7.5 Uses of enzymes in the food industry

Food sector	Proteases	Lipases	Phospholipases	Amylases	Cellulases	Pectinases	Oxidoreductases
Brewing	*			*	*		
Bakery	*		*	*			*
Dairy	*	*		*			*
Meat processing	*	*					
Fats and oils		*	*				
Juice extraction	*					*	
Starch modification				*			
Protein modification	*						
Sweeteners	*	*		*			
Alcohol removal							*
Extraction of plant components	*	*	*	*	*	*	

Adapted from Law (1990).

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- to convert cocoa starch to dextrins to reduce viscosity and to improve the stability of chocolate syrups
- to produce glucose syrups (Delrue, 1987)
- to reduce dough viscosity and to accelerate fermentation by yeast
- to increase loaf volume by breaking down gelatinised starch at a temperature above that survivable by indigenous enzymes (Law, 1990).

Bacterial amylases liquefy starch at higher temperatures (Table 7.4). They are used to produce glucose and maltose syrups and to replace malted grain for brewing. In baking they are used to improve gas production, crust colour, shelf life and toasting characteristics of bread. Glucoamylase is used to increase the alcohol content and to reduce the carbohydrate content of beer, by converting dextrins to fermentable sugars during fermentation. It is also used in the production of vinegar and yeast from starch-based products.

Invertase hydrolyses sucrose to glucose and fructose. It is used to remove sucrose from foods, to prevent crystallisation in molasses, and in the production of invert sugar, confectionery, liquers and frozen desserts. *Lactase* (β -D-galactosidase) hydrolyses lactose to D-glucose and D-galactose. It is used to prevent lactose crystallisation in ice cream and frozen milk concentrates, in starter cultures for cheese, and to prepare foods for those suffering from lactose intolerance (Bauer, 1986).

Glucose isomerase is used for the production of high-fructose corn syrup (HFCS) sweeteners from glucose. Different proportions of fructose and glucose are prepared by adjustment of the incubation time with the enzyme. Two products are widely used as an alternative to sucrose in the bakery and confectionery industries (Law, 1990): HFCS-42 and HFCS-55, containing respectively 42% and 55% fructose (dry weight basis). Other applications include the production of dextrose from corn starch, clarification of fruit juice and wine, removal of glucose from egg white, inversion of sucrose and chillproofing of beer (Hultin, 1983).

The degree of hydrolysis of starch is measured by the dextrose equivalent (DE). Maltodextrin (DE 15-25) is valuable for its rheological properties and is used as fillers, stabilisers, thickeners and pastes in a wide variety of foods. When further hydrolysed, a variety of sweeteners can be made, having dextrose equivalents of 40–45 (maltose), 50–55 (high maltose) and 55–70 (high conversion syrup). Cyclodextrins are molecules containing 6–8 glucose units, linked together in a ring. They can bind other molecules in their cavities and therefore stabilise, solubilise or precipitate other compounds. They are also widely used to encapsulate flavours and aromas. They are produced from starch using the enzyme *cyclodextrin glycosyl transferase* (CGT-ase) (Pszczola, 1988; Nielsen, 1991).

Pectic enzymes

There are three types of pectic enzymes: pectin esterase, polygalacturonase and pectin lyase although the last is not used commercially. *Pectin esterase* hydrolyses the methoxyl group from pectin molecules to form low-methoxyl pectin and polygalacturonic (pectic) acid. *Polygalacturonase* hydrolyses α -(1→4) linkages of polygalacturonic acid to produce oligogalacturonans and galacturonic acid. Polygalacturonase has both endo- and exo- forms which respectively hydrolyse the polymer randomly and sequentially from the ends. Commercially the endo-polygalacturonase is more useful as it produces more rapid depolymerisation of pectin molecules. Fungal pectic enzyme preparations, particularly from *Aspergillus* spp., consisting of polygalacturonase, pectin methylesterase, cellulase, hemicellulase and protease, are used to:

- accelerate rates of filtration of fruit juices
- remove pectin from fruit base prior to gel standardisation in jam manufacture
- prevent undesirable gel formation in fruit and vegetable extracts and purées
- standardise the characteristics of pectin for the varied uses as a thickener
- recover citrus oils
- stabilise cloud in fruit juices.

(Rombouts and Pilnik (1978), King (1991) and Faigh (1995)).

Cellulases and hemicellulases

Fungal cellulase preparations, which contain smaller quantities of hemicellulase and pectinase, act on the α -(1 \rightarrow 6) linkages of glucose units in soluble forms of cellulose. They are used to:

- improve filtration of vanilla extracts
- tenderise vegetables prior to cooking
- degrade nut shells prior to oil extraction to save energy
- extract flavour compounds from vegetables which was previously difficult and expensive.

Hemicellulases reduce the viscosity of several plant gums by conversion of D-xylans to xylo-oligosaccharides, D-xylose and L-arabinose. They are used:

- to reduce the viscosity of coffee concentrates
- in the extraction and clarification of citrus juices
- in the hydrolysis of apple and grape pomace to fermentable sugars
- to increase the yield of essential oils, spices and other plant extracts.

Proteases

Proteases are classified according to their pH optima into acid, neutral and alkaline types. Acid proteases are produced mostly by fungi, and neutral and alkaline proteases are produced by both fungi and bacteria (Table 7.4). Neutral bacterial proteases, which also have significant α -amylase and alkaline protease activity, are used to hydrolyse plant and animal proteins and to improve the flavour of crackers and the handling of pizza doughs. Acid fungal proteases which have significant α -amylase activity are used to:

- hydrolyse gluten to reduce mixing times, to make dough more pliable and to improve the loaf volume and texture
- tenderise meat
- prepare liquid meat products
- reduce the viscosity and prevent gelation of concentrated soluble fish products
- reduce the setting time for gelatin without affecting the gel strength.

Bromelain is a mixture of proteases which hydrolyse plant and animal proteins to amino acids and peptides. It is used to:

- tenderise meat
- improve the handling of pizza doughs
- chillproof beer
- produce waffles, pancakes and wafers.

Papain and *ficin* are proteases that have broad substrate specificities and stability at higher temperatures. They are used to produce savoury flavourings for soups, to

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chillproof beer and as meat tenderisers. Details of the action of papain are given by Law (1990).

Rennet partially coagulates milk proteins to form casein curds in cheese production (Section 7.2.1). A low proteolytic activity is required to prevent solubilisation of the casein and to achieve an adequate yield of correctly flavoured cheese. Calf rennet is expensive and the use of microbial proteases is therefore increasing. Fungal proteases have a lower activity than bacterial proteases and the protease from *M. meihei* or *M. pusillus* is used for short and medium fermentation times. Developments in recombinant deoxyribonucleic acid (DNA) technology applied to cheese manufacture are described by Law (1986). *Chymosin* was the first enzyme to become commercially available from genetically engineered *Kluyveromyces lactis* and *Escherichia coli* (Roller *et al.*, 1991).

Oxidases

Glucose oxidase oxidises glucose in the presence of oxygen to form gluconic acid. It is used to de-sugar, and hence to stabilise egg products, and to increase the shelf life of bottled beer, soft drinks and other oxygen sensitive foods. It has advantages over chemical anti-oxidants because it does not lose its activity over time as it is not itself oxidised. *Catalase* decomposes hydrogen peroxide to form water and oxygen. It is used to provide oxygen for de-sugaring egg products by glucose oxidase.

Lipases

Lipases hydrolyse fats and fatty acid esters to form diglycerides and monoglycerides. Preparations which contain smaller quantities of α -amylase and protease are used to:

- improve whipping properties of egg albumin
- modify or solubilise fats
- break down emulsions
- improve the flavour of dairy products
- produce free fatty acids from butterfat.

The fatty acids are used in small amounts to enhance natural flavours, in larger amounts to give a buttery flavour and in large amounts to give a cheesy flavour. They are used in cheese flavoured dips, sauces and snackfoods, processed cheese, soups, baked products and chocolate confections. Lipases from *Candida cylindracea* and *Mucor mehieii* have been used to inter-esterify triglycerides in palm oil to change the melting curve to one that is similar to cocoa butter and thus increase its value. *Phospholipases* are used to improve the emulsifying properties of phospholipids and can be used in inter-esterification to change their physical properties (Law, 1990).

Other enzymes

Diacetyl reductase converts the flavour compound diacetyl to flavourless acetoin to improve the flavour in beer (Eckett, 1985). Fungal *phosphodiesterases* can be used to make 5'-nucleotide flavour enhancers which accentuate 'meaty' flavours in soups, sauces and gravies. Enzymes are also used for debittering of fruit products; for example *limoninase* which hydrolyses the bitter component 'limonin' in orange juice or *naringinase* which breaks down naringin in grapefruit juice. *Pentosanase* converts pentosans to D-xylose and L-arabinose to reduce bread staling, to reduce dough viscosity, to lighten the crumb of rye bread and to prevent it from separating from the crust during baking. β -glucanases converts β -glucans to β -D-glucose to facilitate filtration of barley wort in brewing. *Stachyase* converts stachyose and raffinose to monosaccharides to

reduce flatulence produced by leguminous foods. The protease *trypsin* retards the development of oxidised flavours in milk and *collagenase* and *elastase* soften and tenderise connective tissues in meat. Other examples of enzyme applications in food processing are given by Whitaker (1990).

7.3 Acknowledgements

Grateful acknowledgement is made for information supplied by the following: Novo Enzymes Division, Novo Alle, DK-2880 Bagsvaerd, Denmark; Rohm Enzyme, Rohm GmbH, D-6100 Darmstadt, Germany; APV Baker Ltd, Peterborough PE4 7AP, UK.

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8

Irradiation

Ionising radiation takes the form of γ -rays from isotopes or, commercially to a lesser extent, from X-rays and electrons. It is permitted in 38 countries to preserve foods by destruction of micro-organisms or inhibition of biochemical changes (Table 8.1). Applications and details of the technology have been comprehensively reviewed by Wilkinson and Gould (1996).

The main advantages of irradiation are as follows:

- there is little or no heating of the food and therefore negligible change to sensory characteristics
- packaged and frozen foods may be treated
- fresh foods may be preserved in a single operation, and without the use of chemical preservatives
- energy requirements are very low
- changes in nutritional value of foods are comparable with other methods of food preservation
- processing is automatically controlled and has low operating costs.

A major disadvantage is the high capital cost of irradiation plant, but concern over the use of food irradiation has also been expressed by some (for example Webb and Lang (1990) and Webb and Henderson (1986)). Other concerns, for example over operator safety, are discussed by Webb and Lang (1987) and by Welt (1985). They describe the main problems as:

- the process could be used to eliminate high bacterial loads to make otherwise unacceptable foods saleable
- if spoilage micro-organisms are destroyed but pathogenic bacteria are not, consumers will have no indication of the unwholesomeness of a food
- there will be a health hazard if toxin-producing bacteria are destroyed after they have contaminated the food with toxins
- the possible development of resistance to radiation in micro-organisms
- loss of nutritional value

- until recently, inadequate analytical procedures for detecting whether foods have been irradiated
- public resistance due to fears of induced radioactivity or other reasons connected to concerns over the nuclear industry.

These concerns have been addressed by the Joint FAO/IAEA/WHO Expert Committee on the Wholesomeness of Irradiated Food (JECFI) who concluded that the maximum average dose of 10 kGy 'presents no toxicological hazard and no special nutritional or microbiological problems in foods' (World Health Organisation, 1977, 1981). This was supported by the Advisory Committee on Irradiated and Novel Foodstuffs (Anon., 1986). The JECFI recommendations were then formed into a standard by the Codex Alimentarius Commission who recommended an international code for the operation of radiation facilities. In most countries where irradiation is permitted, labelling regulations are in force which place a requirement on manufacturers to indicate that the food or any listed ingredients have been treated by irradiation. Additionally, wholesale foods are required to be labelled with the phrase 'Treated by irradiation, do not irradiate again'. This, together with a programme of research into methods to detect whether foods have been irradiated, are in part intended to change negative public perceptions of irradiated foods.

Table 8.1 Applications of food irradiation

Application	Dose range (kGy)	Examples of foods	Countries with commercial processing
Sterilisation	7–10	Herbs, spices	Belgium, Canada, Croatia, Czech Republic, Denmark, Finland, Israel, Korea (Rep.), Mexico, South Africa, USA, Vietnam
	Up to 50	Long term ambient storage of meat (outside permitted dose)	None
Sterilisation of packaging materials	10–25	Wine corks	Hungary
Destruction of pathogens	2.5–10	Spices, frozen poultry, meat, shrimps	Belgium, Canada, Croatia, Czech Republic, Denmark, Finland, France, Iran, Netherlands, South Africa, Thailand, Vietnam
Control of moulds	2–5	Extended storage of fresh fruit	China, South Africa, USA
Extension of chill life from 5 days to 1 month	2–5	Soft fruit, fresh fish and meat at 0–4°C	China, France, Netherlands, South Africa, USA
Inactivation/control of parasites	0.1–6	Pork	–
Disinfestation	0.1–2	Fruit, grain, flour, cocoa beans, dry foods	Argentina, Brazil, Chile, China
Inhibition of sprouting	0.1–0.2	Potatoes, garlic, onions	Algeria, Bangladesh, China, Cuba

Adapted from Ley (1987), Guise (1986a), Goresline (1982), Anon. (1985), Loaharanu (1995) and Wilkinson and Gould (1996).

8.1 Theory

The units used are given as a footnote to this page.¹ Details of the physical and chemical processes involved in the decay of radioactive materials to produce α -, β - and γ radiation, X-rays and free electrons are described by Desrosier and Rosenstock (1960).

γ -rays and electrons are distinguished from other forms of radiation by their ionising ability (that is they are able to break chemical bonds when absorbed by materials). The products of ionisation may be electrically charged (ions) or neutral (free radicals). These then further react to cause changes in an irradiated material known as radiolysis. It is these reactions that cause the destruction of micro-organisms, insects and parasites during food irradiation.

In foods that have a high moisture content, water is ionised by radiation. Electrons are expelled from water molecules and break the chemical bonds. The products then recombine to form hydrogen, hydrogen peroxide, hydrogen radicals ($H\cdot$), hydroxyl radicals ($OH\cdot$) and hydroperoxyl radicals ($HO_2\cdot$) (Fig. 8.1).

The radicals are extremely short lived (less than 10^{-5} s) but are sufficient to destroy bacterial cells. Similar radicals are also present in non-irradiated foods owing to:

- the action of enzymes (for example lipoxygenases and peroxidases)
- the oxidation of fats and fatty acids
- the degradation of fat soluble vitamins and pigments.

In addition, reactive oxygen and its derivatives are produced in foods by peroxidases, xanthine oxidase and amino acid oxidase. Fat-soluble components and essential fatty acids are therefore lost during irradiation and some foods (for example dairy products) are unsuitable for irradiation owing to the development of rancid off-flavours. The presence of oxygen accelerates this process and meat is therefore irradiated in vacuum packs.

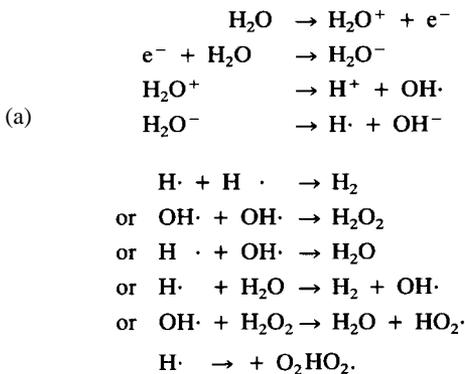


Fig. 8.1 (a) Ionisation of water (after Robinson (1986)); (b) formation of free radicals during irradiation (after Hughes (1982)).

1. Summary of units:

- Becquerel (Bq): One unit of disintegration per second. Curie (Ci) = 3.7×10^{10} Bq.
 Half-life: The time taken for the radioactivity of a sample to fall to half its initial value.
 Electron volt (eV): Energy of radiation (usually as mega-electron volts (MeV)). $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$.
 Grays (Gy): Absorbed dose (where 1 Gy is the absorption of 1 J of energy per kilogram of food). Previously rads (radiological units) were used where $1 \text{ rad} = 10^{-2} \text{ J kg}^{-1}$. 1 Gy therefore equals 100 rads.

8.2 Equipment

Irradiation equipment consists of a high-energy isotope source to produce γ -rays or, less commonly, a machine source to produce a high-energy electron beam. γ -radiation from cobalt-60 (^{60}Co) or caesium-137 (^{137}Cs) is used in most commercial plants. ^{60}Co emits γ -rays at two wavelengths which have energies of 1.17 MeV and 1.33 MeV respectively. The activity of the ^{60}Co or ^{137}Cs sources is rated at $(222\text{--}370) \times 10^{10} \text{ Bq g}^{-1}$ (or $10^{13} \text{ Bq kg}^{-1}$). This generates 15 kW/M Ci (15 kW per $3.7 \times 10^{16} \text{ Bq}$). The residence time of the food is determined by the dose required (Table 8.1) and the power output of the source.

An isotope source cannot be switched off and so is shielded within a pool of water below the process area, to allow personnel to enter. In operation the source is raised, and packaged food is loaded onto automatic conveyors and transported through the radiation field in a circular path. This makes maximum use of the emitted radiation and ensures a uniform dose. Isotope sources require a more complex materials-handling system than that used with machine sources (Fig. 8.2).

Machine sources are electron accelerators which consist of a heated cathode to supply electrons and an evacuated tube in which electrons are accelerated by a high-voltage electrostatic field. Either the electrons are used directly on the food, or a suitable target material is bombarded to produce X-rays. The main advantages of machine sources are:

- they can be switched off
- the electron beams can be directed over the packaged food to ensure an even dose distribution.

Handling equipment is therefore relatively simple. However, machine sources are expensive and relatively inefficient in producing radiation.

Radiation is contained within the processing area by the use of thick concrete walls and lead shielding. Openings in the shielding, for entry of products or personnel, must be carefully constructed to prevent leakage of radiation. A dose of 5 Gy is sufficient to kill an operator and it is therefore essential that even at the lowest commercial doses (0.1 kGy), stringent safety procedures are in place to prevent the source from being raised when personnel are present and to prevent entry to the building during processing.

^{60}Co has a half-life of 5.26 years and therefore requires the replacement of 12.3% of the activity each year to retain the rated output of the plant. Continuous-processing is

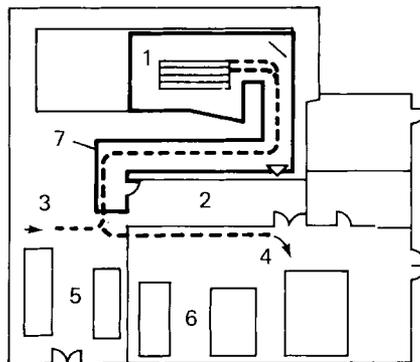


Fig. 8.2 Isotope irradiation plant: 1, irradiation chamber; 2, control room; 3, infeed conveyor; 4, outlet conveyor; 5, raw food store; 6, irradiated product store; 7, concrete shielding wall.
(After Farrall (1976).)

Table 8.2 Energy used in irradiation of chicken pieces compared to some other processes

Process	Energy use (kJ/kg)
Refrigerated (few days shelf life)	17 760
Frozen and stored for 3–5 weeks	46 600
Canned	20 180
Irradiated and refrigerated (few weeks shelf life)	17 860

Adapted from Brynjolfsson (1978).

therefore desirable for economic operation of plant with a continuously decaying source (Wilkinson, 1986). The energy savings incurred when irradiation/refrigeration of chicken pieces is compared to other processes are described in Table 8.2.

8.2.1 Measurement of radiation dose

Dosimeters are made from a number of materials, including photographic film, Perspex and cobalt glass, which are described by McLaughlin *et al.* (1982). Polyvinylchloride (PVC) dosimeters are impregnated with a dye. Hydrogen chloride is released from the PVC by irradiation and it produces a qualitative or quantitative change in the colour of the dye to indicate the dose received.

8.2.2 Dose distribution

Penetration of γ -radiation depends on the density of the food as well as the energy of the rays. Because radiation is absorbed as it passes through the food, the outer parts receive a higher dose than do inner parts. At a density of 1000 kg m^{-3} , half of the rays are absorbed in 11 cm. Halving the density approximately doubles the depth of penetration. For a given food there is thus a limit on both the maximum dose permitted at the outer edge (D_{max}), due to either unacceptable organoleptic changes or legislation, and a minimum limit (D_{min}) to achieve the desired effects of microbial destruction. The uniformity of dose distribution can be expressed as a ratio of $D_{\text{max}}:D_{\text{min}}$. For foods that are sensitive to radiation, such as chicken, this ratio should be as low as possible and not more than about 1.5. Other foods, for example onions, can tolerate a ratio of around 3 without unacceptable changes. The distribution of dose can be controlled by adjusting the thickness of the packed product and irradiating from both sides.

Dosimeters are placed at points throughout the package to determine the dose received and to ensure that the $D_{\text{max}}:D_{\text{min}}$ ratio is achieved.

High energy electrons have a lower penetration than γ -rays and are not suitable for bulk foods. They are used for thin packages or for surface treatments. The selection of a radiation source therefore depends on the type of product and its density, the dimensions of the package and the reason for the treatment.

8.3 Effect on micro-organisms

The reactive ions produced by irradiating foods (Fig. 8.1) injure or destroy micro-organisms immediately, by changing the structure of cell membranes and affecting metabolic enzyme activity. However, a more important effect is on deoxyribonucleic acid (DNA) and ribonucleic acid molecules in cell nuclei, which are required for growth and replication. The

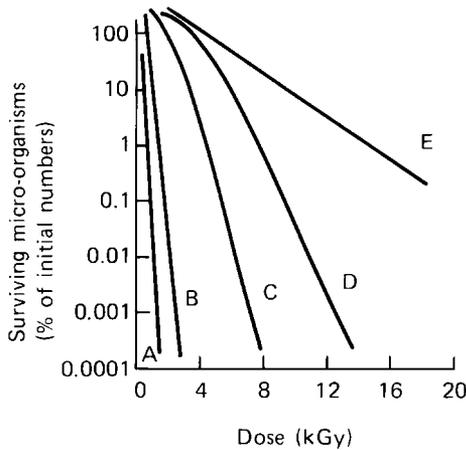


Fig. 8.3 Microbial destruction by irradiation: A, *Pseudomonas* sp.; B, *Salmonella* sp.; C, *Bacillus cereus*; D, *Deinococcus radiodurans*; E, typical virus.
(After Gould (1986).)

effects of irradiation only become apparent after a period of time, when the DNA double-helix fails to unwind and the micro-organism cannot reproduce by cell division.

The rate of destruction of individual cells depends on the rate at which ions are produced and inter-react with the DNA, whereas the reduction in cell numbers depends on the total dose of radiation received. The sensitivity of micro-organisms to radiation is expressed as the D_{10} value (the dose of radiation that reduces the microbial population to 10% of its initial value) by analogy with thermal destruction (Chapter 1). Theoretically, a logarithmic reduction in microbial numbers with increasing dose is expected. As in other food preservation methods the rate of destruction varies with microbial species, and some bacterial species contain more than one molecule of DNA whereas others are capable of repairing damaged DNA. The rate of destruction is not therefore linear with received dose (Fig. 8.3).

A simple guide is that, the smaller and simpler the organism, the higher the dose of radiation that is needed to destroy it. Viruses are very resistant to irradiation and are unlikely to be affected by the dose levels used in commercial processing. Spore forming species (for example *Clostridium botulinum* and *Bacillus cereus*), and those that are able to repair damaged DNA rapidly (for example *Deinococcus radiodurans*) are more resistant than vegetative cells and non-spore forming bacteria. Insects and parasites such as tape worms or trichinella require lower doses (e.g. *Toxoplasma gondii* is inactivated at doses of 0.25 kGy and *Trichinella spiralis* at 0.3 kGy (Olson, 1998)). Examples of D -values for important pathogens are given in Table 8.3.

8.4 Applications

The radiation dose administered to a food depends on the resistance of the organisms present and the objective of the treatment. The maximum recommended dose for foods is 15 kGy, with the average dose not exceeding 10 kGy (World Health Organisation, 1977, 1981, 1994). The types of irradiation process can be categorised by the intention of processing and the dose used.

Table 8.3 *D*-values of important pathogens

Pathogen	<i>D</i> -value (kGy)	Irradiation temperature (°C)	Suspending medium
<i>A. hydrophilia</i>	0.14–0.19	2	Beef
<i>C. jejuni</i>	0.18	2–4	Beef
<i>Escherichia coli</i> 0157:H7	0.24	2–4	Beef
<i>L. monocytogenes</i>	0.45	2–4	Chicken
<i>Salmonella</i> sp.	0.38–0.77	2	Chicken
<i>Staphylococcus aureus</i>	0.36	0	Chicken
<i>Yersinia enterocolitica</i>	0.11	25	Beef
<i>Clostridium botulinum</i> (spores)	3.56	–30	Chicken

Adapted from Olson (1998).

8.4.1 Sterilisation (or ‘radappertisation’)

Although it is technically possible to sterilise meats and other products, the dose required exceeds the current limit of 10 kGy. A dose of 48 kGy is needed for a 12*D* reduction of *Cl. botulinum* (Lewis, 1990) but such a high dose would make products such as meat organoleptically unacceptable. There is thus little commercial interest in sterilisation, with the exception of herbs and spices which are frequently contaminated by heat resistant, spore-forming bacteria. These products can be sterilised using a dose of 8–10 kGy (Table 8.1), which reduces the microbial load to an acceptable level without significant loss of volatile oils, the main quality characteristic. The main advantage of irradiating spices is the replacement of chemical sterilisation using ethylene oxide, which has been banned by the European Union since 1991 as a result of concerns over residues in the product and safety of workers handling the gas.

8.4.2 Reduction of pathogens (or ‘radicidation’)

Food poisoning bacteria (for example *Salmonella typhimurium*) are less resistant to radiation than for example *Clostridium botulinum*, and doses of 3–10 kGy are sufficient for destruction (Guise, 1986a). This is likely to become one of the most important applications of food irradiation as the incidence of food poisoning is steadily increasing in many countries (Guise, 1986b; Loaharanu, 1995). Fresh poultry carcasses irradiated with a dose of 2.5 kGy are virtually free of *Salmonella* spp. and the shelf life is doubled when the product is held below 5°C. Higher doses, up to 10 kGy, can be applied to frozen poultry or shellfish (–18°C) to destroy *Campylobacter* spp. *Escherichia coli* 0157:H7 or *Vibrio* sp. (e.g. *V. cholerae*, *V. parahaemolyticus*, *V. vulnificus*) without causing the unacceptable organoleptic changes that occur in fresh meat. These applications have been reviewed by Crawford and Ruff (1996).

8.4.3 Prolonging shelf life (or ‘radurisation’)

Relatively low doses (Table 8.1) are needed to destroy yeasts, moulds and non-spore forming bacteria. This process is used to increase shelf life by an overall reduction in vegetative cells. Bacteria which survive irradiation are more susceptible to heat treatment and the combination of irradiation with heating is therefore beneficial in causing a greater reduction in microbial numbers than would be achieved by either treatment alone (Gould, 1986).

Two potential problems of irradiation that are raised with respect to microbial destruction are:

1. that by destroying spoilage micro-organisms and not destroying pathogenic bacteria a valuable indicator of unwholesomeness is removed
2. that the destruction of toxin-producing bacteria after they have contaminated the food with toxins is a health hazard.

These are problems associated with poor manufacturing practice and occur in other types of food processing (for example aflatoxin production by *Aspergillus* species in nuts and grains). It is therefore essential that codes of Good Manufacturing Practice (for example Anon., 1998) are adhered to.

8.4.4 Control of ripening

Some types of fruits and vegetables, such as strawberries and tomatoes, can be irradiated to extend their shelf life about 2–3 times when stored at 10°C. A combination of irradiation and modified atmosphere packaging (Chapter 20) has been shown to have a synergistic effect and as a result, a lower radiation dose can be used to achieve the same effect. However, these products should be ripe before irradiation as the ripening process is inhibited. Ripening and maturation of fruits and vegetables are arrested by inhibiting hormone production and interrupting the biochemical processes of cell division and growth. It should be noted, however, that enzymic spoilage of foods is not entirely prevented by irradiation and a separate heat treatment is required for prolonged storage. A two-fold increase in shelf life of mushrooms and inhibition of cap opening can be achieved by doses of 2–3 kGy.

8.4.5 Disinfestation

Grains and tropical fruits may be infested with insects and larvae, which lowers their export potential and requires a quarantine period for disinfestation. Low doses, below 1 kGy, are effective for disinfestation and also extend the shelf life by delaying ripening. Further advantages are the avoidance of pesticides such as ethylene dibromide and methyl bromide which are now banned or restricted in many countries (Loaharanu, 1995) as a result of concern over toxic residues in foods or, in the case of methyl bromide, because of its potential to deplete the ozone layer.

8.4.6 Inhibition of sprouting

The technology is effective in inhibiting sprouting of potatoes and in Japan for example, doses of about 150 Gy have been used since 1973 on potatoes intended for further processing (Stevenson, 1990). Similar doses are effective in preventing sprouting of onions and garlic.

8.5 Effect on foods

8.5.1 Induced radioactivity

At recommended doses, ^{60}Co and ^{137}Cs have insufficient emission energies to induce radioactivity in the food. Machine sources of electrons and X-rays do have sufficient

energy, but the levels of induced radioactivity are insignificant (2% of the acceptable radiation dose in the worst case and 0.0001% under realistic processing and storage conditions) (Gaunt, 1986).

8.5.2 Radiolytic products

The ions and radicals produced during irradiation (Section 8.1) are capable of reacting with components of the food to produce radiolytic products. The extent of radiolysis depends on the type of food and the radiation dose employed. However, the majority of the evidence from feeding experiments, in which animals were fed irradiated foods and high doses of radiolytic products, indicates that there are no adverse effects. Radiolytic type products can also arise from other methods of food processing (Gaunt, 1986) and as a result it has, until recently, been difficult to devise a test to determine whether foods have been irradiated.

8.5.3 Nutritional and sensory value

At commercial dose levels, ionising radiation has little or no effect on the digestibility of proteins or the composition of essential amino acids (Josephson *et al.*, 1975). At higher dose levels, cleavage of the sulphhydryl group from sulphur amino acids in proteins causes changes in the aroma and taste of foods. Carbohydrates are hydrolysed and oxidised to simpler compounds and, depending on the dose received, may become depolymerised and more susceptible to enzymic hydrolysis. However, there is no change in the degree of utilisation of the carbohydrate and hence no reduction in nutritional value. The effect on lipids is similar to that of autoxidation, to produce hydroperoxides and the resulting unacceptable changes to flavour and odour. The effect is reduced by irradiating foods while frozen, but foods that have high concentrations of lipid are generally unsuitable for irradiation.

There is conflicting evidence regarding the effect on vitamins as many studies have used vitamin solutions, which show greater losses than those found in the heterogeneous mixtures of compounds in foods. Water soluble vitamins vary in their sensitivity to irradiation. The extent of vitamin loss also depends on the dose received and the type and physical state of food under investigation. There is also conflicting evidence at low dose levels. For example, in grain disinfection there are little or no vitamin losses, whereas inhibition of sprouting is variously reported to cause 0% and 28% loss of vitamin C at 0.1 kGy and 0.11 kGy respectively (Faizur Rahman, 1975; Gounelle *et al.*, 1970). The effects on thiamine in meat and poultry are likewise inconsistent but other vitamins of the B group are largely unaffected (Table 8.4). The order of sensitivity is reported as thiamin > ascorbic acid > pyridoxine > riboflavin > folic acid > cobalamin > nicotinic acid. Fat-soluble vitamins vary in their susceptibility to radiation. Vitamins D and K are largely unaffected whereas vitamins A and E undergo some losses, which vary according to the type of food examined. The order of sensitivity is vitamin E > carotene > vitamin A > vitamin K > vitamin D (World Health Organisation, 1994). A comparison of irradiated and heat sterilised chicken meat (Table 8.5) indicates similar levels of vitamin loss.

In summary, the consensus of opinion is that, at commercial dose levels, irradiation causes no greater damage to nutritional quality than other preservation operations used in food processing. Changes in nutritional quality are described in detail by Kraybill (1982).

Table 8.4 Effect of irradiation on water-soluble vitamins in selected foods

Food	Treatment (kGy)	Loss (%)					
		Thiamin	Riboflavin	Niavin	Pyridoxine	Pantothenic acid	Vitamin B ₁₂
Beef	4.7–7.1	60	4	14	10	–	–
Pork	4.5	15	22	22	2	–	–
Haddock	1.5	22	0	0	+15	+78	10
Wheat	2.0	12	13	9	–	–	–
Flour	0.3–0.5	0	0	11	0	–	–

+ apparent increase. Adapted from Brooke *et al.* (1966) and Josephson *et al.* (1975).

Table 8.5 A comparison of vitamin contents of heat sterilised and irradiated (58 kGy at 25°C) chicken meat

Vitamin	Vitamin concentration (mg/kg dry weight) ^a			
	Frozen control	Heat sterilised	γ-irradiated	Electron irradiated
Thiamin HCl	2.31	1.53 ^b	1.57 ^b	1.98
Riboflavin	4.32	4.60	4.46	4.90 ^c
Pyridoxine	7.26	7.62	5.32	6.70
Nicotinic acid	212.9	213.9	197.9	208.2
Pantothenic acid	24.0	21.8	23.5	24.9
Biotin	0.093	0.097	0.098	0.013
Folic acid	0.83	1.22	1.26	1.47 ^c
Vitamin A	2716	2340	2270	2270
Vitamin D	375.1	342.8	354.0	466.1
Vitamin K	1.29	1.01	0.81	0.85
Vitamin B ₁₂	0.008	0.016 ^c	0.014 ^c	0.009

^a Concentrations of vitamin D and vitamin K are given as IU/kg.

^b Significantly lower than frozen control.

^c Significantly higher than frozen control.

From Satin (1993).

8.6 Effect on packaging

Radiation is able to penetrate packaging materials and therefore reduces the risk of post-processing contamination and allows easier handling of products. However, packaging materials are themselves subject to changes induced by radiation (Table 8.6) and may produce low molecular weight hydrocarbons and halogenated polymers, which have the potential to migrate into the product and produce unacceptable tainting. Careful choice of packaging materials as well as adhesives, additives and printing materials is necessary to prevent contamination of the food with radiolytic products.

8.7 Detection of irradiated foods

There has been considerable research since the late 1980s to develop and validate a series of detection methods that can be used by enforcement officers to detect whether a food has been irradiated. A review of the international collaboration to develop standard

Table 8.6 Changes to packaging materials caused by irradiation

Packaging material	Maximum dose (kGy)	Effect of radiation above maximum dose
Polystyrene	5000	–
Polyethylene	1000	–
PVC	100	Browning, evolution of hydrogen chloride
Paper and board	100	Loss of mechanical strength
Polypropylene	25	Becomes brittle
Glass	10	Browning

Adapted from the data of Guise (1986a) and McLaughlin *et al.* (1982).

methods is given by Delincée (1998). Because irradiation produces no major chemical, physical or sensory changes to foods at commercial doses, detection methods focus on minute changes in chemical composition, physical or biological changes to the food. These methods are based on either detecting products formed by irradiation, physical changes such as cell membrane damage or determining the ratio of live:dead bacteria. At present there are a number of techniques under development, but it is not likely that one method will be applicable to all irradiated foods. These developments have been reviewed by Delincée (1998). So far the following methods have either been validated or are likely to prove useful.

8.7.1 Physical methods

Electron spin resonance spectroscopy

Electron spin resonance (ESR) spectroscopy detects radicals produced by irradiation, which are stable in solid or dry components of foods (e.g. bones). It has been used to detect irradiated bone-containing meat and fish products and shellfish, and may have application to a wide range of food products, including foods that contain crystalline cellulose and have a low moisture content (e.g. pistachio nuts and paprika). It is a non-destructive method that is specific, rapid and relatively simple, although the high cost of ESR spectrometers may limit its application.

Thermoluminescence

Thermoluminescence (TL) is based on the emission of light, when energy trapped in crystalline lattices during irradiation is released by heating the food. These lattices may be contaminating dust (silicate materials) on spices, minerals from seabeds in the intestines of shellfish, or minerals in fruits and vegetables. The minerals are isolated from the food and when they are heated in a controlled way, the stored energy is released as light and measured by a sensitive photon counter. The method is widely applicable and gives an unequivocal determination that a food has been irradiated, but it has a number of disadvantages: it is laborious because a sufficient amount of minerals (a few mg), free of organic matter, has to be prepared; strict procedures are needed to prevent contamination by dust in the laboratory; TL analysers are expensive; and a radiation source is needed for standardisation of the method. A recent adaptation of the method is photostimulated luminescence (PSL) in which pulsed infrared light is used instead of heat to release the stored energy. The method does not require isolation of the minerals and a small sample of food can be used directly to obtain a result within a few minutes. It is also more efficient than TL in detecting an irradiated component in a mixture of materials and may be capable of being developed into a 'spot-test' for irradiation.

Other methods that detect physical changes are measurement of electrical impedance, changes in viscosity, electric potential, nuclear magnetic resonance and near-infrared spectroscopy (World Health Organisation, 1994).

8.7.2 Chemical methods

The lack of chemical changes to foods as a result of irradiation has caused difficulties in devising suitable tests. One method that has been developed is analysis of radiolytic hydrocarbons produced from fats using gas chromatography (GC). Although the products are formed in other types of food processing, they have a characteristic distribution pattern following irradiation. The use of liquid chromatography coupled to GC increases the sensitivity of the method (Delincée, 1998).

2-alkylcyclobutanones

2-alkylcyclobutanones (2-CBs) are radiolytic products formed from fatty acids, but are not found as a result of other degradative processes. They are detected using mass spectrometry after separation by gas chromatography and can be identified as positive markers to indicate that a food has been irradiated (Crone *et al.*, 1993; Stevenson, 1994). The method has been used to detect irradiated poultry meat, pork, beef or lamb meat and liquid whole egg. More recently the test has been used to detect irradiated exotic fruits, including mango, papaya and avocado (Stewart *et al.*, 1998). Other methods that have been used to detect 2-CBs include thin-layer chromatography (TLC), high pressure liquid chromatography (HPLC) and supercritical fluid extraction/TLC.

Detection of DNA fragmentation by microgel electrophoresis of single cells or nuclei has shown good results but the test is limited to foods that have not been heat treated, as this also results in DNA fragmentation. There are also prospects for routine use of enzyme linked immunosorbant assay (ELISA) tests as simpler and more rapid methods to detect 2-CBs and dihydrothymidine, a DNA breakdown product of irradiation. Details are given by Nolan *et al.* (1998) and Tyreman *et al.* (1998) respectively. In each case the monoclonal antibody used in the assay is raised against the particular marker chemical and subjected to the ELISA testing procedure. The results give both qualitative and quantitative identification of the marker in irradiated samples of food and may be developed into a positive 'spot-test' for irradiation.

8.7.3 Biological methods

The *Limulus* Amoebocyte Lysate test in conjunction with a Gram-negative bacteria count (LAL/GNB), is used to estimate the reduced viability of micro-organisms in a food after irradiation, measuring both dead and alive micro-organisms. This method and the Direct Epifluorescent Filter Technique with an aerobic plate count (DEFT/APC) give information about the numbers of bacteria destroyed by irradiation. If the DEFT count exceeds the APC by 10^4 or more, it indicates that the food has been irradiated (World Health Organisation, 1994). These methods also indicate the hygiene status before and after irradiation, and thus help to enforce Good Manufacturing Practice. They are used for a wide range of irradiated foods, especially to detect irradiated poultry meat. The last method may be limited if initial contamination is low or if low dose levels are used.

Other detection methods are being developed including capillary gel electrophoresis to detect irradiated meat and plant material. Here proteins and peptides are separated on the

basis of their size and this was used to detect changes in egg white caused by irradiation (Day and Brown, 1998).

8.8 Acknowledgement

Grateful acknowledgement is made for information supplied by Isotron plc, Swindon, Wiltshire SN2 6DU, UK.

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9

Processing using electric fields, high hydrostatic pressure, light or ultrasound

Over the last ten years, consumer demand has increasingly required processed foods to have a more 'natural' flavour and colour, with a shelf life that is sufficient for distribution and a reasonable period of home storage before consumption. This can be achieved by *minimal processing methods* that preserve foods but also retain to a greater extent their nutritional quality and sensory characteristics by reducing the reliance on heat as the main preservative action. Traditionally, fermented foods (Chapter 7) have many of these characteristics; irradiation (Chapter 8) has been adopted in some countries as a minimal method of food preservation; and chilling (Chapter 19) and controlled or modified atmospheres (Chapter 20) are now widely adopted to suppress microbial growth. There has also been increasing interest in developing other combinations of existing and novel methods to achieve mild preservation. Examples of novel minimal processing technologies are shown in Table 9.1. Of these, pulsed electric fields, high pressure processing, high intensity light and ultrasound are described in this chapter, with a brief summary of magnetic fields and photodynamic systems in Section 9.5.

The principle underlying the use of combined techniques is known as the 'Hurdle' concept (described in Chapter 1, Section 1.8.2) and includes the use of combinations of temperature, water activity, preservatives, modified atmospheres, acidity and redox potential to inhibit microbial growth. In each minimal processing method, processing destroys micro-organisms, and in some cases enzymes, and there are no substantial increases in product temperature. There is therefore little damage to pigments, flavour compounds or vitamins and, in contrast to heat processing (Part III), the sensory characteristics and nutritional value of foods are not degraded to a significant extent. The resulting products have higher quality and consumer appeal in markets where the retention of natural sensory characteristics can command premium prices.

Pulsed electric fields and high hydrostatic pressure processing have been studied for many years and are now at the stage of initial commercial exploitation. Ultrasound has been used for many years to homogenise foods (Chapter 4) and in plant cleaning (Chapter 26) and is now being combined with heat treatments under pressure to reduce the amount of heating needed for microbial destruction or enzyme inactivation. Processing using pulsed light is a more recent development that may have good potential for the surface

Table 9.1 Examples of novel processes that may have applications for minimal processing of foods

Electro-heating (radio-frequency, microwave and ohmic heating)
High pressure processing
High voltage electrical discharge
High intensity light
Ultrasound
Modified atmosphere packaging
Jet impactation
Gamma radiation
Lasers and masers
Microfiltration
X-rays
Cryogenic thermal shock
Immobilised enzymes
Active packaging
Ozone
Nitrous oxide

treatment of foods and packaging materials or for water treatment. The comparative advantages and limitations of these technologies are summarised in Table 9.2, together with examples of potential products that may become commercially important.

Microfiltration is described in Chapter 6, immobilised enzymes in Chapter 7, irradiation in Chapter 8, radio-frequency, microwave and ohmic heating in Chapter 18, modified atmospheres in Chapter 19 and active packaging systems in Chapter 24.

In all new developments of minimal processing, it is not only the improved eating quality of products that is important. The process must be capable of operating in a factory environment and not just in a laboratory with highly qualified staff; it should ensure a financial benefit to the manufacturer; and it should be sufficiently flexible to accommodate a wide range of products, often having short production runs and brief product life cycles (Manvell, 1996).

9.1 Pulsed electric field processing

The origin of High Intensity Pulsed Electric Field (HIPEF) processing is the 'ElectroPure' process, a forerunner of ohmic heating (Chapter 18), which was developed in the 1920s and used for more than twenty years in the USA to pasteurise milk. This process produced only thermal destruction of micro-organisms because only low electricity voltages were used. By the 1960s the use of higher voltages (3000–4000 V) demonstrated that, in addition to thermal effects, there was enhanced microbial destruction caused by the electricity itself. Non-thermal destruction of micro-organisms and enzymes using electric discharges was then demonstrated in model food systems, and this research was extended during the 1980s and 1990s to process a variety of liquid foods, including fruit juices, soups, liquid egg and milk. One such process was termed the 'ELSTERIL' process for the electric sterilisation of pumpable conductive foods. The same German company developed the 'ELCRACK' process, using similar HIPEF technology to disrupt vegetable and animal cells to assist in recovery of edible oils and fats. These developments are reviewed by Sitzmann (1995) and Vega-Mercado *et al.* (1999). HIPEF is not yet used on a commercial scale but its relatively low energy

Table 9.2 Advantages and limitations of some novel methods of minimal processing

Process	Advantages	Limitations	Examples of commercial applications and products
Pulsed electric fields	<ul style="list-style-type: none"> • Kills vegetative cells • Colours, flavours and nutrients are preserved • No evidence of toxicity • Relatively short treatment time 	<ul style="list-style-type: none"> • No effect on enzymes and spores • Difficult to use with conductive materials • Only suitable for liquids or particles in liquids • Only effective in combination with heat • Products of electrolysis may adversely affect foods • Safety concerns in local processing environment • Energy efficiency not yet certain • Regulatory issues remain to be resolved • May be problems with scaling-up process 	<ul style="list-style-type: none"> • For liquid foods • Pasteurisation of fruit juices, soups, liquid egg and milk • Accelerated thawing • Decontamination of heat sensitive foods
High pressure	<ul style="list-style-type: none"> • Kills vegetative bacteria (and spores at higher temperatures) • No evidence of toxicity • Colours, flavours and nutrients are preserved • Reduced processing times • Uniformity of treatment throughout food • Desirable texture changes possible • In-package processing possible • Potential for reduction or elimination of chemical preservatives • Positive consumer appeal 	<ul style="list-style-type: none"> • Little effect on food enzyme activity • Some microbial survival • Expensive equipment • Foods should have approx. 40% free water for anti-microbial effect • Batch processing • Limited packaging options • Regulatory issues to be resolved 	<ul style="list-style-type: none"> • Pasteurisation and sterilisation of fruit products, sauces, pickles, yoghurts and salad dressings • Pasteurisation of meats and vegetables • Decontamination of high risk or high value heat sensitive ingredients, including shellfish, flavourings, vitamins

Table 9.2 Continued

Process	Advantages	Limitations	Examples of commercial applications and products
Pulsed light	<ul style="list-style-type: none"> • Medium cost • Very rapid process • Little or no changes to foods • Low energy input • Suitable for dry foods 	<ul style="list-style-type: none"> • Only surface effects and difficult to use with complex surfaces • Not proven effective against spores • Possible adverse chemical effects • Possible resistance in some micro-organisms • Reliability of equipment to be established • Advantages over high intensity UV light to be established 	<ul style="list-style-type: none"> • Packaging materials • Baked products • Fresh fruit and vegetables • Meats, seafood and cheeses • Surfaces, water and air
Ultrasound	<ul style="list-style-type: none"> • Effective against vegetative cells, spores and enzymes • Reduction of process times and temperatures • Little adaptation required of existing processing plant • Heat transfer increased • Possible modification of food structure and texture • Batch or continuous operation • Effect on enzyme activity 	<ul style="list-style-type: none"> • Complex mode of action • Depth of penetration affected by solids and air in product • Possible damage by free radicals • Unwanted modification of food structure and texture • Needs to be used in combination with another process (e.g. heating) • Potential problems with scaling-up plant 	Any food that is heated
Magnetic field	<ul style="list-style-type: none"> • Kills vegetative cells • Colours, flavours and nutrients are preserved • Low energy input • Low cost equipment 	<ul style="list-style-type: none"> • No effect on spores or enzymes • Anti-microbial effect is 'patchy' and some vegetative cell growth stimulated • Mode of action not well understood • Poor penetration in electrically conductive materials • Safety concerns in local processing environment • Regulatory issues to be resolved 	Uncertain at present, possibly similar to high pressure applications

Table 9.2 Continued

Process	Advantages	Limitations	Examples of commercial applications and products
Photodynamic systems	<ul style="list-style-type: none">• Low cost• No additives required• Natural light suitable to activate system• Can be incorporated into packaging or used as a factory process	<ul style="list-style-type: none">• Good photosensitisers are not currently 'food-grade'• Oxidation of sensitive foods• Some bacterial resistance• Food constituents can act as quenching agents• Oxygen has limited mobility from immobilising agent• Regulatory issues to be resolved	<ul style="list-style-type: none">• Active packaging• Decontamination in washing processes• Water treatment• Sanitation of factory environments by incorporating photosensitisers into paints and plastic surfaces
Gamma radiation	<ul style="list-style-type: none">• Well established and understood• Excellent penetration into foods• Suitable for sterilisation• Suitable for non-microbial applications (e.g. sprout inhibition)• Permitted in some countries• Reliable• Little loss of food quality• Suitable for large-scale production• Low energy costs• Insecticidal• Improvement in flavour in some foods (e.g. strawberries)• Suitable for dry foods	<ul style="list-style-type: none">• High capital cost• Localised risks from radiation• Poor consumer understanding• 'Politics' of nuclear energy• Changes in flavour due to oxidation• Difficult to detect	<ul style="list-style-type: none">• Fruit and vegetables• Herbs and spices• Packaging• Meat and fish

Adapted from Earnshaw (1996) and Manvell (1996).

consumption, and the low processing temperatures which result in high retention of sensory characteristics and nutritional properties, indicate a good potential for producing high quality foods.

9.1.1 Theory

When an electric field with a strength in the range of 12–35 kV cm⁻¹ is applied to a liquid food in a short pulse (1–100 μs), there is a pronounced lethal effect on micro-organisms. The precise mechanisms by which micro-organisms are destroyed by electric fields are not well understood, but are likely to include:

- formation of pores in cell membranes when the applied electric field causes the electrical potential of the membrane to exceed the natural level of 1 V (Zimmermann *et al.*, 1974) – the pores then cause swelling and rupturing of the cells
- electrolysis products or highly reactive free radicals produced from components of the food by the electric arc, depending on the type of electrode material used and the chemical composition of the food
- induced oxidation and reduction reactions within the cell structure that disrupt metabolic processes (Gilliland and Speck, 1967)
- heat produced by transformation of induced electric energy.

The degree of inactivation of micro-organisms by HIPEF is greater at higher electric field intensities and/or with an increase in the number and duration of the pulses. Other factors that influence the degree of inactivation include the temperature of the food, its pH, ionic strength and electrical conductivity (Vega-Mercado *et al.*, 1999).

Studies in which foods were inoculated with target micro-organisms and processed by HIPEF have resulted in cell reductions of up to six log cycles (6D reduction – see Chapter 1) (Table 9.3). However, because the lethal effects depend on the specific apparatus and operating conditions used by different researchers, it is difficult to draw direct comparisons between these findings.

In addition to microbial destruction, Sitzmann (1995) reported a reduction in lipase activity in milk and a reduction in the ascorbic acid content after HIPEF treatment, but in

Table 9.3 Applications of HIPEF to foods

Product	Processing conditions				Inoculum	Log reduction (D)
	Field intensity (kV cm ⁻¹)	Temperature (°C)	Number of pulses	Duration of pulses (μs)		
Orange juice	33.6–35.7	42–65	35	1–100	Nat. micro. ^a	3
Orange juice	6.7	45–50	5	20	Nat. micro.	almost 5
Milk	28.6	42.8	23	100	<i>E.coli</i>	3
Milk	36.7	63	40	100	<i>S. dublin</i>	3
Milk	22	45–50	20	20	<i>L.brevis</i>	4.6
Yoghurt	23–28	63	20	100	Mixture ^b	2
Liquid egg	25.8	37	100	4	<i>E.coli</i>	6
Pea soup	25–33	53–55	10–30	2	<i>E.coli, B.subtilis</i>	4.4

^a Natural microflora.

^b *S. cerevisiae, L. bulgaricus* and *S.thermophilus*.

Adapted from Vega-Mercado *et al.* (1997).

general, vitamins and enzymes are not inactivated to any appreciable extent by HIPEF processing. Other studies reported by Vega-Mercado *et al.* (1997) indicate that the flavour and colour of fruit juices was unaltered by processing.

9.1.2 Equipment

Typical HIPEF equipment consists of a high-voltage power supply, capacitors to store the charge, a discharge switch to release the charge to electrodes which pass an electric field through the product contained in a treatment chamber (Fig. 9.1). Inductors are used to modify the shape and width of the electric field pulse. Although the process is intended to operate at ambient temperatures, the HIPEF treatment may cause a rise in the product temperature, depending on the field strength, pulse frequency (Hz) and number of pulses, and equipment is therefore fitted with refrigeration coils to control the temperature. The entire apparatus is contained within a restricted-access area due to the risk to operators from the high voltages and all connections to the chamber including product pipework and refrigeration units must be isolated and earthed to prevent leakage of energy. At present the initial investment costs are high, ranging from \$450 000–2 000 000 (Vega-Mercado *et al.*, 1999), which may limit widespread adoption of the process.

9.2 High pressure processing

The first reported use of high pressures as a method of food processing was in 1899 at the West Virginia University in the USA, where experiments were conducted using high hydrostatic pressures to preserve milk, fruit juice, meat and a variety of fruits. They demonstrated that micro-organisms in these products could be destroyed by pressures of 658 MPa (6500 atm) for 10 minutes. In the early years of the twentieth century, other

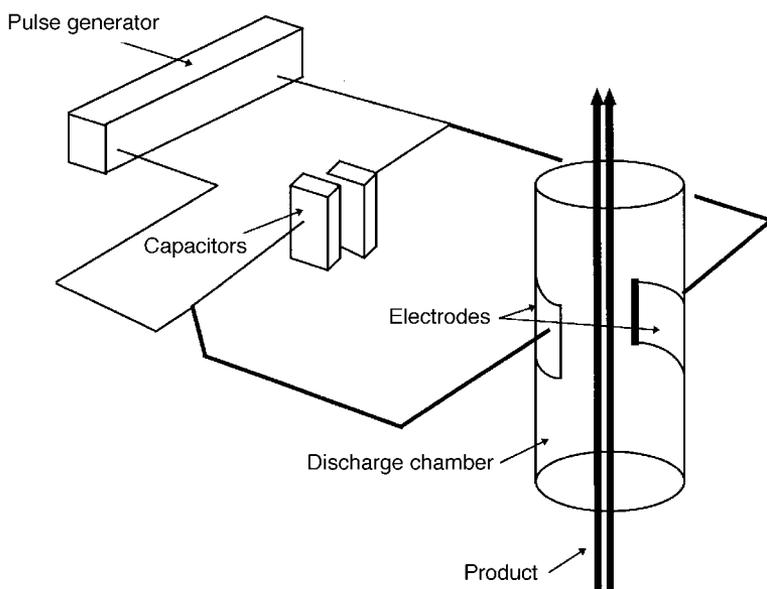


Fig. 9.1 Main components of a HIPEF plant.
(Adapted from Sitzmann (1995).)

research showed that protein structure in egg-white could be altered by high pressures. However, these early researchers found that the potential was limited because enzymes were largely unaffected, particularly in milk. They were also constrained by both difficulties in manufacturing high pressure units and inadequate packaging materials to contain the foods during processing, and research was discontinued. Advances in the design of presses together with rapid advances in packaging materials during the 1970s, enabled research to begin again on high pressure processing in the late 1980s, focused mainly in Japan.

By 1990 the first commercial products produced by high pressure processing went on sale in Japan. One company introduced a range of pressure-processed jams, including apple, kiwi, strawberry and raspberry in flexible sealed plastic packs, and two other companies started production of bulk orange juice and grapefruit juice. The jams had a shelf life of two months under chilled storage, which is required to prevent enzyme activity. Other products included fruit jellies, sauces, fruit yoghurts and salad dressings. The products currently sell at three to four times the cost of conventional products, but the higher quality, particularly flavour and texture of the fruit, has so far ensured sufficient demand for commercial viability. Similar products have recently reached the US market (Mermelstein, 1997), but are not currently (2000) available in Europe. The advantages and limitations of high pressure processing, compared to other minimal processing techniques, are described in Table 9.2.

9.2.1 Theory

When high pressures, up to 1000 MPa (10 000 bar), are applied to packages of food that are submerged in a liquid, the pressure is distributed instantly and uniformly throughout the food (i.e. it is 'isostatic'). The high pressure causes destruction of micro-organisms. In general, bacteria in the log phase of growth are more barosensitive (sensitive to high pressures) than cells in the stationary, dormant or death phases. Moderately high pressures (300–600 MPa) cause vegetative microbial cells to be killed or inactivated. Typically, a pressure of 350 MPa applied for 30 min or 400 MPa applied for 5 min will cause a ten-fold reduction in vegetative cells of bacteria, yeasts or moulds (Hoover *et al.*, 1989). Pulsed pressure treatments have been found to be more effective than static pressure for pasteurisation of pineapple juice (Aleman *et al.*, 1996). Higher pressures are required to cause bacterial spores to germinate, followed by inactivation of the germinated cells. However, when combined with moderate heating (e.g. to 60°C), spores are destroyed at pressures of 400 MPa to different extents, depending on the strains that are present (Seyderhelm and Knorr, 1992).

Research is continuing in order to understand the complex factors that cause these effects, but it is known that high pressures cause collapse of intracellular vacuoles, and damage to cell walls and cytoplasmic membranes. Knorr (1995a) describes possible hypotheses for disruption to metabolic processes caused by the effects of high pressures on cellular enzymes and these aspects are reviewed by Earnshaw (1995), Isaacs and Chilton (1995) and Patterson *et al.* (1995).

Enzymes that are related to food quality vary in their barosensitivity: some can be inactivated at room temperature by pressures of a few hundred MPa whereas others can withstand 1000 MPa (Cano *et al.*, 1997) and for example peroxidase in peas and pectin methyl esterase in strawberries can withstand 1200 MPa (Manvell, 1996). Yet others have their activity enhanced by high pressures. Pressure activation or inactivation is also strongly dependent on pH, substrate composition and temperature. The situation is further

complicated by effects of high pressures on cellular membranes, which when ruptured, may permit reactions between released intracellular enzymes and their substrates (Hendrickx *et al.*, 1998).

At present it is known that the high pressures only affect non-covalent chemical bonds (i.e. ionic, hydrogen and hydrophobic bonds), leaving covalent bonds intact. This permits destruction of microbial activity without significantly affecting food molecules that contribute to the texture or flavour of the food. As the process can be operated at ambient or even chill temperatures, there is little heat damage to nutrients or natural flavours and colours, which results in high quality products. Additionally, the process does not require the use of chemical preservatives to achieve an adequate shelf life of processed products.

The uniform application of high pressure to all parts of a food, irrespective of its size or shape is a significant advantage over other methods of processing, because the food is treated evenly throughout. This overcomes problems of lack of uniformity in processing that are found for example in conductive or convective heating (Chapter 1), microwaves and dielectric heating (due to variation in loss factors, Chapter 18) or radiant heating (variation in surface properties, Chapter 18).

High pressure processing has no 'heating' or 'cooling' periods, and there are rapid pressurisation/de-pressurisation cycles, thus reducing processing times compared to thermal processing. It is likely that high pressure processing will be capable of being used in combination with other types of processing and thus expand the unit operations available to food processors, leading to the development of new products and processes.

9.2.2 Processing and equipment

The construction of high pressure machinery is a specialised and expensive operation (in 1996 a high pressure fruit juice plant was twenty times the cost of an equivalent capacity plate heat exchanger system (Manvell, 1996)). However, companies that make equipment to press metal and ceramic engineering components, and quartz crystals for the electronics industry, have the necessary expertise. This is being adapted for use in the food industry and batch presses are available, having vessels of up to 9400 l capacity, which can operate at pressures of 200–500 MPa with operating cycles of as little as two to three minutes. Palou *et al.* (1999) report a batch press having a throughput of 600 l h⁻¹, operating at 420 MPa, which is used for the commercial production of pineapple juice in Japan.

The main components of a high pressure system are:

- a pressure vessel and its closure
- a pressure generation system
- a temperature control device
- a materials handling system (Mertens, 1995).

Most pressure vessels are made from a high tensile steel alloy 'monoblocs' (forged from a single piece of material), which can withstand pressures of 400–600 MPa. For higher pressures, pre-stressed multi-layer or wire-wound vessels are used (Mertens, 1995). Vessels are sealed by a threaded steel closure, a closure having an interrupted thread, which can be removed more quickly, or by a sealed frame that is positioned over the vessel. In operation, after all air has been removed, a pressure transmitting medium (either water or oil) is pumped from a reservoir into the pressure vessel using a pressure intensifier until the desired pressure is reached (Fig. 9.2). This is termed 'indirect compression' and requires static pressure seals. Another method, termed 'direct

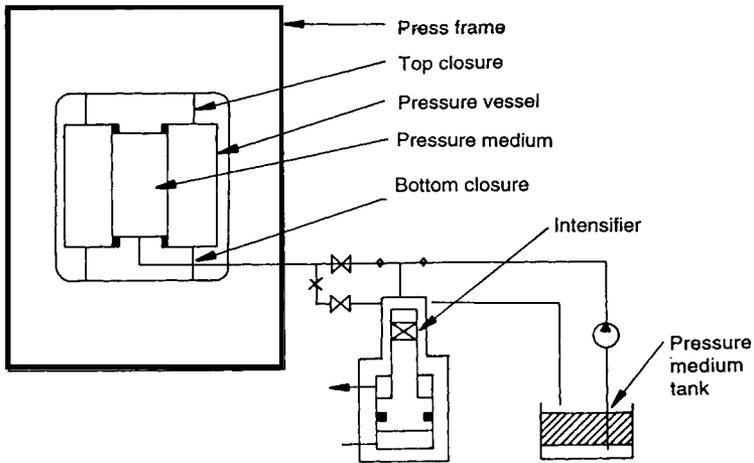


Fig. 9.2 Indirect compression equipment for high pressure processing.
(After Mertens (1995).)

compression' uses a piston to compress the vessel, but this requires dynamic pressure seals between the piston and internal vessel surface, which are subject to wear and are not used in commercial applications.

Temperature control in commercial operations can be achieved by pumping a heating/cooling medium through a jacket that surrounds the pressure vessel. This is satisfactory in most applications as a constant temperature is required, but if it is necessary to regularly change the temperature, the large thermal inertia of the vessel and relatively small heat transfer area make this type of temperature control very slow to respond to changes. In such situations, an internal heat exchanger is fitted.

There are two methods of processing foods in high pressure vessels: in-container processing and bulk processing. Because foods reduce in volume at the very high pressures used in processing (for example, water reduces in volume by approximately 15% at 600 MPa), there is considerable stress and distortion to the package and the seal when in-container processing is used. It is likely that conventional plastic and foil pouches (Chapter 24) will prove suitable and research is continuing on the optimum design of the package, seal integrity and other suitable packaging materials. Materials handling for in-container processing is achieved using automatic equipment, similar to that used to load/unload batch retorts (Chapter 12). Bulk handling is simpler, requiring only pumps, pipes and valves. A comparison of the advantages and limitations of in-container and bulk processing is shown in Table 9.4.

A representation of a commercial processing unit is shown in Fig. 9.3. Semi-continuous processing of fruit juices at $4000\text{--}6000\text{ l h}^{-1}$ using pressures of $400\text{--}500\text{ MPa}$ for 1–5 min at ambient temperature is used by one company in Japan, whereas another uses a similar process operating at $120\text{--}400\text{ MPa}$ followed by a short heat treatment before the juice is packaged. The process is highly energy efficient although at present the capital costs of equipment remain high. It is possible that such liquid foods could also be used as the pressurising fluid by direct pumping with high pressure pumps. Such systems would reduce the capital cost of a pressure vessel and simplify materials handling. If liquids were also rapidly decompressed through a small orifice, the high velocity and turbulent flow would increase the shearing forces on micro-organisms and thus increase their rate of destruction (Earnshaw, 1992). Developments in high pressure

Table 9.4 Advantages and limitations of in-container and bulk high pressure processing

In-container processing	Bulk processing
<i>Advantages</i>	
<ul style="list-style-type: none"> • Applicable to all solid and liquid foods • Minimal risk of post-processing contamination • No major developments needed for high pressure processing • Easier cleaning 	<ul style="list-style-type: none"> • Simple materials handling • Greater flexibility in choice of container • Maximum efficiency (>90%) in use of high pressure vessel volume • Minimum vessel dead-time (no opening/closing of vessel needed, faster loading/unloading)
<i>Limitations</i>	
<ul style="list-style-type: none"> • Complex materials handling • Little flexibility in choice of container • Greater dead-time in use of pressure vessel 	<ul style="list-style-type: none"> • Only suitable for pumpable foods • Aseptic filling of containers required – potential post-processing contamination • All pressure components in contact with food must have aseptic design and be suitable for cleaning-in-place (CIP) and sterilising-in-place

Adapted from Mertens (1995).

processing, reported by Knorr (1995a), include combined freeze concentration (Chapter 22), pressure freezing and high pressure blanching. Initial results suggest that pressure blanched fruits are dried more rapidly than those treated by conventional hot water blanching (Chapter 10).

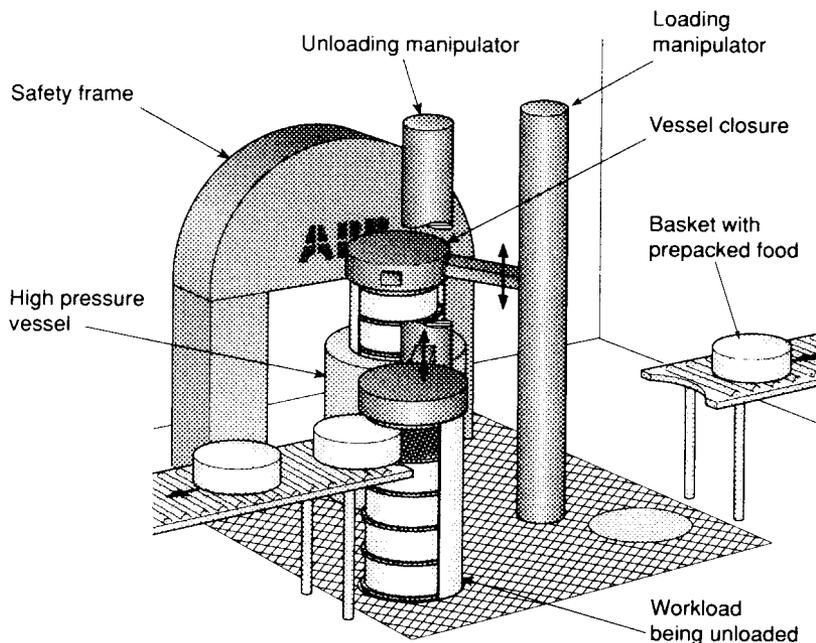


Fig. 9.3 Schematic drawing of a production unit for high pressure treatment at pressures between 400–800 MPa.
(From Olsson (1995).)

9.2.3 Effect on micro-organisms, enzymes and food components

Examples of the effect of high pressure treatments on micro-organisms are shown in Table 9.5. Germination of spores under high pressures is temperature dependent: near 0°C spores resist germination even at pressures of 1000 MPa, whereas at moderate temperatures, pressure induced germination can be achieved at 100 MPa. Germinated spores can be destroyed at a pressure of 600 MPa and a temperature of 50–70°C. However, these effects are not consistent and a combination of high pressure and moderate heating can have either synergistic or antagonistic effects on microbial growth, enzyme activity and chemical reactivity. For example high pressure can either make micro-organisms more sensitive to heat or it can prevent their destruction at higher temperatures, depending on the type of micro-organism being studied (Galazka and Ledward, 1995).

As fruit processing has so far been the main application of high pressure technology, many studies of enzyme inactivation are concerned with those enzymes that affect the quality of fruit products. For example polyphenoloxidase has been shown to resist pressures of up to 1200 MPa for 10 minutes before inactivation (Knorr, 1993), although it is more sensitive at higher pH levels. Hendrickx *et al.* (1998) report differences in polyphenoloxidase barosensitivity from different sources, with potato and mushroom polyphenoloxidase being very pressure stable (800–900 MPa required for inactivation), and more pressure sensitive enzymes from apricot, strawberry and grape (100, 400 and 600 MPa respectively). Pectinesterase is responsible for cloud destabilisation in juices, gelation of fruit concentrates and loss of consistency in tomato products. It is less resistant than polyphenoloxidase; its activity decreases above 300 MPa and it can be inactivated at pressures above 700 MPa at 45°C for 10 minutes. Orange pectin esterase is partially (90%) inactivated at 600 MPa at room temperature and does not reactivate during storage (Irwe and Olsson, 1994). Reviews of high pressure processing on enzymes and micro-organisms have been made by Balny *et al.* (1992), Mertens (1993) and Hayashi (1993).

The effects on microbial and enzyme activity of combined high pressures with low water activity, compressed or supercritical CO₂, pre-treatments with biopolymers (e.g. chitosan) or enzymes (e.g. lysozyme, glucose oxidase), ethanol, sodium sulphite, ultrasonic waves and high electric field pulses have also been studied and are reported in a number of reviews (Knorr, 1993; Balny *et al.*, 1992; Gould and Jones, 1989; Ledward *et al.*, 1995).

High pressure processing causes complex changes to the structure and reactivity of biopolymers such as starches and proteins. In proteins, the pressure causes unfolding of the molecular structure and then aggregation with either different proteins in a food or into a different form, resulting in changes to the texture of the food. Gel formation is

Table 9.5 Effect of high pressure treatments on selected micro-organisms

Micro-organism	Treatment conditions		Decimal reduction	Media
	MPa	Time (min)		
<i>Saccharomyces cerevisiae</i>	300	5	5	Satsuma mandarin juice
<i>Aspergillus awamori</i>	300	5	5	Satsuma mandarin juice
<i>Listeria innocua</i>	360	5	1	Minced beef muscle
<i>Listeria monocytogenes</i>	350	10	4	Phosphate buffer saline
<i>Vibrio parahaemolyticus</i>	172	10	2.5	Phosphate buffer saline
<i>Salmonella typhimurium</i>	345	10	1.8	Phosphate buffer
Total plate count	340	5	1.9	Fresh cut pineapple

Adapted from Palou *et al.* (1999).

observed in some proteins, such as soya, meat, fish and egg albumin. Compared to heat treated gels, pressure induced gels maintain their natural colour and flavour and are described as smooth, glossy and soft, and having greater elasticity. These results are being evaluated in relation to surimi products on an experimental scale. Research is also being undertaken to unfold the structure of lower quality proteins using high pressures to improve their functional properties (e.g. emulsifying and gelling capacity). The effects of high pressures on protein structure are described by Hendrickx *et al.* (1998) and Heremans (1995), and the effects on protein functionality have been reviewed by Messens *et al.* (1997) and Palou *et al.* (1999).

A further potential application of high pressure processing is the tenderisation of meat. Processing at 103 MPa and 40–60°C for 2.5 min improves the eating quality of meat and reduces cooking losses. The extent of tenderisation depends on all three factors involved: pressure, temperature and holding time. Commercially produced products include pressure-processed salted raw squid and fish sausages (Hayashi, 1995). Other possible applications are improved microbiological safety and elimination of cooked flavours from sterilised meats and pâté. These effects are reviewed by Johnston (1995).

Starch molecules are similarly opened and partially degraded, to produce increased sweetness and susceptibility to amylase activity. Other research has found that the appearance, odour, texture and taste of soybeans and rice did not change after processing, whereas root vegetables, including potato and sweet potato, became softer, more pliable, sweeter and more transparent (Galazka and Ledward, 1995). Fruit products are reported to retain the flavour, texture and colour of the fresh fruit. Other changes are described by Knorr (1995b).

Other applications include tempering chocolate, where the high pressures transform cocoa butter into the stable crystal form (Chapter 23), preservation of honey and other viscous liquids, seafoods, dairy products such as unpasteurised milk and mould ripened cheese.

9.3 Processing using pulsed light

The use of ultra-violet (UV) light to destroy micro-organisms is well documented (for example, Jagger, 1967; Koller, 1965; and Smith, 1977), particularly in relation to water purification, but also as bactericidal lamps used to prevent surface mould growth on bakery products, and for air purification. Details of the commercial applications of UV light are reviewed by Rahman (1999). However, a new technology, using pulsed white light that has a similar spectrum to sunlight, has been developed by a US company for the surface disinfection or sterilisation of foods and packaging materials. The information below is based on an article by Dunn *et al.* (1995), describing the development of the technology. The advantages and limitations of pulsed light, compared to other methods of minimal processing, are described in Table 9.2.

9.3.1 Theory

The antimicrobial effects of light at UV wavelengths are due to absorption of the energy by highly conjugated double carbon bonds in proteins and nucleic acids, which disrupts cellular metabolism. Pulsed light contains a broad spectrum of 'white' light, from UV wavelengths of 200 nm to infra-red wavelengths of 1000 nm with peak emissions between 400–500 nm (Fig. 9.4). This light is in the 'non-ionising' part of the

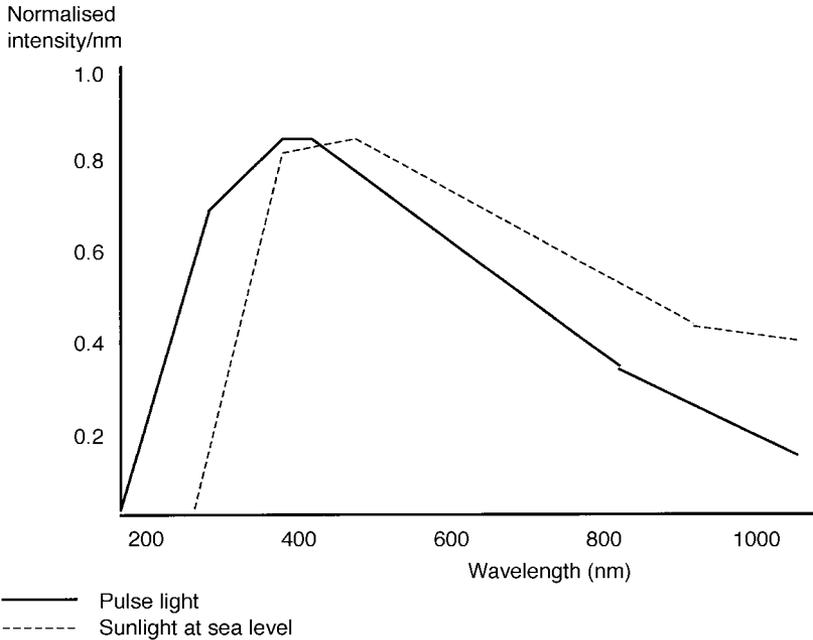


Fig. 9.4 A comparison of the wavelength distribution of pulsed light and sunlight. (From Dunn *et al.* (1995).)

electromagnetic spectrum (Fig. 18.1 in Chapter 18) and, in contrast to irradiation (Chapter 8), it does not cause ionisation of small molecules.

Pulsed light has a similar spectrum to sunlight, except that it also contains some UV wavelengths that are filtered out of sunlight by the earth's atmosphere. The light is produced in short, high intensity pulses that are approximately 20 000 times the intensity of sunlight (at sea level) and last for a few hundred microseconds. The energy imparted by the light to the surface of a food or packaging material is measure as 'fluence' and is often quoted in units of J cm^{-2} .

9.3.2 Equipment and operation

Electricity at normal mains voltage is used to charge capacitors, which then release the power within thousandths of a second to light an inert gas lamp. The intense burst of light in rapid pulses of tens per second is directed over the surface of the food or packaging material to be treated. As only a few pulses are needed for microbial destruction, this enables high product throughput rates to be achieved. The process is best suited to foods that have a smooth surface, and contain few fissures that could shield micro-organisms from the light.

9.3.3 Effect on micro-organisms and foods

Pulsed light inactivates micro-organisms by a combination of photothermal and photochemical effects. The UV component of light has a photochemical effect but as most of the energy is in the visual spectrum, the effect is mostly photothermal: that is a large amount of energy is transferred rapidly to the surface of the food, raising the

temperature of a thin surface layer sufficiently to destroy vegetative cells. Studies reported by Dunn *et al.* (1995) using inoculated agar plates, indicate that concentrations of 10^7 CFU¹ per gram of *Staphylococcus aureus* are destroyed by two pulses of 0.75 J cm^{-1} , giving a total fluence of 1.5 J cm^{-1} . Other pathogenic bacteria, including *Escherichia coli* O157:H7, *Listeria monocytogenes*, *Bacillus pumilus* and the mould *Aspergillus niger*, were each destroyed at concentrations of 10^5 CFU per gram using a single pulse of $0.5\text{--}1 \text{ J cm}^{-1}$ and decimal reductions of 7–9 logs (7-9D) were achieved by using a few flashes at 1 J cm^{-1} per pulse. When water was treated with pulsed light, it was found that oocysts of *Klebsiella* and *Cryptosporidium*, which are not affected by chlorination or traditional UV treatments, were reduced by 6–7 logs/ml by either two pulses of 0.5 J cm^{-1} or a single pulse of 1 J cm^{-1} .

When applied to foods, the shelf life of bread, cakes, pizza and bagels, packaged in clear film, was extended to eleven days at room temperature after treatment by pulsed light. Shrimps had an extension of shelf life to seven days under refrigeration and fresh meats had a 1–3 log reduction in total bacterial count, lactic, enteric and *Pseudomonas* counts. Preliminary studies indicated that the pulsed light treatment had no effect on the sensory characteristics or nutritional quality of treated foods. The lower levels of microbial destruction on foods, compared to those in water or on the smooth surfaces of agar plates or packaging materials is attributed to the presence of surface fissures and folds in foods that shield some of the micro-organisms from the light.

9.4 Processing using ultrasound

Ultrasound waves are similar to sound waves but have a frequency that is above 16 kHz and cannot be detected by the human ear. In nature, bats and dolphins use low-intensity ultrasound to locate prey, and some marine animals use high-intensity pulses of ultrasound to stun their prey. In food processing, a similar division is made between low-intensity ultrasound ($<1 \text{ W cm}^{-2}$), which is used as a non-destructive analytical method to assess the composition, structure or flow rate of foods (Chapter 2) and high-intensity ultrasound ($10\text{--}1000 \text{ W cm}^{-2}$) which is used at higher frequencies (up to 2.5 MHz) to cause physical disruption of tissues, create emulsions (Chapter 4), clean equipment (Chapter 26) or promote chemical reactions (e.g. oxidation). The advantages and limitations of ultrasonic waves as a method of processing, compared to other methods of minimal processing, are described in Table 9.2 and are reviewed by Earnshaw (1998).

9.4.1 Theory

When ultrasonic waves hit the surface of a material, they generate a force. If the force is perpendicular to the surface, it results in a compression wave that moves through the food, whereas if the force is parallel to the surface it produces a shearing wave. Both types of wave become attenuated as they move through the food. Ultrasound produces very rapid localised changes in pressure and temperature that cause shear disruption, ‘cavitation’ (creation of bubbles in liquid foods), thinning of cell membranes, localised heating and free radical production, which have a lethal effect on micro-organisms. Details of cavitation are given by Leighton (1998) and the physics of ultrasound are

1. CFU = colony forming units.

described by Suslick (1988). A review of the effects of ultrasound on micro-organisms is given by Sala *et al.* (1995), and McClements (1995) outlines more recent developments in the application of high-intensity ultrasound to food processing.

9.4.2 Application to processing

The shearing and compression effects of ultrasound cause denaturation of proteins that result in reduced enzyme activity, although short bursts of ultrasound may increase enzyme activity, possibly by breaking down large molecular structures and making the enzymes more accessible for reactions with substrates. The effects of ultrasound on meat proteins produce tenderisation in meat tissues after prolonged exposure, and the release of myofibrillar proteins that in meat products result in improved water binding capacity, tenderness and cohesiveness (McClements, 1995). However, despite these findings it is unlikely that ultrasonication will be used by itself for food preservation. This is because the resistance of most micro-organisms and enzymes to ultrasound is so high that the intensity of treatment would produce adverse changes to the texture and other physical properties of the food and substantially reduce its sensory characteristics.

The shear forces and rapidly changing pressures created by ultrasound waves are effective in destroying microbial cells, especially when combined with other treatments, including heating, pH modification and chlorination (Lillard, 1994). The mechanism of cell destruction and effects on different micro-organisms have been reviewed by Rahman (1999). A combined heat and ultrasound treatment under pressure, termed 'Mano-Thermo-Sonication' (MTS) is described by Sala *et al.* (1995). The initial studies indicated that the lethality of MTS treatments was 6–30 times greater than that of a corresponding heat treatment at the same temperature and was greater for yeasts than for bacterial spores. MTS effectiveness depended on the intensity, amplitude and time of ultrasonication and the applied pressure. The death rate resulting from MTS is logarithmic (Chapter 1) and is thus the same as for heat treatments. It is therefore likely that ultrasound reduces the heat resistance of micro-organisms by physical damage to cell structures, caused by extreme pressure changes, and disruption of cellular protein molecules. This makes them more sensitive to denaturation by heat. Similar changes to protein structures in enzymes may partly explain the synergistic effect of ultrasound and heat on enzyme inactivation (Sala *et al.*, 1995). There may thus be future applications for ultrasound to reduce the intensity of conventional heat treatments (e.g. thermosonication as a minimal pasteurisation process) and thus improve the sensory characteristics and nutritional properties of foods produced by traditional heat processes.

Rahman (1999) has also reviewed research into the use of ultrasound to assist drying and diffusion (*acoustic drying*). In some foods (for example gelatin, yeast and orange powder), the rates of drying are increased by two to three times. This is thought to be due both to the creation of microscopic channels in solid foods by the oscillating compression waves, and by changing the pressure gradient at the air/liquid interface, which increases the rate of evaporation. Acoustic drying has the potential to be an important operation because heat sensitive foods can be dried more rapidly and at a lower temperature than in conventional hot air driers (Chapter 15). Additionally, unlike high-velocity air drying, the food is not blown about or damaged by acoustic drying.

9.5 Other methods

Magnetic fields, having field strengths of 5–50 Tesla that are either stable or oscillating at 1 kHz to 10 MHz, are able to destroy vegetative cells. From studies conducted to date, there is no effect on spores or enzymes and some types of vegetative cells may be stimulated to grow. The effects of magnetic fields are not well understood, but may involve translocation of free radicals and disruption of cell membranes. These field strengths can only be achieved using liquid helium cooled coils and there may be safety concerns over the use of such powerful magnetic fields in a local processing environment. The advantages and limitations of this technology are summarised in Table 9.2 but it is not yet clear whether the technology will be developed into a viable commercial process.

Photodynamic systems involve the immobilisation of a photosensitive chemical onto a substrate such as a plastic packaging material, plastic equipment or work surface. This is then activated using natural or laser light to release a chemical preservative or sanitiser. At present there are 'active packaging' applications under development, described in more detail in Chapter 24.

9.6 References

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Part III

Processing by application of heat

Heat treatment remains one of the most important methods used in food processing, not only because of the desirable effects on eating quality (many foods are consumed in a cooked form and processes such as baking produce flavours that cannot be created by other means), but also because of the preservative effect on foods by the destruction of enzymes, micro-organisms, insects and parasites. The other main advantages of heat processing are:

1. relatively simple control of processing conditions
2. capability to produce shelf-stable foods that do not require refrigeration
3. destruction of anti-nutritional factors (e.g. trypsin inhibitor in some legumes)
4. improvement in the availability of some nutrients (e.g. improved digestibility of proteins, gelatinisation of starches and release of bound niacin).

However, heat also alters or destroys components of foods that are responsible for their individual flavour, colour, taste or texture and as a result they are perceived to have a lower quality and lower value. Fortunately the differences in D-values (Chapter 1) between these components and micro-organisms or enzymes can be exploited using higher temperatures and shorter times in heat processing. High-temperature short-time (HTST) processing can be designed to produce the same level of microbial or enzyme destruction at lower temperatures for longer times, but the sensory characteristics and nutritional value of foods is substantially retained. Developments in blanching (Chapter 10), pasteurisation (Chapter 11), heat sterilisation (Chapter 12), evaporation (Chapter 13) and dehydration (Chapter 15) have each focused on improved technology and better control of processing conditions to achieve higher quality products. Extrusion (Chapter 14) is by its nature a HTST process and other processes, including dielectric and ohmic heating (Chapter 18) are designed to cause minimal damage to the quality of foods.

Other more severe heat processes, including baking, roasting (Chapter 16) and frying (Chapter 17) are intended to change the sensory characteristics of a product, and preservation is achieved by either further processing (e.g. chilling or freezing, Chapters 19 and 21) or by selection of suitable packaging systems (Chapters 20, 24 and 25).

Another important effect of heating is the selective removal of volatile components from a food. In evaporation (Chapter 13) and dehydration (Chapter 15), the removal of water inhibits microbial growth and enzyme activity and thus achieves preservation. In distillation (Chapter 13) either alcohol is selectively removed to produce concentrated spirits, or flavour components are recovered and added back to foods to improve their sensory characteristics.

A. Heat processing using steam or water

10

Blanching

Blanching serves a variety of functions, one of the main ones being to destroy enzymic activity in vegetables and some fruits, prior to further processing. As such, it is not intended as a sole method of preservation but as a pre-treatment which is normally carried out between the preparation of the raw material (Chapter 3) and later operations (particularly heat sterilisation, dehydration and freezing (Chapters 12, 15 and 21)). Blanching is also combined with peeling and/or cleaning of food (Chapter 3), to achieve savings in energy consumption, space and equipment costs.

A few processed vegetables, for example onions and green peppers, do not require blanching to prevent enzyme activity during storage, but the majority suffer considerable loss in quality if blanching is omitted or if they are under-blanching. To achieve adequate enzyme inactivation, food is heated rapidly to a pre-set temperature, held for a pre-set time and then cooled rapidly to near ambient temperatures. The factors which influence blanching time are:

- type of fruit or vegetable
- size of the pieces of food
- blanching temperature
- method of heating.

10.1 Theory

The theory of unsteady-state heat transfer by conduction and convection, which is used to calculate blanching time, and a sample problem (Sample problem 1.7) are described in Chapter 1.

The maximum processing temperature in freezing and dehydration is insufficient to inactivate enzymes. If the food is not blanched, undesirable changes in sensory characteristics and nutritional properties take place during storage. In canning, the time taken to reach sterilising temperatures, particularly in large cans, may be sufficient to allow enzyme activity to take place. It is therefore necessary to blanch foods prior to

these preservation operations. Under-blanching may cause more damage to food than the absence of blanching does, because heat, which is sufficient to disrupt tissues and release enzymes, but not inactivate them, causes accelerated damage by mixing the enzymes and substrates. In addition, only some enzymes may be destroyed which causes increased activity of others and accelerated deterioration.

The heat resistance of enzymes is characterised by D and z values (Chapter 1). Enzymes which cause a loss of eating and nutritional qualities in vegetables and fruits include lipoxygenase, polyphenoloxidase, polygalacturonase and chlorophyllase. Two heat-resistant enzymes which are found in most vegetables are catalase and peroxidase. Although they do not cause deterioration during storage, they are used as marker enzymes to determine the success of blanching. Peroxidase is the more heat resistant of the two, so the absence of residual peroxidase activity would indicate that other less heat-resistant enzymes are also destroyed. The factors that control the rate of heating at the centre of the product are discussed in Chapter 1 and can be summarised as:

- the temperature of the heating medium
- the convective heat transfer coefficient
- the size and shape of the pieces of food
- the thermal conductivity of the food.

Blanching reduces the numbers of contaminating micro-organisms on the surface of foods and hence assists in subsequent preservation operations. This is particularly important in heat sterilisation (Chapter 12), as the time and temperature of processing are designed to achieve a specified reduction in cell numbers. If blanching is inadequate, a larger number of micro-organisms are present initially and this may result in a larger number of spoiled containers after processing. Freezing and drying do not substantially reduce the number of micro-organisms in unblanched foods and these are able to grow on thawing or rehydration.

Blanching also softens vegetable tissues to facilitate filling into containers and removes air from intercellular spaces which increases the density of food and assists in the formation of a head-space vacuum in cans (Chapters 12 and 25).

10.2 Equipment

The two most widespread commercial methods of blanching involve passing food through an atmosphere of saturated steam or a bath of hot water. Both types of equipment are relatively simple and inexpensive. Microwave blanching is not yet used commercially on a large scale. It is discussed further in Chapter 18. There have been substantial developments to blanchers in recent years to reduce the energy consumption and also to reduce the loss of soluble components of foods, which reduces the volume and polluting potential of effluents (Chapter 26) and increases the yield of product.

The yield¹ of food from the blanching operation is the most important factor in determining the commercial success of a particular method. In some methods the cooling stage may result in greater losses of product or nutrients than the blanching stage, and it is therefore important to consider both blanching and cooling when comparing different methods. Steam blanching results in higher nutrient retention provided that cooling is by cold-air or cold-water sprays. Cooling with running water (fluming) substantially

1. Weight of food after processing compared to the weight before processing.

increases leaching losses,² but the product may gain weight by absorbing water and the overall yield is therefore increased. Air cooling causes weight loss of the product due to evaporation, and this may outweigh any advantages gained by nutrient retention (Bomben *et al.*, 1975).

There are also substantial differences in yield and nutrient retention due to differences in the type of food and differences in the method of preparation (for example slicing and peeling (Chapter 3) increase losses and reduce the yield).

Recycling of water does not affect the product quality or yield but substantially reduces the volume of effluent produced. However, it is necessary to ensure adequate hygienic standards for both the product and equipment by preventing a build-up of bacteria in cooling water, and the improved hygiene control may result in additional costs which outweigh savings in energy and higher product yield.

10.2.1 Steam blanchers

The advantages and limitations of steam blanchers are described in Table 10.1. In general this is the preferred method for foods with a large area of cut surfaces as leaching losses are much smaller than those found using hot-water blanchers.

At its simplest a steam blancher consists of a mesh conveyor belt that carries food through a steam atmosphere in a tunnel. The residence time of the food is controlled by the speed of the conveyor and the length of the tunnel. Typically a tunnel is 15 m long and 1–1.5 m wide. The efficiency of energy consumption is 19% when water sprays are used at the inlet and outlet to condense escaping steam. Alternatively, food may enter and leave the blancher through rotary valves or hydrostatic seals to reduce steam losses and increase energy efficiency to 27%, or steam may be re-used by passing through Venturi valves. Energy efficiency is improved to 31% using combined hydrostatic and Venturi devices (Scott *et al.*, 1981).

In conventional steam blanching, there is often poor uniformity of heating in the multiple layers of food. The time–temperature combination required to ensure enzyme inactivation at the centre of the bed results in overheating of food at the edges and a consequent loss of texture and other sensory characteristics. Individual quick blanching

Table 10.1 Advantages and limitations of conventional steam and hot-water blanchers

Equipment	Advantages	Limitations
Conventional steam blanchers	Smaller loss of water-soluble components. Smaller volumes of waste and lower disposal charges than water blanchers, particularly with air cooling instead of water. Easy to clean and sterilise	Limited cleaning of the food so washers also required. Uneven blanching if the food is piled too high on the conveyor. Some loss of mass in the food.
Conventional hot-water blancher	Lower capital cost and better energy efficiency than steam blanchers	Higher costs in purchase of water and charges for treatment of large volumes of dilute effluent (Chapter 26). Risk of contamination by thermophilic bacteria.

2. Washing of soluble components from the food.

(IQB) which involves blanching in two stages, was developed to overcome this problem (Lazar *et al.*, 1971). In the first stage the food is heated in a single layer to a sufficiently high temperature to inactivate enzymes. In the second stage (termed *adiabatic holding*) a deep bed of food is held for sufficient time to allow the temperature at the centre of each piece to increase to that needed for enzyme inactivation. The reduced heating time (for example 25 s for heating and 50 s for holding 1 cm diced carrot compared with 3 min for conventional blanching), results in an improvement in the efficiency of energy consumption to 86–91% (Cumming *et al.*, 1984). The mass of product blanched per kilogram of steam increases from 0.5 kg per kilogram of steam in conventional steam blanchers to 6–7 kg per kilogram of steam, when small-particulate foods (for example peas, sliced or diced carrots) are blanched.

Nutrient losses during steam blanching are reduced by exposing the food to warm air (65°C) in a short preliminary drying operation (termed '*pre-conditioning*'). Surface moisture evaporates and the surfaces then absorb condensing steam during IQB. Weight losses are reduced to 5% of those found using conventional steam blanching (Lazar *et al.*, 1971). Pre-conditioning and individual quick blanching are reported to reduce nutrient losses by 81% for green beans, by 75% for Brussels sprouts, by 61% for peas and by 53% for lima beans and there is no reduction in the yield of blanched food (Bomben *et al.*, 1973).

The equipment for IQB steam blanching (Fig. 10.1(a)) consists of a bucket elevator which carries the food to a heating section. The elevator is located in a close fitting tunnel to reduce steam losses. A single layer of food is heated on a conveyor belt and then held on a holding elevator before cooling. The cooling section employs a fog spray to saturate the cold air with moisture. This reduces evaporative losses from the food and reduces the amount of effluent produced. Typically the equipment processes up to 4500 kg h⁻¹ of food. The complete inactivation of peroxidase is achieved with a minimum loss in quality, indicated by the retention of 76–85% of ascorbic acid.

Batch *fluidised-bed blanchers* operate using a mixture of air and steam, moving at approximately 4.5 m s⁻¹, which fluidises and heats the product simultaneously. The design of the blanching chamber promotes continuous and uniform circulation of the food until it is adequately blanched. Although these blanchers have not yet been widely used at a commercial scale, they are reported to overcome many of the problems associated with both steam and hot-water methods (Gilbert *et al.*, 1980). The advantages include:

- faster, more uniform heating
- good mixing of the product
- a substantial reduction in the volume of effluent
- shorter processing times and hence smaller losses of vitamins and other soluble heat sensitive components of food.

A continuous fluidised-bed blancher is described by Philippon (1984).

10.2.2 Hot-water blanchers

There are a number of different designs of blancher, each of which holds the food in hot water at 70–100°C for a specified time and then removes it to a dewatering-cooling section. The advantages and limitations of hot-water blanchers are described in Table 10.1.

In the widely used *reel blancher*, food enters a slowly rotating cylindrical mesh drum which is partly submerged in hot water. The food is moved through the drum by internal flights. The speed of rotation and length control the heating time. *Pipe blanchers* consist

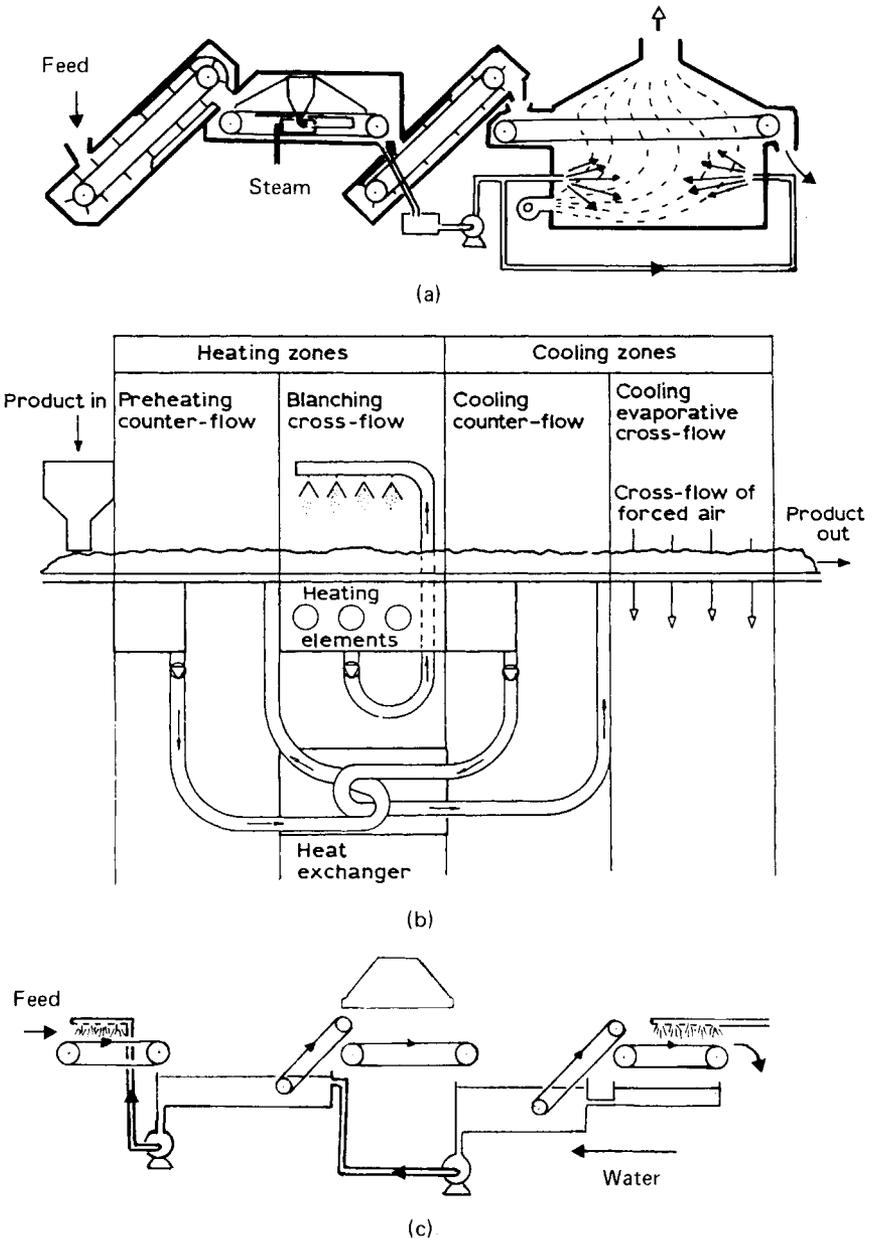


Fig. 10.1 Blanchers: (a) IQB steam blancher (after Timbers *et al.* (1984)); (b) blancher-cooler (from Hallstrom *et al.* (1988)) and (c) counter-current blancher (after Wendt *et al.* (1983)).

of a continuous insulated metal pipe fitted with feed and discharge ports. Hot water is recirculated through the pipe and food is metered in. The residence time of food in the blancher is determined by the length of the pipe and the velocity of the water. These blanchers have the advantage of a large capacity while occupying a small floor space. In some applications they may be used to transport food simultaneously through a factory.

Developments in hot-water blanchers, based on the IQB principle, reduce energy consumption and minimise the production of effluent. For example, the *blancher-cooler*

has three sections: a pre-heating stage, a blanching stage and a cooling stage (Fig. 10.1(b)). The food remains on a single conveyor belt throughout each stage and therefore does not suffer the physical damage associated with the turbulence of conventional hot-water blanchers. The food is pre-heated with water that is recirculated through a heat exchanger. After blanching, a second recirculation system cools the food. The two systems pass water through the same heat exchanger, and this heats the pre-heat water and simultaneously cools the cooling water. Up to 70% of the heat is recovered. A recirculated water-steam mixture is used to blanch the food, and final cooling is by cold air. Effluent production is negligible and water consumption is reduced to approximately 1 m^3 per 10t of product. The mass of product blanched is 16.7–20 kg per kilogram of steam, compared with 0.25–0.5 kg per kilogram in conventional hot-water blanchers. An alternative design, used for blanching broccoli, lima beans, spinach and peas, is described by Wendt *et al.* (1983) in which water and food move counter-currently (Fig. 10.1(c)).

10.3 Effect on foods

The heat received by a food during blanching inevitably causes some changes to sensory and nutritional qualities. However, the heat treatment is less severe than for example in heat sterilisation (Chapter 12), and the resulting changes in food quality are less pronounced. In general, the time–temperature combination used for blanching is a compromise which ensures adequate enzyme inactivation but prevents excessive softening and loss of flavour in the food (Fig. 10.2).

10.3.1 Nutrients

Some minerals, water-soluble vitamins and other water-soluble components are lost during blanching. Losses of vitamins are mostly due to leaching, thermal destruction and, to a lesser extent, oxidation. The extent of vitamin loss depends on a number of factors including:

- the maturity of the food and variety
- methods used in preparation of the food, particularly the extent of cutting, slicing or dicing

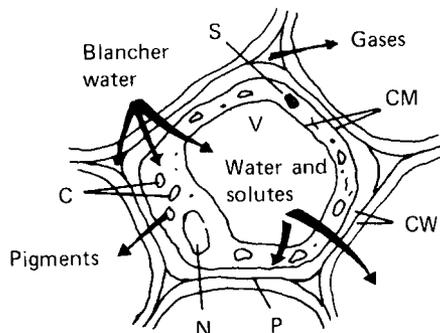


Fig. 10.2 Effect of blanching on cell tissues: S, starch gelatinised; CM, cytoplasmic membranes altered; CW, cell walls little altered; P, pectins modified; N, nucleus and cytoplasmic proteins denatured; C, chloroplasts and chromoplasts distorted.

Table 10.2 Effect of blanching method on ascorbic acid losses in selected vegetables

Treatment	Loss (%) of ascorbic acid		
	Peas	Broccoli	Green beans
Water blanch–water cool	29.1	38.7	15.1
Water blanch–air cool	25.0	30.6	19.5
Steam blanch–water cool	24.2	22.2	17.7
Steam blanch–air cool	14.0	9.0	18.6

Differences in both steam versus water blanching and air versus water cooling are significant at the 5% level. Adapted from Cumming *et al.* (1981).

- the surface-area-to-volume ratio of the pieces of food
- method of blanching
- time and temperature of blanching (lower vitamin losses at higher temperatures for shorter times)
- the method of cooling
- the ratio of water to food (in both water blanching and cooling).

Losses of ascorbic acid are used as an indicator of food quality, and therefore the severity of blanching (Table 10.2).

10.3.2 Colour and flavour

Blanching brightens the colour of some foods by removing air and dust on the surface and thus altering the wavelength of reflected light. The time and temperature of blanching also influence the change in food pigments according to their *D* value (Chapter 1). Sodium carbonate (0.125% w/w) or calcium oxide are often added to blancher water to protect chlorophyll and to retain the colour of green vegetables, although the increase in pH may increase losses of ascorbic acid. Enzymic browning of cut apples and potatoes is prevented by holding the food in dilute (2% w/w) brine prior to blanching. When correctly blanched, most foods have no significant changes to flavour or aroma, but under-blanching can lead to the development of off-flavours during storage of dried or frozen foods (Chapters 15 and 21). Changes in colour and flavour are described in more detail by Selman (1987).

10.3.3 Texture

One of the purposes of blanching is to soften the texture of vegetables to facilitate filling into containers prior to canning. However, when used for freezing or drying, the time–temperature conditions needed to achieve enzyme inactivation cause an excessive loss of texture in some types of food (for example certain varieties of potato) and in large pieces of food. Calcium chloride (1–2%) is therefore added to blancher water to form insoluble calcium pectate complexes and thus to maintain firmness in the tissues.

10.4 Acknowledgement

Grateful acknowledgement is made for information supplied by Reekcroft Ltd, Epworth, South Yorkshire DN9 1EP, UK.

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11

Pasteurisation

Pasteurisation is a relatively mild heat treatment, in which food is heated to below 100°C. In low acid foods (pH > 4.5, for example milk) it is used to minimise possible health hazards from pathogenic micro-organisms and to extend the shelf life of foods for several days. In acidic foods (pH < 4.5, for example bottled fruit) it is used to extend the shelf life for several months by destruction of spoilage micro-organisms (yeasts or moulds) and/or enzyme inactivation (Table 11.1). In both types of food, minimal changes are caused to the sensory characteristics or nutritive value.

Processing containers of food, either which have a naturally low pH (for example fruit pieces) or in which the pH is artificially lowered (for example pickles) is similar to canning (Chapter 12). It is often termed *pasteurisation* to indicate the mild heat treatment employed. In this chapter the pasteurisation of liquid foods either packaged in containers or unpackaged, using heat exchangers is described.

11.1 Theory

The sensible heat required to raise the temperature of a liquid during pasteurisation is found using:

$$Q = mc(\theta_A - \theta_B) \quad \boxed{11.1}$$

where Q (W) = specific rate of heat transfer, m (kg s⁻¹) = mass flow rate, c (kJ kg⁻¹ °C⁻¹) = specific heat capacity and $(\theta_A - \theta_B)$ (°C) = temperature change. Sample problems of heat transfer during pasteurisation are given in Chapter 1 (Sample problems 1.7 and 1.8) and in Section 11.2.2.

The extent of the heat treatment required to stabilise a food is determined by the D value of the most heat-resistant enzyme or micro-organism which may be present (Chapter 1). For example milk pasteurisation is based on D_{60} and a 12 logarithmic cycle reduction in the numbers of *C. burnetii* (Harper, 1976), and liquid whole egg is treated to produce a $9D$ reduction in numbers of *S. seftenberg* (Hammid-Samimi and Swartzel, 1984). As flavours, colours and vitamins are also characterised by D values, pasteurisation

Table 11.1 Purpose of pasteurisation for different foods

Food	Main purpose	Subsidiary purpose	Minimum processing conditions ^a
<i>pH</i> < 4.5			
Fruit juice	Enzyme inactivation (pectinesterase and polygalacturonase)	Destruction of spoilage micro-organisms (yeasts, fungi)	65°C for 30 min; 77°C for 1 min; 88°C for 15 s
Beer	Destruction of spoilage micro-organisms (wild yeasts, <i>Lactobacillus</i> species), and residual yeasts (<i>Saccharomyces</i> species)	–	65–68°C for 20 min (in bottle); 72–75°C for 1–4 min at 900–1000 kPa
<i>pH</i> > 4.5			
Milk	Destruction of pathogens: <i>Brucella abortus</i> , <i>Mycobacterium tuberculosis</i> , (<i>Coxiella burnetii</i>) ^b	Destruction of spoilage micro-organisms and enzymes	63°C for 30 min; 71.5°C for 15 s
Liquid egg	Destruction of pathogens <i>Salmonella seftenburg</i>	Destruction of spoilage micro-organisms	64.4°C for 2.5 min 60°C for 3.5 min
Ice cream	Destruction of pathogens	Destruction of spoilage micro-organisms	65°C for 30 min; 71°C for 10 min; 80°C for 15 s

^a Followed by rapid cooling to 3–7°C.

^b Rickettsia organism which causes Q fever.

Adapted from Fricker (1984), Wiggins and Barclay (1984), Lund (1975) and Hammid-Samimi and Swartzel (1984).

conditions can be optimised for retention of nutritional and sensory quality by the use of high-temperature short-time (HTST) conditions. For example in milk processing the lower-temperature longer-time process operating at 63°C for 30 min (the *holder* process) causes greater changes to flavour and a slightly greater loss of vitamins than HTST processing at 71.8°C for 15 s (Table 11.2) and it is less often used. Higher temperatures and shorter times (for example 88°C for 1 s, 94°C for 0.1 s or 100°C for 0.01 s for milk) are described as higher-heat shorter-time processing or ‘flash pasteurisation’.

Alkaline phosphatase is a naturally occurring enzyme in raw milk which has a similar *D* value to heat-resistant pathogens (Fig. 11.1). The direct estimation of pathogen numbers by microbiological methods is expensive and time consuming, and a simple test for phosphatase activity is therefore routinely used. If phosphatase activity is found, it is assumed that the heat treatment was inadequate to destroy the pathogenic bacteria or that unpasteurised milk has contaminated the pasteurised product. A similar test for the effectiveness of liquid-egg pasteurisation is based on residual α -amylase activity (Brooks, 1962).

11.2 Equipment

11.2.1 Pasteurisation of packaged foods

Some liquid foods (for example beers and fruit juices) are pasteurised after filling into containers. Hot water is normally used if the food is packaged in glass, to reduce the

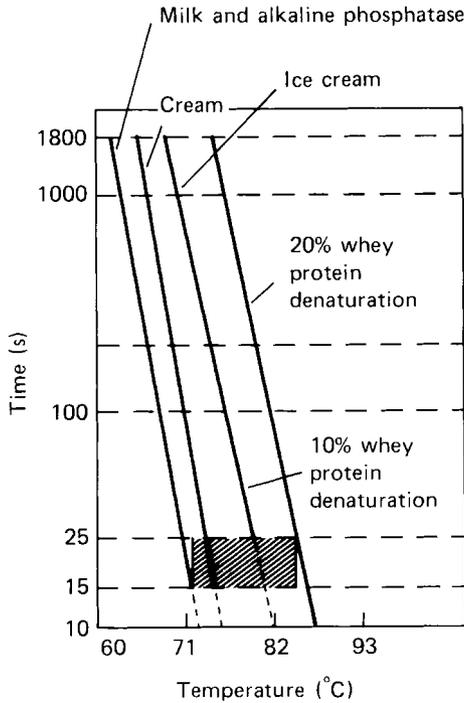


Fig. 11.1 Time-temperature relationships for pasteurisation. The hatched area shows the range of times and temperatures used in commercial milk pasteurisation. (After Harper (1976).)

risk of thermal shock to the container (fracture caused by rapid changes in temperature). Maximum temperature differences between the container and water are 20°C for heating and 10°C for cooling. Metal or plastic containers are processed using steam-air mixtures or hot water as there is little risk of thermal shock. In all cases the food is cooled to approximately 40°C to evaporate surface water and therefore to minimise external corrosion to the container or cap, and to accelerate setting of label adhesives. Hot-water pasteurisers may be batch or continuous in operation. The simplest batch equipment consists of a water bath in which crates of packaged food are heated to a pre-set temperature and held for the required length of time. Cold water is then pumped in to cool the product. A continuous version consists of a long narrow trough fitted with a conveyor belt to carry containers through heating and cooling stages.

A second design consists of a tunnel divided into a number of heating zones. Very fine (atomised) water sprays heat the containers as they pass through each zone on a conveyor, to give incremental rises in temperature until pasteurisation is achieved. Water sprays then cool the containers as they continue through the tunnel. Savings in energy and water consumption are achieved by recirculation of water between pre-heat sprays, where it is cooled by the incoming food, and cooling zones where it is heated by the hot products (Anon., 1982). Steam tunnels have the advantage of faster heating, giving shorter residence times, and smaller equipment. Temperatures in the heating zones are gradually increased by reducing the amount of air in the steam-air mixtures. Cooling takes place using fine sprays of water or by immersion in a water bath.

11.2.2 Pasteurisation of unpackaged liquids

Swept surface heat exchangers (Barclay *et al.*, 1984) or open boiling pans (Chapter 13) are used for small-scale batch pasteurisation of some liquid foods. However, the large-scale pasteurisation of low viscosity liquids (for example milk, milk products, fruit juices, liquid egg, beers and wines) usually employs plate heat exchangers. Some products (for example fruit juices, wines) also require de-aeration to prevent oxidative changes during storage. They are sprayed into a vacuum chamber and dissolved air is removed by a vacuum pump, prior to pasteurisation.

The *plate heat exchanger* (Fig. 11.2) consists of a series of thin vertical stainless steel plates, held tightly together in a metal frame. The plates form parallel channels, and liquid food and heating medium (hot water or steam) are pumped through alternate channels, usually in a counter-current flow pattern (Fig. 11.3). Each plate is fitted with a synthetic rubber gasket to produce a watertight seal and to prevent mixing of the product

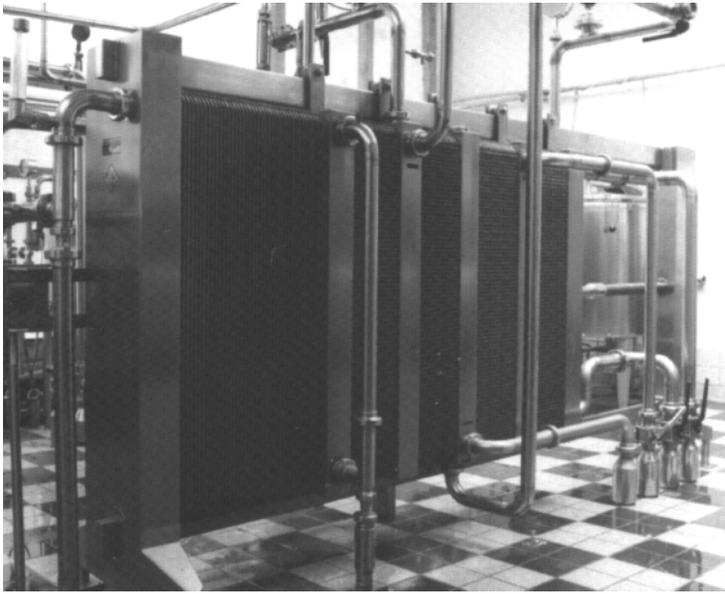


Fig. 11.2 Plate heat exchanger.
(Courtesy of Wincanton Engineering Ltd.)

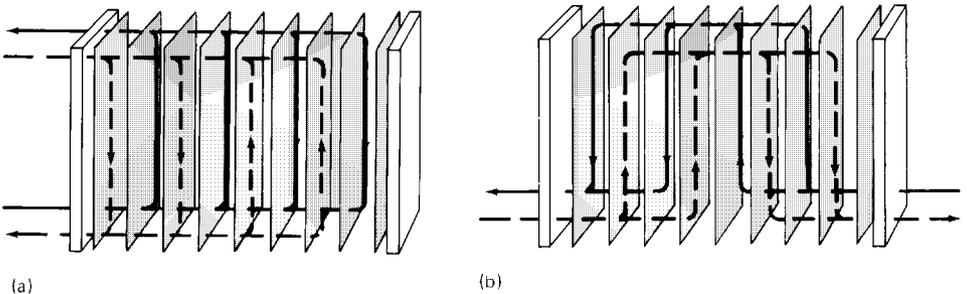


Fig. 11.3 Counter-current flow through plate heat exchanger: (a) one pass with four channels per medium; (b) two passes with two channels per pass and per medium.
(Courtesy of HRS Heat Exchangers Ltd.)

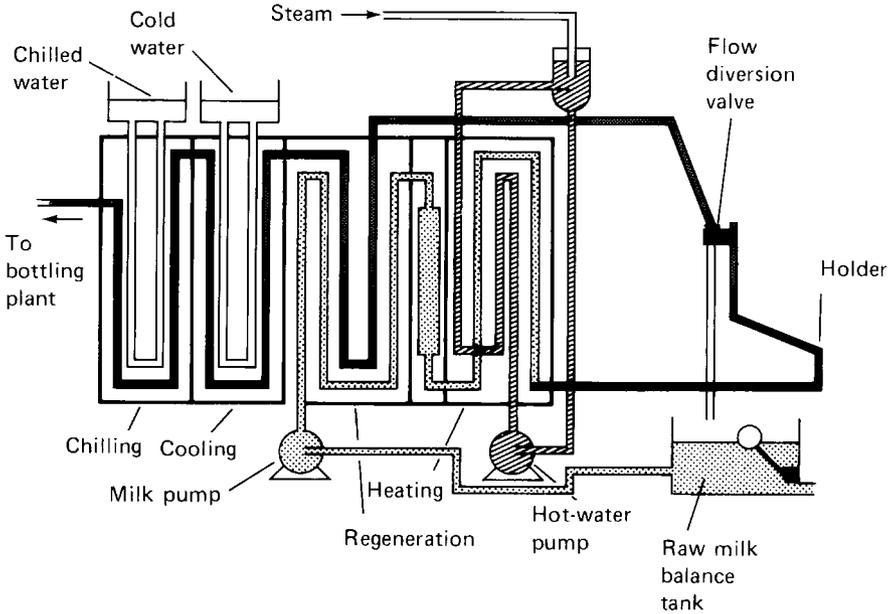


Fig. 11.4 Pasteurising using a plate heat exchanger.
(Courtesy of APV Ltd.)

and the heating and cooling media. The plates are corrugated to induce turbulence in the liquids and this, together with the high velocity induced by pumping, reduces the thickness of boundary films (Chapter 1) to give high heat transfer coefficients ($3000\text{--}11\,500\text{ W m}^{-2}\text{ K}^{-1}$). The capacity of the equipment varies according to the size and number of plates, up to $80\,000\text{ h}^{-1}$.

In operation (Fig. 11.4), food is pumped from a balance tank to a ‘regeneration’ section, where it is pre-heated by food that has already been pasteurised. It is then heated to pasteurising temperature in a heating section and held for the time required to achieve pasteurisation in a holding tube. If the pasteurising temperature is not reached, a flow diversion valve automatically returns the food to the balance tank to be repasteurised. The pasteurised product is then cooled in the regeneration section (and simultaneously pre-heats incoming food) and then further cooled by cold water and, if necessary, chilled water in a cooling section.

The regeneration of heat in this way leads to substantial savings in energy and up to 97% of the heat can be recovered. Heat recovery is calculated using:

$$\text{heat recovery (\%)} = \frac{\theta_2 - \theta_1}{\theta_3 - \theta_1} \times 100 \quad \boxed{11.2}$$

where θ_1 (°C) = inlet temperature, θ_2 (°C) = pre-heating temperature and θ_3 (°C) = pasteurisation temperature.

The advantages of heat exchangers over in-bottle processing include:

- more uniform heat treatment
- simpler equipment and lower maintenance costs
- lower space requirements and labour costs
- greater flexibility for different products
- greater control over pasteurisation conditions.

Sample problem 11.1

Raw whole milk at 7°C is to be pasteurised at 72°C in a plate heat exchanger at a rate of 5000 l h⁻¹ and then cooled to 4.5°C. The hot water is supplied at 7500 l h⁻¹ at 85°C and chilled water has a temperature of 2°C. Each heat exchanger plate has an available area of 0.79 m². The overall heat transfer coefficients are calculated as 2890 W m⁻² K⁻¹ in the heating section, 2750 W m⁻² K⁻¹ in the cooling section and 2700 W m⁻² K⁻¹ in the regeneration section (see Chapter 1, Sample problem 1.8). 75% of the heat exchange is required to take place in the regeneration section. Calculate the number of plates required in each section. (Assume that the density of milk is 1030 kg m⁻³, the density of water is 958 kg m⁻³ at 85°C and 1000 kg m⁻³ at 2°C, the specific heat of water is constant at 4.2 kJ kg⁻¹ K⁻¹ and the specific heat of milk is constant at 3.9 kJ kg⁻¹ K.)

Solution to Sample problem 11.1

To calculate the number of plates in each section, 1 litre = 0.001 m³; therefore the volumetric flow rate of milk is 5/3600 = 1.39 × 10⁻³ m³ s⁻¹ and the volumetric flow rate of hot water is 7.5/3600 = 2.08 × 10⁻³ m³ s⁻¹. From equation (11.1),

$$\begin{aligned} \text{heat required to heat milk to } 72^\circ\text{C} \\ &= 1.39 \times 10^{-3} \times 1030 \times 3900 (72 - 7) \\ &= 3.63 \times 10^5 \text{ W} \end{aligned}$$

For the regeneration stage,

$$\begin{aligned} \text{heat supplied} &= 75\% \text{ of } 3.63 \times 10^5 \\ &= 2.72 \times 10^5 \text{ W} \end{aligned}$$

and

$$\begin{aligned} \text{temperature change of the milk} &= 75\% \text{ of } (72 - 7) \\ &= 48.75^\circ\text{C} \end{aligned}$$

Therefore the cold milk leaves the regeneration section at 48.75 + 7 = 55.75°C and the hot milk is cooled in the regeneration section to 72 - 48.75 = 23.25°C. The temperature difference across the heat exchanger plates is 72 - 55.75 = 16.25°C.

From equation (1.22) ($Q = UA(\theta_a - \theta_b)$),

$$A = \frac{2.72 \times 10^5}{2700 \times 16.25} = 6.2 \text{ m}^2$$

As each plate area is 0.79 m²,

$$\begin{aligned} \text{number of plates} &= \frac{6.2}{0.79} \\ &= 7.8 \approx 8 \end{aligned}$$

In the heating stage,

$$\begin{aligned} Q = 25\% \text{ of total heat supplied} &= 3.63 \times 10^5 \times 0.25 \\ &= 9.1 \times 10^4 \text{ W} \end{aligned}$$

From equation (11.1), for hot water,

$$\begin{aligned}\theta_A - \theta_B &= \frac{9.1 \times 10^4}{2.08 \times 10^{-3} \times 958 \times 4200} \\ &= 10.85^\circ\text{C} \\ &= 11^\circ\text{C}\end{aligned}$$

The temperature of the hot water leaving the heating section is $85 - 11 = 74^\circ\text{C}$. The temperature of the milk entering the heating section is 55.75°C and the temperature of the milk after heating is 72°C .

From equation (1.23) (log mean temperature difference),

$$\begin{aligned}\Delta\theta_m &= \frac{(74 - 55.75) - (85 - 72)}{\ln[(74 - 55.75)/(85 - 72)]} \\ &= 15.44^\circ\text{C}\end{aligned}$$

From equation (1.22),

$$\begin{aligned}A &= \frac{9.1 \times 10^4}{2890 \times 15.44} \\ &= 2.04 \text{ m}^2\end{aligned}$$

Therefore,

$$\begin{aligned}\text{number of plates} &= \frac{2.04}{0.79} \\ &= 3\end{aligned}$$

For the cooling stage, for milk, from equation (11.1),

$$\begin{aligned}Q &= 1.39 \times 10^{-3} \times 1030 \times 3900 (23.25 - 4.5) \\ &= 1.046 \times 10^5 \text{ W}\end{aligned}$$

From equation (1.23),

$$\begin{aligned}\Delta\theta_m &= \frac{(23.25 - 4.5) - (4.5 - 2)}{\ln[(23.25 - 4.5)/(4.5 - 2)]} \\ &= 8.06^\circ\text{C}\end{aligned}$$

From equation (1.22),

$$\begin{aligned}A &= \frac{1.046 \times 10^5}{2750 \times 8.06} \\ &= 4.72 \text{ m}^2\end{aligned}$$

Therefore,

$$\begin{aligned}\text{number of plates} &= \frac{4.72}{0.79} \\ &= 6\end{aligned}$$

Other types of heat exchanger are also used for pasteurisation. In particular, the concentric tube heat exchanger is suitable for more viscous foods and is used with dairy products, mayonnaise, tomato ketchup and baby foods. It consists of a number of concentric stainless steel coils, each made from double- or triple-walled tube. Food passes through the tube, and heating or cooling water is recirculated through the tube walls. Liquid food is passed from one coil to the next for heating and cooling, and heat is regenerated to reduce energy costs.

Pasteurised food is immediately filled into cartons or bottles (Chapters 24 and 25) and sealed to prevent recontamination. Significant levels of spoilage and risks from pathogens can arise from post-pasteurisation contamination, particularly when foods (for example milk) are not re-heated before consumption, and great care with cleaning and hygiene is therefore necessary (also Chapter 26). Products should then be stored at refrigerated temperature until consumption.

11.3 Effect on foods

Pasteurisation is a relatively mild heat treatment and even when combined with other unit operations (for example irradiation (Chapter 8) and chilling (Chapter 19)) there are only minor changes to the nutritional and sensory characteristics of most foods. However, the shelf life of pasteurised foods is usually only extended by a few days or weeks compared with many months with the more severe heat sterilisation (Chapter 12). Minimising post-processing contamination is essential to ensure an adequate shelf life.

11.3.1 Colour, flavour and aroma

In fruit juices the main cause of colour deterioration is enzymic browning by polyphenoloxidase. This is promoted by the presence of oxygen, and fruit juices are therefore routinely deaerated prior to pasteurisation. The difference between the whiteness of raw milk and that of pasteurised milk is due to homogenisation, and pasteurisation alone has no measurable effect. Other pigments in plant and animal products are also mostly unaffected by pasteurisation. A small loss of volatile aroma compounds during pasteurisation of juices causes a reduction in quality and may also unmask other 'cooked' flavours. Volatile recovery (Chapter 13) may be used to produce high quality juices but this is not routinely used, due to the high cost. Loss of volatiles from raw milk removes a hay-like aroma and produces a blander product.

11.3.2 Vitamin loss

In fruit juices, losses of vitamin C and carotene are minimised by deaeration. Changes to milk are confined to a 5% loss of serum proteins and small changes to the vitamin content (Table 11.2). Changes to nutritional quality during storage of pasteurised milk are discussed by Schroder *et al.* (1985), Allen and Joseph (1985) and Harper (1976).

Table 11.2 Vitamin losses during pasteurisation of milk

Vitamin	Method of pasteurisation	
	HTST	Holder
Vitamin A		
Vitamin D		
Riboflavin		
Vitamin B ₆	0	0
Pantothenic acid		
Nicotinic acid		
Biotin		
Folic acid		
Thiamin	6.8	10
Vitamin C	10	20
Vitamin B ₁₂	0	10

From Ford *et al.* (1969).

11.4 Acknowledgements

Grateful acknowledgement is made for information supplied by the following: Wincanton Engineering Ltd, Sherborne, Dorset DT9 3ND, UK; HRS Heat Exchangers Ltd, Watford, Hertfordshire WD1 2DW, UK; APV International Ltd, Crawley, West Sussex RH10 2QB, UK; De Laval Separator Co, USA.

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12

Heat sterilisation

Heat sterilisation is the unit operation in which foods are heated at a sufficiently high temperature and for a sufficiently long time to destroy microbial and enzyme activity. As a result, sterilised foods have a shelf life in excess of six months at ambient temperatures. The severe heat treatment during the older process of in-container sterilisation (canning) may produce substantial changes in nutritional and sensory qualities of foods. Developments in processing technology therefore aim to reduce the damage to nutrients and sensory components, by either reducing the time of processing in containers or processing foods before packaging (aseptic processing). More recent developments, including ohmic heating, are described in Chapter 18. The theory of thermal destruction of micro-organisms and the effect of heat on nutrients and sensory components of foods is described in Chapter 1. In this chapter the effects of microbial heat resistance on the design of heat sterilisation procedures and equipment are described, first for in-container heat sterilisation and then for ultra high-temperature (UHT) processes.

12.1 In-container sterilisation

12.1.1 Theory

The length of time required to sterilise a food is influenced by:

- the heat resistance of micro-organisms or enzymes likely to be present in the food
- the heating conditions
- the pH of the food
- the size of the container
- the physical state of the food.

In order to determine the process time for a given food, it is necessary to have information about both the heat resistance of micro-organisms, particularly heat resistant spores, or enzymes that are likely to be present and the rate of heat penetration into the food.

Heat resistance of micro-organisms

The factors that influence heat resistance of micro-organisms or enzymes and their characterisation by D and z values are described in Chapter 1 (Section 1.4.5). Most heat resistant spores have a z value of around 10°C . This temperature rise will result in a ten-fold reduction in processing time needed to achieve the same lethality. In low-acid foods ($\text{pH} > 4.5$), the heat resistant, spore forming micro-organism, *Clostridium botulinum* is the most dangerous pathogen likely to be present. Under anaerobic conditions inside a sealed container it can grow to produce a powerful exotoxin, botulin, which is sufficiently potent to be 65% fatal to humans. *Cl. botulinum* is ubiquitous in soil and it is therefore likely to be found in small numbers on any raw material that has contact with soil. Because of the extreme hazard from botulin, the destruction of this micro-organism is therefore a *minimum* requirement of heat sterilisation. Normally, foods receive more than this minimum treatment as other more heat-resistant spoilage bacteria may also be present (Table 12.1). In more acidic foods ($\text{pH} 4.5\text{--}3.7$), other micro-organisms (for example yeasts and fungi) or heat-resistant enzymes are used to establish processing times and temperatures. In acidic foods ($\text{pH} < 3.7$), enzyme inactivation is the main reason for processing and heating conditions are less severe (sometimes referred to as *pasteurisation*).

Thermal destruction of micro-organisms takes place logarithmically (Chapter 1) and a sterile product cannot therefore be produced with certainty no matter how long the process time. However, the *probability* of survival of a single micro-organism can be predicted using details of the heat resistance of the micro-organism and the temperature and time of heating. This gives rise to a concept known as *commercial sterility*. For example, a process that reduces cell numbers by twelve decimal reductions (a $12D$ process), applied to a raw material which contains 1000 spores per container would reduce microbial numbers to 10^{-9} per container, or the probability of one microbial spore surviving in one billion containers processed. Commercial sterility means in practice that

Table 12.1 Heat resistance of some spore-forming bacteria^a used as a basis for heat sterilisation of low acid foods

Micro-organism	z value ($^{\circ}\text{C}$)	D_{121} value (min)	Typical foods
<i>Thermophilic</i> (35–55 $^{\circ}\text{C}$)			
<i>Bacillus stearothermophilus</i>	9–10	3.0–4.0	Vegetables, milk
<i>Clostridium thermosaccharolyticum</i>	7.2–10	3.0–4.0	Vegetables
<i>Mesophilic</i> (10–40 $^{\circ}\text{C}$)			
<i>Clostridium sporogenes</i>	8.8–11.1	0.7–1.5	Meats
<i>Bacillus subtilis</i>	4.1–7.2	0.3–0.76	Milk products
<i>Cl. botulinum</i> toxins A and B	5.5	0.1–0.3	Low-acid foods
<i>B. coagulans</i>	6–9	0.01–0.07	Milk
<i>B. cereus</i>	36	3.8	Milk
<i>Psychrophilic</i> (–5–1.5 $^{\circ}\text{C}$)	10	3.0 (60 $^{\circ}\text{C}$)	Low-acid foods
<i>Cl. botulinum</i> toxin E			

^aNote: the data is intended to be indicative only as the thermal resistance of micro-organisms is influenced by the nature of the food. Original literature gives precise information for particular products.

Adapted from Lund (1975), Burton (1988), Brennan *et al.* (1990), Heldman and Hartel (1997) and Licciardello *et al.* (1967).

the heat processing inactivates substantially all micro-organisms and spores which, if present, would be capable of growing in the food under defined storage conditions (Brennan *et al.*, 1990).

The level of survival is determined by the type of micro-organism that is expected to contaminate the raw material. A 12D process is used when *C. botulinum* is likely to be present in low acid foods, but in foods that contain more heat-resistant spoilage micro-organisms (Table 12.1), the application of a 12D process would result in over-processing and excessive loss of quality. In practice a 2D to 8D process is therefore used to give the most economical level of food spoilage consistent with adequate food quality and safety. However, because of the lower heat resistance of *C. botulinum*, the probability of survival remains similar to that obtained in a 12D process. For these processes to operate successfully, the microbial load on raw materials must be kept at a low level by hygienic handling and preparation procedures (Chapter 3), and in some foods by blanching (Chapter 10). Any failure in these procedures would increase the initial numbers of cells and, because of the logarithmic rate of destruction, would increase the incidence of spoilage after processing. In canning factories, accelerated storage trials on randomly selected cans of food ensure that these levels of commercial sterility are maintained before foods are released for retail sale. When *Cl. botulinum* grows and produces toxin in a sealed container there is characteristic production of gas which can cause visible swelling of the container (although this is not the only cause of swelling). Routine quality assurance measures therefore include observation for swollen or bloated cans.

In addition to information on heat resistance, it is necessary to collect data describing the rate of heat penetration into the food in order to calculate the processing time needed for commercial sterility.

Rate of heat penetration

Heat is transferred from steam or pressurised water through the container and into the food. Generally the surface heat transfer coefficient (Chapter 1) is very high and is not a limiting factor in heat transfer. The following factors are important influences on the rate of heat penetration into a food:

- *Type of product.* Liquid or particulate foods (for example peas in brine) in which natural convection currents are established heat faster than solid foods in which heat is transferred by conduction (for example meat pastes and corned beef) (Fig. 12.1). The low thermal conductivity of foods is a major limitation to heat transfer in conduction heating foods.
- *Size of the container.* Heat penetration to the centre is faster in small containers than in large containers.
- *Agitation of the container.* End-over-end agitation (Fig. 12.2) and, to a lesser extent, axial agitation increases the effectiveness of natural convection currents and thereby increases the rate of heat penetration in viscous or semi-solid foods (for example beans in tomato sauce).
- *Temperature of the retort.* A higher temperature difference between the food and the heating medium causes faster heat penetration.
- *Shape of the container.* Tall containers promote convection currents in convective heating foods.
- *Type of container.* Heat penetration is faster through metal than through glass or plastics owing to differences in their thermal conductivity (Table 1.5).

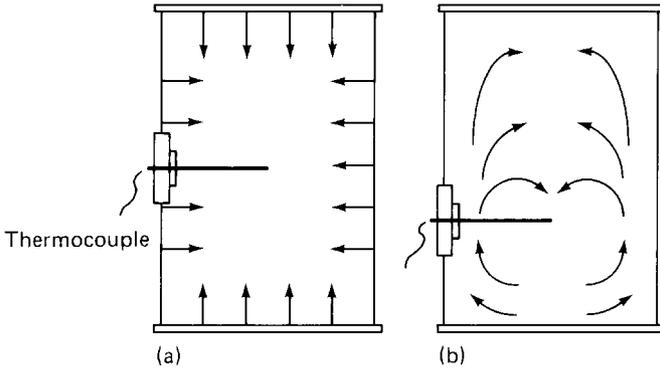


Fig. 12.1 Heat transfer into containers by (a) conduction and (b) convection.

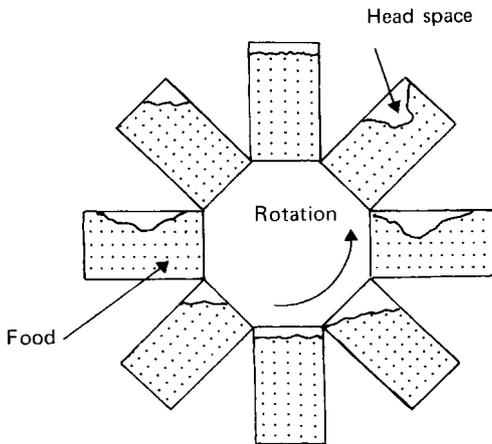


Fig. 12.2 End-over-end agitation of containers.
(After Hersom and Hulland (1980).)

The rate of heat penetration is measured by placing a thermocouple at the thermal centre of a container (the point of slowest heating) to record temperatures in the food during processing (Fig. 12.3). It is assumed that all other points in the container receive more heat and are therefore adequately processed. In continuous sterilisers, self-contained miniature temperature recorders-transmitters can be placed at the thermal centre of the container to measure heat penetration.

In cylindrical containers the thermal centre is at the geometric centre for conductive heating foods and approximately one third up from the base of the container for convective heating foods (Fig. 12.1). However, in convective heating, the exact position varies and should be found experimentally. Convective heating is more rapid than conductive heating and the rate depends mostly on the viscosity of the food. In commercial processing, containers of viscous food may be agitated to increase the rate of convective heating (Section 12.1.3).

A typical heating curve is produced by plotting temperature versus time on semilogarithmic graph paper (Fig. 12.4). A broken heating curve occurs when a food is initially heated by convective heating but then undergoes a rapid transition to conductive heating (for example in foods which contain a high concentration of starch which undergoes a sol-to-gel transition).

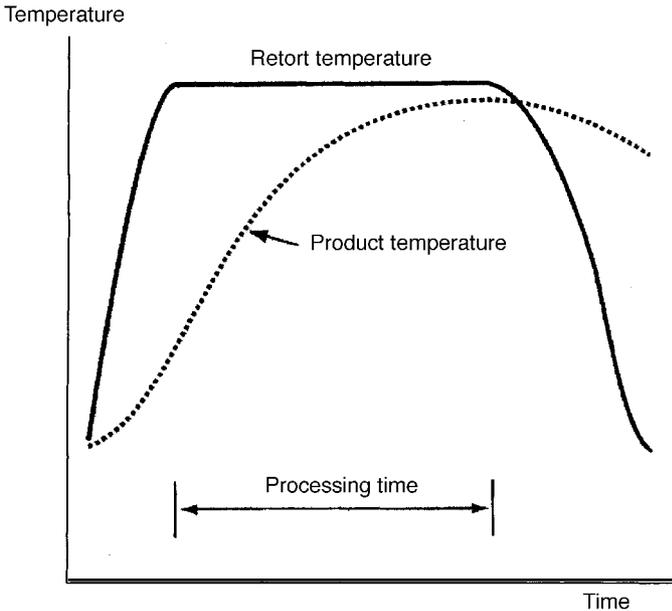


Fig. 12.3 Heat penetration into a can of conductive heating food: (a) = retort temperature; (b) = temperature at the slowest heating point.

The thermal death time (TDT), or *F value*, is used as a basis for comparing heat sterilisation procedures. It is the time required to achieve a specified reduction in microbial numbers at a given temperature and it thus represents the total time–temperature combination received by a food. It is quoted with suffixes indicating the retort temperature and the *z* value of the target micro-organism. For example, a process operating at 115°C based on a micro-organism with a *z* value of 10°C would be expressed as F_{115}^{10} . The *F* value may also be thought of as the time needed to reduce microbial numbers by a multiple of the *D* value. It is found using:

$$F = D (\log n_1 - \log n_2) \quad \boxed{12.1}$$

where n_1 = initial number of micro-organisms and n_2 = final number of micro-organisms.

A reference *F* value (F_0) is used to describe processes that operate at 121°C which are based on a micro-organism with a *z* value of 10°C. Typical F_0 values are 3–6 min for vegetables in brine, 4–5 min for cream soups and 12–15 min for meat in gravy.

Calculation of process times

The slowest heating point in a container may not reach the processing temperature (Fig. 12.3), but once the temperature of the food rises above approximately 70°C, thermal destruction of micro-organisms takes place. The purpose of calculating processing time is to enable a retort operator to know how long a food in a given can size should be held at a set processing temperature in order to achieve the required thermal destruction at the slowest heating point in the container. Two methods are described in the following section, the first being a mathematical method based on the equivalent lethality of different time–temperature combinations and the second being a graphical method. Both are discussed in detail by Stumbo (1973) and Ball and Olson (1957) who also describe a rapid method based on the use of nomograms. Holdsworth (1997) compares a number of other mathematical methods.

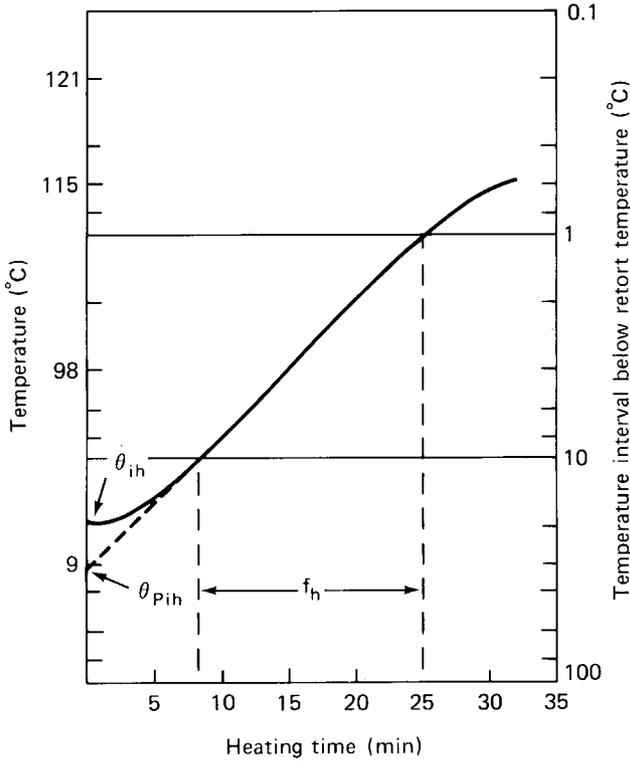


Fig. 12.4 Heating curve.

Formula (or mathematical) method

This method enables rapid calculation of process times for different retort temperatures or container sizes, but is limited by the assumptions made about the nature of the heating process. The method is based on:

$$B = f_h \log \left(\frac{j_h I_h}{g} \right) \quad \boxed{12.2}$$

where B (min) = time of heating, f_h (min), the heating rate constant = the time for the heat penetration curve to cover one logarithmic cycle, j_h = the thermal lag factor found by extrapolating the curve in Fig 12.4 to find the pseudo-initial product temperature (θ_{pih}).

$$j_h = \frac{\theta_r - \theta_{pih}}{\theta_r - \theta_{ih}} \quad \boxed{12.3}$$

where I_h ($= \theta_r - \theta_{ih}$) ($^{\circ}\text{C}$) = the difference between the retort temperature and the initial product temperature, g = the difference between the retort temperature and the final product temperature at the slowest heating point, θ_r ($^{\circ}\text{C}$) = retort temperature and θ_{ih} ($^{\circ}\text{C}$) = initial product temperature.

The heating rate constant varies according to the surface area:volume ratio of the container and therefore depends on the shape and size of the pack. It also depends on whether the product heats by convection or conduction. With the exception of g the above information can be found from the heating curve (Fig. 12.4). Cooling rate data are plotted in a similar way.

The value of g is influenced by the following factors:

- the TDT of the micro-organism on which the process is based
- the slope f_h of the heating curve
- the z value of the target micro-organism
- the difference between the retort temperature and the temperature of the cooling water.

To take account of these variables, Ball (1923) developed the concept of comparing the F value at the retort temperature (denoted F_1) with a reference F value of 1 min at 121°C (denoted F). The TDT at the retort temperature is described by the symbol U and is related to the reference F value and F_1 using:

$$U = FF_1 \tag{12.4}$$

If the reference F value is known, then it is possible to calculate U by consulting F_1 tables (Table 12.2). The value of g may then be found from f_h/u and g tables (Table 12.3).

One further factor which influences the value of g is the difference between the retort temperature and the temperature of the cooling water. In conductive heating foods, there is a lag before cooling water begins to lower the product temperature, and this results in a significant amount of heating after the steam has been turned off. It is therefore necessary to include a cooling lag factor j_c . This is defined as the ‘time taken for the cooling curve to cover one logarithmic cycle’, and is analogous to j_h , the heating lag factor. The cooling portion of the heat penetration curve is extrapolated to find the pseudo-initial product temperature θ_{pic} at the start of cooling, in a similar way to θ_{pih} . j_c is found using:

$$j_c = \frac{\theta_c - \theta_{pic}}{\theta_c - \theta_{ic}} \tag{12.5}$$

where θ_c (°C) = cooling water temperature and $-\theta_{ic}$ (°C) = the actual product temperature at the start of cooling. When using Table 12.3, the appropriate value of j_c can then be used to find g .

Finally, in batch retorts, only 40% of the time taken for the retort to reach operating temperature (the come-up time l) is at a sufficiently high temperature to destroy micro-organisms. The calculated time of heating (B) is therefore adjusted to give the corrected processing time:

$$\text{process time} = B - 0.4l \tag{12.6}$$

Table 12.2 F_1 values for selected z values at retort temperatures below 121°C

121- θ_r (°C)	z value					
	4.4°C	6.7°C	8.9°C	10°C	11.1°C	12°C
5.6	17.78	6.813	4.217	3.594	3.162	2.848
6.1	23.71	8.254	4.870	4.084	3.548	3.162
6.7	31.62	10.00	5.623	4.642	3.981	3.511
7.2	42.17	12.12	6.494	5.275	4.467	3.899
7.8	56.23	14.68	7.499	5.995	5.012	4.329
8.3	74.99	17.78	8.660	6.813	5.623	4.806
8.9	100.0	21.54	10.00	7.743	6.310	5.337
9.4	133.4	26.10	11.55	8.799	7.079	5.926
10.0	177.8	31.62	13.34	10.00	7.943	6.579
10.6	237.1	38.31	15.40	11.36	8.913	7.305

Adapted from Stumbo (1973).

Table 12.3 Selected f_h/U and g values when $z = 10$ and $j_c = 0.4-2.0$

f_h/U	Values of g for the following j_c values					
	0.40	0.80	1.00	1.40	1.80	2.00
0.50	0.0411	0.0474	0.0506	0.0570	0.0602	0.0665
0.60	0.0870	0.102	0.109	0.123	0.138	0.145
0.70	0.150	0.176	0.189	0.215	0.241	0.255
0.80	0.226	0.267	0.287	0.328	0.369	0.390
0.90	0.313	0.371	0.400	0.458	0.516	0.545
1.00	0.408	0.485	0.523	0.600	0.676	0.715
2.00	1.53	1.80	1.93	2.21	2.48	2.61
3.00	2.63	3.05	3.26	3.68	4.10	4.31
4.00	3.61	4.14	4.41	4.94	5.48	5.75
5.00	4.44	5.08	5.40	6.03	6.67	6.99
10.0	7.17	8.24	8.78	9.86	10.93	11.47
20.0	9.83	11.55	12.40	14.11	14.97	16.68
30.0	11.5	13.6	14.6	16.8	18.9	19.9
40.0	12.8	15.1	16.3	18.7	21.1	22.3
50.0	13.8	16.4	17.7	20.3	22.8	24.1
100.0	17.6	20.8	22.3	25.4	28.5	30.1
500.0	26.0	30.6	32.9	37.5	42.1	44.4

Adapted from Stumbo (1973).

More complex formulae are necessary to calculate processing times where the product displays a broken heating curve.

Sample problem 12.1

A low-acid food is heated at 115°C using a process based on $F_{121.1}^{10} = 7$ min. From heat penetration data the following information was obtained: $\theta_{ih} = 78^\circ\text{C}$, $f_h = 20$ min, $j_c = 1.80$, $f_c = 20$ min, $\theta_{pih} = 41^\circ\text{C}$ and $\theta_{ih} = 74^\circ\text{C}$. The retort took 11 min to reach process temperature. Calculate the processing time.

Solution to Sample problem 12.1

From equation (12.3),

$$j_h = \frac{115 - 41}{115 - 74}$$

$$= 2.00$$

and

$$I_h = 115 - 78$$

$$= 37^\circ\text{C}$$

From Table 12.2 (for $121.1 - \theta_r = 6.1$ and $z = 10^\circ\text{C}$),

$$F_1 = 4.084$$

From equation (12.4),

$$U = 7 \times 4.084$$

$$= 28.59,$$

$$\frac{f_h}{U} = \frac{20}{28.59}$$

$$= 0.7$$

From Table 12.3 (for $f_h/U = 0.7$, $j_c = 1.80$),

$$g = 0.241^\circ\text{C}$$

(that is the thermal centre reaches 114.76°C). From equation (12.2),

$$B = 20 \log \left(\frac{2.00 \times 37}{0.241} \right)$$

$$= 49.7 \text{ min.}$$

From equation (12.6),

$$\text{process time} = 49.7 - (0.4 \times 11)$$

$$= 45.3 \text{ min}$$

This gives the process time for $F_0 = 7$ min. If the process time had been given, it would be possible to reverse the calculation to find F_0 .

Improved general (graphical) method

This method is based on the fact that different combinations of temperature and time have the same lethal effect on micro-organisms (Chapter 1). *Lethality* is therefore the integrated effect of temperature and time on micro-organisms. As the temperature increases, there is a logarithmic reduction in the time needed to destroy the same number of micro-organisms. This is expressed as the *lethal rate* (a dimensionless number that is the reciprocal of TDT) and is shown by the following equation:

$$\text{Lethal rate} = 10^{(\theta-121)/z} \quad \boxed{12.7}$$

where θ ($^\circ\text{C}$) = temperature of heating.

The TDT at a given processing temperature is compared to a reference temperature (T) of 121°C . For example, if a product is processed at 115°C and the most heat-resistant micro-organism has a z value of 10°C ,

$$\text{Lethal rate} = 10^{(115-121)/10}$$

$$= 0.25$$

As the temperature of a food increases during processing, there is a higher rate of microbial destruction. The initial heating part of the process contributes little towards total lethality until the retort temperature is approached and most of the accumulated lethality takes place in the last few minutes, before cooling begins.

The lethal rate depends on the z value of the micro-organism on which the process is based and the product temperature, and tables of lethal rate values are available (Table 12.4 is for $z = 10$, the value for most spoilage micro-organisms). This method is preferable in practical situations for determining the impact of a process in terms of equivalent temperature/time relationships.

Sample problem 12.2

A convective heating food is sterilised at 115°C to give $F_0 = 7$ min. The come-up time of retort is 11 min. Calculate the processing time from the following heat penetration data. Cooling started after 60 min.

Process time (min)	Temperature (°C)	Process time (min)	Temperature (°C)
0	95	35	115.5
5	101	40	115.5
10	108.5	45	115.5
15	111.5	50	115.6
20	113	55	115.6
25	115.5	60	115.6
30	115.5	65	100

Solution to Sample problem 12.2

Lethal rates can be found at selected points on a heat penetration curve either by constructing a TDT curve and taking the reciprocal of TDTs (from Fig. 1.14) at the selected temperatures, or by consulting the appropriate lethal rate table (Table 12.4). Lethal rates are then plotted against processing time (Fig. 12.5) and the area under the curve is measured by counting squares or using a planimeter.

Process time (min)	Lethal rate	Process time (min)	Lethal rate
0	0.002	35	0.218
5	0.01	40	0.218
10	0.055	45	0.224
15	0.109	50	0.224
20	0.155	55	0.224
25	0.218	60	0.224
30	0.218	65	0.005

For convection heating foods, the lethal rate curve is used to find the point in the process when heating should cease. A line is drawn parallel to the cooling part of the curve so that the total area enclosed by the curve is equal to the required lethality. The area under the curve ACE is 100.5 cm^2 . As 1 cm^2 is 0.1 min at 121°C, the area ACE represents 10.05 min at 121°C. Therefore by reducing the area under the curve ABD to 70 cm^2 ($F = 7$ min), the process time is 45 min. Thus the process time required for $F_0 = 7$ min is 45 min.

Examples of F_0 values used commercially are shown in Table 12.5. With conduction heating foods the temperature at the centre of the container may continue to rise after cooling commences, because of the low rate of heat transfer. For these foods it is necessary to determine lethality after a number of trials in which heating is stopped at different times.

Table 12.4 Lethal rates for $z = 10^\circ\text{C}$

Temperature (°C)	Lethal rate (min ^a)	Temperature (°C)	Lethal rate (min)
90	0.001	108	0.049
92	0.001	110	0.077
94	0.002	112	0.123
96	0.003	114	0.195
98	0.005	116	0.308
100	0.008	118	0.489
102	0.012	120	0.774
104	0.019	122	1.227
106	0.031	124	1.945

^a At 121°C per minute at θ_r .
Adapted from Stumbo (1973).

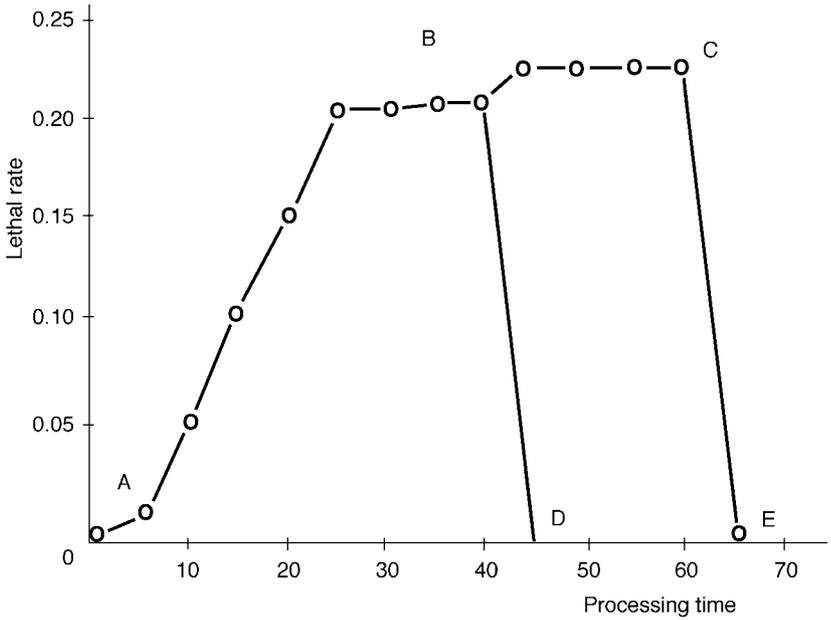


Fig. 12.5 Lethal rate curve.

Table 12.5 F_0 values for selected commercial processes

Product	F_0 values
Carrots in brine	3–4
Beans in tomato sauce	4–6
Herrings in tomato sauce	6–8
Meat in gravy	12–15

12.1.2 Retorting (heat processing)

The shelf life of sterilised foods depends in part on the ability of the container to isolate the food completely from the environment. The four major types of heat-sterilisable container are:

1. metal cans
2. glass jars or bottles
3. flexible pouches
4. rigid trays.

These materials are described in Chapter 24 and methods of filling and sealing are described in Chapter 25.

Before filled containers are processed, it is necessary to remove air by an operation termed 'exhausting'. This prevents air expanding with the heat and therefore reduces strain on the container. The removal of oxygen also prevents internal corrosion and oxidative changes in some foods. Steam replaces the air and on cooling forms a partial vacuum in the head space. Containers are exhausted by:

- hot filling the food into the container (commonly used as it also pre-heats food which reduces processing times)
- cold filling the food and then heating the container and contents to 80–95°C with the lid partially sealed (clinched)
- mechanical removal of the air using a vacuum pump
- steam flow closing, where a blast of steam (at $34\text{--}41.5 \times 10^3 \text{ Pa}$) carries air away from the surface of the food immediately before the container is sealed. This method is best suited to liquid foods where there is little air trapped in the product and the surface is flat and does not interrupt the flow of steam.

Heating by saturated steam

Latent heat is transferred to food when saturated steam condenses on the outside of the container. If air is trapped inside the retort, it forms an insulating boundary film (Chapter 1) around the cans which prevents the steam from condensing and causes under-processing of the food. It also produces a lower temperature than that obtained with saturated steam (Table 12.6). It is therefore important that all air is removed from the retort by the incoming steam using a procedure known as *venting*.

A major problem with processing solid or viscous foods is the low rate of heat penetration to the thermal centre. As a result, over-processing causes damage to nutritional and sensory characteristics of food near the walls of the container in addition to long processing times and hence low productivity. Methods that are used to increase the rate of heat transfer include the use of thinner profile containers and agitation of containers. An increase in retort temperature would also reduce processing times and protect nutritional and sensory qualities, but this is usually impractical; the higher pressures would require substantially stronger and hence more expensive containers and processing equipment.

After sterilisation the containers are cooled by sprays of water. Steam is rapidly condensed in the retort, but the food cools more slowly and the pressure in the containers remains high. Compressed air is therefore used to equalise the pressure to prevent strain on the container seams (pressure cooling). When the food has cooled to below 100°C, the over-pressure of air is removed and cooling continues to approximately 40°C. At this temperature, moisture on the container dries which prevents surface corrosion and allows label adhesives to set more rapidly.

Table 12.6 Temperatures of saturated steam at gauge pressures from 0 kPa to 199 kPa (0–29 lb ft⁻²)

Temperature (°C)	Pressure		Temperature (°C)	Pressure	
	(lb ft ⁻²)	(kPa)		(lb ft ⁻²)	(kPa)
100.0	0	0	121.0	15	103.4
101.9	1	6.9	122.0	16	110.3
103.6	2	13.8	123.0	17	117.2
105.3	3	20.7	124.1	18	124.1
106.9	4	27.6	125.0	19	131.0
108.4	5	34.5	126.0	20	137.9
109.8	6	41.4	126.9	21	144.8
111.3	7	48.3	127.9	22	151.7
112.6	8	55.2	128.7	23	158.6
113.9	9	62.1	129.6	24	165.5
115.2	10	68.9	130.4	25	172.4
116.4	11	75.8	131.2	26	179.3
117.6	12	82.7	132.1	27	186.2
118.8	13	89.6	133.0	28	193.1
119.9	14	96.5	133.6	29	199.9

Heating by hot water

Foods are processed in glass containers or flexible pouches under hot water with an overpressure of air. Glass containers are thicker than metal cans to provide adequate strength. This, together with the lower thermal conductivity of glass (Table 1.5), results in slower heat penetration and longer processing times than for cans and there is a higher risk of thermal shock to the container. Foods in rigid polymer trays or flexible pouches heat more rapidly owing to the thinner material and smaller cross-section of the container. This enables savings in energy and causes minimum overheating near the container wall. Liquid or semi-liquid foods are often processed horizontally to ensure that the thickness of food is constant across the pouch. Vertical packs promote better circulation of hot water in the retort, but special frames are necessary to prevent the pouches from bulging at the bottom, which would alter the rate of heat penetration and hence the degree of sterilisation achieved. Although pouches are popular in the Far East and for containing military rations, they have yet to achieve large-scale commercial use in Europe and the United States.

Heating by flames

Sterilisation at atmospheric pressure using direct flame heating of spinning cans is described by Beauvais *et al.* (1961), Casimir (1975) and Anon. (1984). High rates of heat transfer are possible at flame temperatures of 1770°C. The consequent short processing times produce foods of high quality and reduce energy consumption by 20% compared with conventional canning. No brine or syrup is used in the can and smaller cans may be used which reduces transport costs by 20–30%. However, high internal pressures (275×10^3 Pa at 130°C) limit this method to small cans. It is used, for example, to process mushrooms, sweetcorn, green beans, pears and cubed beef.

12.1.3 Equipment

Sterilising retorts may be batch or continuous in operation. Batch retorts may be vertical or horizontal; the latter are easier to load and unload and have facilities for agitating

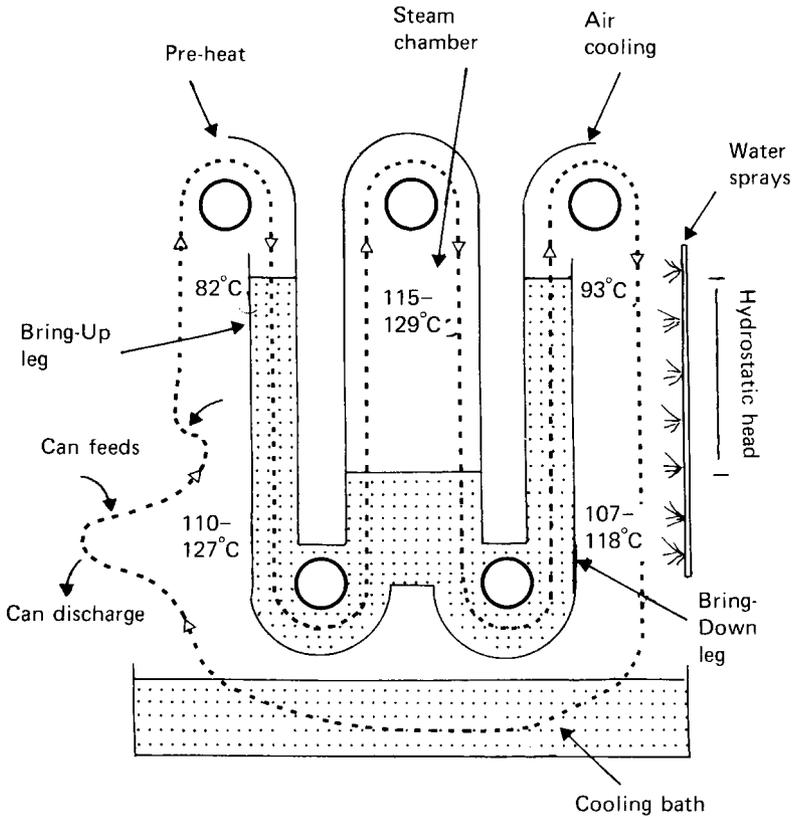


Fig. 12.6 Continuous hydrostatic steriliser.

containers, but require more floor space. For example, the 'Orbitort' consists of a pressure vessel that contains two concentric cages. Cans are loaded horizontally into the annular space between the cages and when full, the retort is sealed. The cages hold the cans against guide rails as they are slowly rotated to cause the headspace bubble to stir the contents (Brennan *et al.*, 1990).

Continuous retorts (for example, Fig 12.6) permit close control over the processing conditions and hence produce more uniform products. They produce gradual changes in pressure inside cans, and therefore less strain on the can seams compared with batch equipment. The main disadvantages include a high in-process stock which would be lost if a breakdown occurred, and in some, problems with metal corrosion and contamination by thermophilic bacteria if adequate preventative measures are not taken.

The main types are cooker-coolers, rotary sterilisers and hydrostatic sterilisers. Cooker-coolers carry cans on a conveyor through three sections of a tunnel that are maintained at different pressures for pre-heating, sterilising and cooling. Rotary sterilisers consist of a slowly rotating drum inside a pressure vessel. The vessel has a helical track on the inner wall and cans are moved along this by the drum, through three pressure sections separated by pressure locks. Again the contents are mixed as cans travel around the helix. Nair (1964) describes four types of hydrostatic steriliser in detail. In practice, large continuous sterilisers are used for the production of high-volume products

(for example, 1000 cans per min) where there is no requirement to regularly change the container size or processing conditions.

Computer control of retorts is described by Bown (1985, 1987), Hayakawa (1977), Holdsworth (1983) and Simpson *et al.* (1993). Selected process variables are monitored including:

- temperature of the raw material
- temperature of the cooling water
- temperature of steam
- time of processing
- heating and cooling rates.

This information is then processed by computer to calculate the accumulated lethality and to control the air, steam and water flow rates, to produce the required degree of sterility in the product with minimum energy expenditure. Further details of automatic process control are given in Chapter 2.

12.2 Ultra high-temperature (UHT)/aseptic processes

Higher processing temperatures for a shorter time are possible if the product is sterilised before it is filled into pre-sterilised containers in a sterile atmosphere. This forms the basis of UHT processing (also termed *aseptic processing*). It is used to sterilise a wide range of liquid foods, including milk, fruit juices and concentrates, cream, yoghurt, wine, salad dressing, egg and ice cream mix. It can also be used to process foods which contain small discrete particles, for example cottage cheese, baby foods, tomato products, fruit and vegetables, soups and rice desserts. Processes for larger-particulate foods have been developed (Manvell, 1987), and more recently, ohmic heating (Chapter 18) has been successfully used for UHT processing. The high quality of UHT foods competes well with chilled and frozen foods (Chapters 19 and 21), and UHT has an important additional advantage of a shelf life of at least six months without refrigeration.

The advantages of UHT processing compared with canning are summarised in Table 12.7. For example, UHT processing conditions are independent of container size. Whereas conventional retorting of A2 cans of vegetable soup requires 70 min at 121°C to achieve an F_0 value of 7 min, followed by 50 min cooling, aseptic processing in a scraped-surface heat exchanger at 140°C for 5 s gives an F_0 value of 9 min. Increasing the can size to A10 increases the processing time to 218 min, whereas with aseptic processing the sterilisation time is the same. This permits the use of very large containers (for example 1 tonne aseptic bags of tomato purée or liquid egg, used as an ingredient for other manufacturing processes).

The main limitations of UHT processing are the cost and complexity of the plant, which arises from the necessity to sterilise packaging materials, associated pipework and tanks, the maintenance of sterile air and surfaces in filling machines, and the higher skill levels required by operators and maintenance staff (Rose, 1986).

12.2.1 Theory

For a given increase in temperature, the rate of destruction of micro-organisms and many enzymes increases faster than the rate of destruction of nutrients and sensory components

Table 12.7 Comparison of conventional canning and aseptic processing and packaging

Criteria	Retorting	Aseptic processing and packaging
Product sterilisation		
Delivery	Unsteady state	Precise, isothermal
Process calculations		
Fluids	Routine – convection	Routine
Particulates	Routine – conduction or broken heating	Complex
Other sterilisation required	None	Complex (process equipment, containers, lids, aseptic tunnel)
Energy efficiency	Lower	30% saving or more
Sensory quality	Unsuited to heat sensitive foods	Superior – suitable for homogenous heat sensitive foods
Nutrient loss	High	Minimal
Value added	Lower	Higher
Convenience	Shelf stable	Shelf stable
Suitability for microwave heating	Glass and semi-rigid containers	All non-foil rigid and semi-rigid containers
Production rate	High (600–1000/min)	Medium (500/min)
Handling/labour costs	High	Low
Downtime	Minimal (mostly seamer and labeller)	Re-sterilisation needed if loss of sterility in filler or steriliser
Flexibility for different container sizes	Need different process delivery and/or retorts	Single filler for different container sizes
Survival of heat resistant enzymes	Rare	Common in some foods (e.g. milk)
Spoilage troubleshooting	Simple	
Low acid particulate processing	Routine	Not in practice (data from high acid systems being used to design low acid systems)
Post-process additions	Not possible	Possible to add filter sterilised enzymes or probiotics after heat processing

Adapted from David (1996).

(Fig. 12.7 and Chapter 1) and food quality is therefore better retained at higher processing temperatures. However some enzymes, for example proteases and lipases that are secreted by psychrotrophic micro-organisms in milk, are more heat resistant. These are not destroyed by some UHT treatments and may cause changes to the flavour of products during prolonged storage (David, 1996).

In contrast with in-container sterilisation where the most lethal effect frequently occurs at the end of the heating stage and the beginning of the cooling stage, UHT processes heat the food rapidly to a holding temperature and the major part of the lethality accumulates at a constant temperature. The sterilising value is calculated by multiplying the lethal rate at the holding temperature by the holding time. The come-up time and cooling periods are very short and in most cases are treated as a safety factor. The flow rate for the fastest moving particle and longest time needed for heat transfer from the liquid to the centre of the particle are together used to determine the time and temperature needed to achieve the required F_0 value. The criteria for UHT processing are therefore the same as for canning: that is the attainment of commercial sterility. Typical minimum time–temperature conditions needed to destroy *Cl. botulinum* ($F_0 = 3$) are 1.8 s at 141°C. In the UK the minimum heat treatment for dairy products are set out in regulations (1 s at 135°C for milk, 2 s at 140°C for cream and milk-based products and 2 s at 148.9°C for ice cream mixes) (Lewis, 1993).

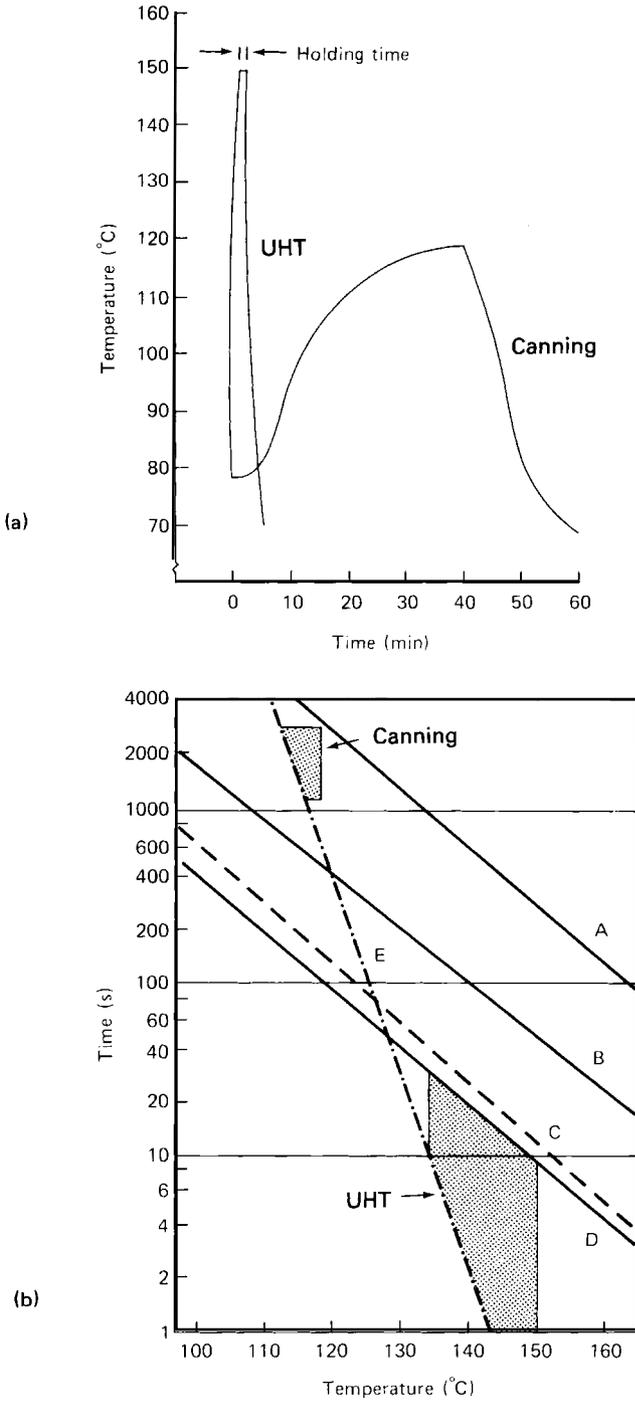


Fig. 12.7 (a) Time-temperature conditions for UHT and canning; (b) rates of microbial and nutrient destruction in UHT processing: line A, 40% thiamin; line B, 10% thiamin; line C, 1% lysine; line D, 3% thiamin; line E, microbial. (After Killeit (1986).)

In addition to the use of F_0 to assess microbial destruction, a further two parameters are used in dairy UHT processing: the B^* value is used to measure the total integrated lethal effect of a process and the C^* value which measures the total chemical damage taking place during a process. The reference temperature used for these values is 135°C. A process that is given a B^* value = 1 will result in a 9D reduction in spores ($z = 10.5^\circ\text{C}$) and would be equivalent to 10.1 s at 135°C. Similarly a process given a C^* value = 1 will cause 3% loss of thiamine and would be equivalent to 30.5 s at 135°C (Lewis, 1993).

Calculation of holding time uses equations (12.8) and (12.9):

$$B^* = 10^{(\theta-135)/10.5} \cdot t / 10.1 \quad \boxed{12.8}$$

$$C^* = 10^{(\theta-135)31.4} \cdot t / 30.5 \quad \boxed{12.9}$$

where θ (°C) = processing temperature and t (s) = holding time.

Ideally a process should maximise B^* and minimise C^* , unless a specific chemical (for example an enzyme or natural toxin such as trypsin inhibitor) is to be destroyed or vegetable tissues are required to be softened.

12.2.2 Processing

Food is heated in relatively thin layers in a continuous heat exchanger with close control over the sterilisation temperature and holding time. It is important to know the shortest time that any particle can take to pass through the holding section and the rate of heat transfer from the liquid to the centre of the particle, to ensure that microbial spores cannot survive the process. The length of the holding tube is often calculated as twice the size of the average liquid flow rate (Ohlsson, 1992). It is also important to achieve turbulent flow (Chapter 1) if possible because the spread of residence times is smaller. With viscous foods, flow is likely to be streamline and result in a wider spread of residence times; the minimum may be only half the average time. The minimum time should therefore be greater than that specified for the product to avoid under-processing. Similarly there should be close control over the particle size range in particulate products. For example, if a process is designed to sterilise 14 mm particles to $F_0 = 6$, it can be calculated that the holding tube should be 13 m long. However, if a 20 mm particle passes through under these conditions, it will only reach $F_0 = 0.5$ and will thus be seriously under-processed. Conversely, a 10 mm diameter particle will reach $F_0 = 20$ and will be over-processed (Ohlsson, 1992).

The sterilised product is cooled in a second heat exchanger, or in a vacuum chamber if deaeration is also required. Containers are not required to withstand sterilisation conditions, and laminated cartons (Chapter 24) are therefore widely used. They have considerable economic advantages compared with cans and bottles, in both the cost of the pack and the transport and storage costs. Cartons are pre-sterilised with hydrogen peroxide, and filling machines are enclosed and maintained in a sterile condition by ultraviolet light and filtered air. A positive air pressure is maintained in the filling machine to prevent entry of contaminants (also Chapter 25).

The process is successfully applied to liquid and small-particulate foods but until recently, there were problems in processing larger pieces of solid food. The major difficulties were:

- enzyme inactivation at the centre of the pieces of food causes overcooking of the surfaces, thus limiting particle sizes

- agitation is necessary to improve the rate of heat transfer and to aid temperature distribution, but this causes damage to the product
- until recently there was a lack of suitable equipment for processing and filling
- settling of solids is a problem if the equipment has a holding tube. This causes uncontrolled and overlong holding times and variable proportions of solids in the filled product (Hersom, 1984).

These problems have now been addressed for larger particulates (up to 2.5 cm) using a number of processes, including the APV 'Jupiter' system, the Alfa-Laval 'Twintherm' system, the Stork 'single flow fraction specific thermal processing (FSTP)' system (Section 12.2.3) or ohmic heating (Chapter 18). Details of a protocol for validating the successful aseptic processing of particulates for the American Food and Drug Administration are given by Palaniappan and Sizer (1997). The flow of two-phase particulates through heat exchangers is highly complex and research is continuing to gain a better understanding and control of heat transfer in these systems. In particular the residence time distribution of each component should be known and the fastest particles used to monitor safety and the slowest used to monitor quality (Lewis, 1993).

12.2.3 Equipment

A theoretically ideal UHT process would heat the product instantly to the required temperature, hold it at that temperature to achieve sterility and cool it instantly to filling temperature. In practice the degree to which this is achieved depends in part on the method used to heat the food and in part on the sophistication of control and hence the cost of equipment. It also depends on the properties of the food (for example viscosity, presence of particles, heat sensitivity and tendency to form deposits on hot surfaces). With the exception of ohmic heating, equipment used for UHT processing has the following characteristics:

- operation above 132°C
- exposure of a relatively small volume of product to a large surface area for heat transfer
- maintenance of turbulence in the product as it passes over the heating surface
- use of pumps to give a constant delivery of product against the pressure in the heat exchanger
- constant cleaning of the heating surfaces to maintain high rates of heat transfer and to reduce burning-on of the product. (The chemical composition and formation of deposits during UHT treatment of milk are described by Lalande *et al.* (1984).)

Equipment is classified according to the method of heating into:

- direct systems (steam injection and steam infusion)
- indirect systems (plate heat exchangers, tubular heat exchangers (concentric tube or shell-and-tube) and scraped surface heat exchangers)
- other systems (microwave, dielectric, ohmic and induction heating (Chapter 18)).

Direct methods

Details of equipment from different manufacturers are reviewed by Ramesh (1999).

Steam injection (uperisation) and steam infusion are each used to intimately combine the product with potable (culinary) steam. In steam injection, steam at a pressure of 965×10^3 Pa is introduced into a pre-heated liquid product in fine bubbles by a steam

injector and rapidly heats the product to 150°C. After a suitable holding period (for example 2.5 s) the product is flash cooled in a vacuum chamber to 70°C, and condensed steam and volatiles in the product are removed. The moisture content of the product therefore returns to approximately the same level as the raw material.

The main advantages of this system are as follows:

- it is one of the fastest methods of heating and the fastest method of cooling and is therefore suitable for more heat-sensitive foods
- volatile removal is an advantage with some foods (for example milk).

However, there are limitations:

- the method is only suitable for low-viscosity products
- there is relatively poor control over processing conditions
- there is a requirement for potable steam which is more expensive to produce than normal processing steam
- regeneration of energy is less than 50% compared with more than 90% in indirect systems
- flexibility for changing to different types of product is low.

Further details are given by Burton and Perkins (1970), Zadow (1975), Burton (1988), Lewis and Heppel (2000) and Carlson (1996).

In steam infusion the food is sprayed in a free-falling film into high-pressure (450×10^3 Pa) potable steam in a pressurised vessel. It is heated to 142–146°C in 0.3 s, and is held for 3 s in a holding tube before flash cooling in a vacuum chamber to 65–70°C. Heat from the flash cooling is used to pre-heat the feed material.

In both systems microcomputers control temperature, pressure, level, flow rate, valve operation and the cleaning sequence, at production rates of up to 9000 kg h⁻¹ (Swientek, 1983). Steam infusion has advantages over injection methods because the liquid does not contact hotter surfaces and burning-on is therefore reduced. Other advantages include:

- almost instantaneous heating of the food to the temperature of the steam, and very rapid cooling which results in high retention of sensory characteristics and nutritional properties
- greater control over processing conditions than steam injection
- lower risk of localised overheating of the product
- the method is more suitable for higher viscosity foods compared to steam injection.

The main disadvantages, in addition to the disadvantages of steam injection, are blockage of the spray nozzles and separation of components in some foods. Further details are given by Burton (1988).

Indirect systems

A description of the historical development of different types of heat exchangers for indirect UHT heating is given by Carlson (1996). *Plate heat exchangers* are described in detail for pasteurisation (Chapter 11). In UHT sterilisation, they have a number of limitations which are due to the higher temperatures and pressures involved (Table 12.8). *Tube and shell heat exchangers* are described in Chapter 13, in their application to evaporation by boiling. The advantages and limitations of this type of equipment for UHT processing are described in Table 12.8.

There are a large number of designs of tube and shell heat exchangers, including the *concentric tube heat exchanger* which is a combination of both plate and tubular designs

Table 12.8 Comparison of plate and tube-and-shell heat exchangers for UHT processing

Plate heat exchanger		Tube-and-shell heat exchanger	
Advantages	Limitations	Advantages	Limitations
<ul style="list-style-type: none"> • Relatively inexpensive • Economical in floor space and water consumption • Efficient in energy use (>90% energy regeneration) • Flexible changes to production rate, by varying the number of plates • Easily inspected by opening the plate stack 	<ul style="list-style-type: none"> • Operating pressures limited by the plate gaskets to approximately 700 kPa • Liquid velocities at relatively low pressure also low ($1.5\text{--}2\text{ m s}^{-1}$) • Low flow rates can cause uneven heating and solids deposits on the plates which require more frequent cleaning • Gaskets susceptible to high temperatures and caustic cleaning fluids and are replaced more regularly than in pasteurisation • Limited to low viscosity liquids (up to 1.5 N s m^{-2}) • Careful initial sterilisation of the large mass of metal in the plate stack is necessary for uniform expansion to prevent distortion and damage to plates or seals • Liable to fouling 	<ul style="list-style-type: none"> • Few seals and easier cleaning and maintenance of aseptic conditions • Operation at higher pressures (7000–10 000 kPa) and higher liquid flow rates (6 m s^{-1}) than plate heat exchangers • Turbulent flow at tube walls due to higher flow rates • Hence more uniform heat transfer and less product deposition 	<ul style="list-style-type: none"> • Difficulty in inspecting heat transfer surfaces for food deposits • Limited to relatively low-viscosity foods (up to 1.5 N s m^{-2}) • Lower flexibility to changes in production capacity • Larger-diameter tubes cannot be used because higher pressures needed to maintain the liquid velocity and large-diameter pipes have a lower resistance to pressure • Any increase in production rate requires duplication of the equipment

(Fig. 12.8(a)). Counter-current flow and helical corrugations are used to generate turbulence and hence to increase the rate of heat transfer. This equipment is able to operate at high pressures (up to $2000 \times 10^3\text{ Pa}$) with viscous liquids. Turbulence can be further increased at the expense of throughput or maximum particle size, by altering the relative positions of tubes (Fig. 12.8(b)).

Scraped-surface heat exchangers are also used for freezing (Chapter 21), for evaporation by boiling (Chapter 13) and for the continuous production of margarine and butter (Chapter 4). Their main advantages for UHT processing are their suitability for viscous foods and particulates (less than 1 cm), and their flexibility for different products by changing the geometry of the rotor assembly. However, they have high capital and operating costs and heat recovery is not possible. They are used to process fruit sauces and fruit bases for yoghurts and pies.

During the 1970s and 1980s, systems were developed that involve separate treatment of the liquid and particulate components of a food to enable greater control over the F_0 values, particularly for sterilisation of the particles. For example, the '*Jupiter*' *double-cone heat exchanger* combines indirect heating in a jacketed double cone, with direct heating by steam or superheated liquor. It has been used for processing large (2–2.5 cm) particles of food. In a sequence of microprocessor-controlled operations, solid pieces of

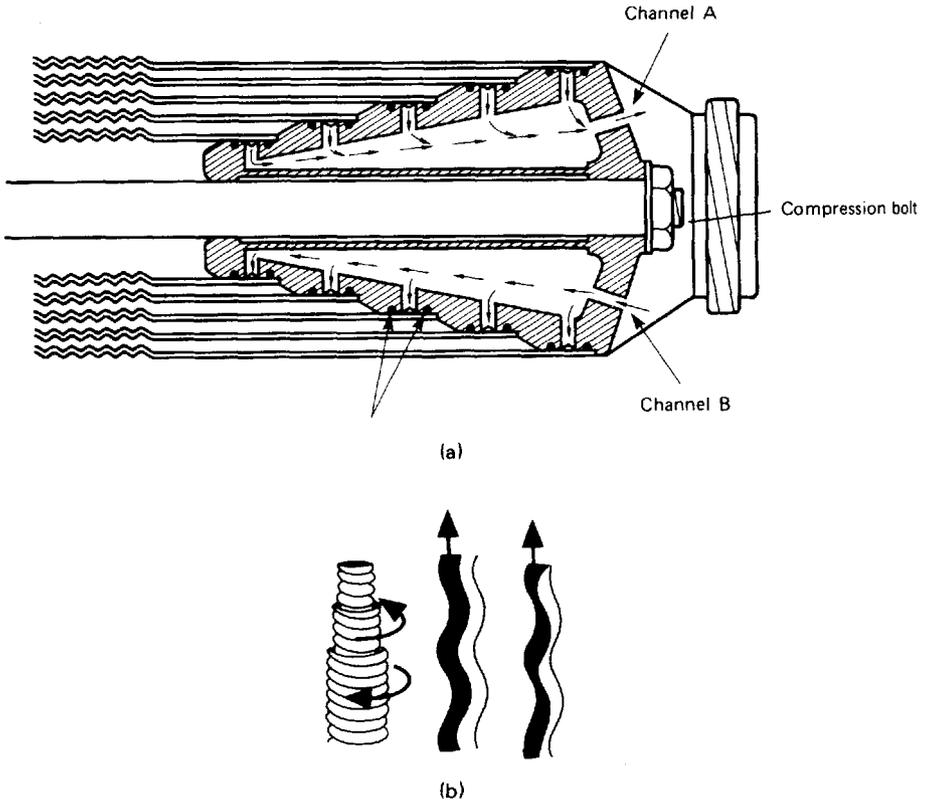


Fig. 12.8 Concentric tube heat exchanger: (a) cross-section; (b) effect of rotation of tubes. (Courtesy of HRS Heat Exchangers Ltd.)

food are fed into a double-cone vessel, which is then rotated slowly (4–12 rpm) on a horizontal axis. Steam at 206×10^3 Pa is introduced and the product is tumbled through the steam. Steam in the jacket is at the same temperature (for example 137°C) to prevent the food from burning onto the cone. Liquor, sterilised separately, is added during sterilisation to prevent damage to the solids by the tumbling action. Sterilisation times are for example 2–4 min to achieve $F_0 = 10$ for carrot cubes, depending on their size. After sterilisation the product is rapidly cooled with cold water and sterile air, and the condensate-water-stock is removed. The liquid portion of the product is sterilised separately in a plate or tubular system and added to the solids. The cone then acts as a mixer. The blended solids–liquids are discharged to an aseptic filler using an over-pressure of sterile air. This avoids pumping the softened product and further reduces damage to the food. Cooking liquor from the solids is used to make sauce to top up containers or to inject into solids during subsequent processing. However, the Jupiter has a relatively low capacity, complex operation and relatively high capital costs, and for these reasons has not been widely adopted.

The ‘Twintherm’ system is a semi-continuous process in which particulate food is heated by direct steam injection in a pressurised, horizontal, cylindrical vessel that rotates slowly. Once the particles have been held for the required time to achieve F_0 values, they are cooled evaporatively and liquid, which has been sterilised in conventional UHT heat exchangers, is used to carry the particles to an aseptic filler. It is claimed to allow more uniform and gentle treatment of particles, compared to continuous processes and it is

used commercially to produce soups for the European market (Ohlsson, 1992; Alkskog, 1991).

The single flow FSTP system employs a separate holding section which is a cylindrical vessel containing slowly rotating fork blades on a central shaft. These blades form cages which hold the particles as they are rotated around the cylinder from the inlet to discharge pipes. Liquid moves freely through the cages, giving rapid heat transfer. Different holding sections can be used for different particle sizes which reduces the risk of over-processing of smaller particles that is found in more traditional systems. Again the liquid component is sterilised separately in conventional tubular heat exchangers and is then used to carry the sterilised particles to the filler. The system is described in detail by Hermans (1991).

More recent developments, described by Carlson (1996) and Lewis and Heppel (2000), include *tube-in-tube heat exchangers* which are a development of plate heat exchangers, in which the thin-walled plates are formed into a tube, and corrugations or twists in the tubes are introduced to promote turbulent flow. One tube is inserted inside another, which may be repeated two or more times and heat transfer takes place across the tube walls. Incoming material is heated by sterilised product to regenerate heat and increase energy efficiency. Steam from hot water is used for the final heating and after initial cooling by the incoming material, the product is cooled with cold water. This system is relatively low cost and is widely used, although it suffers from some drawbacks: seal integrity is critical to prevent mixing of incoming material, product or heating and cooling media; the seal strength limits the pressure that can be used and seals may be difficult to clean. Additionally, the equipment is restricted to relatively low viscosity liquids that do not cause significant fouling (Carlson, 1996), but has been widely used for fruit juices, milk and dairy products.

The problems encountered in straight tube heat exchangers described above are largely overcome by forming a single tube into a continuous helix or coil, which has a carefully defined ratio between the diameter of the coil and the diameter of the tube. The coil is contained within an insulating material to minimise heat losses. The design of the coil promotes secondary flow of liquid within the tube, and this causes turbulence at relatively low flow rates, and high rates of heat transfer (between two and four times the rates in tube-in-tube or shell-and-tube heat exchangers (Carlson, 1996). This enables processing of heat sensitive products (e.g. liquid egg) and products that cause fouling of heat exchanger surfaces. The mixing action in the coil gives a uniform distribution of particles, making the equipment suitable for salad dressings, fruit purées and other foods that contain a range of particle sizes, as well as for high viscosity liquids such as cheese sauce. Additionally, the continuous tube has no seals and is easily cleaned-in-place, and the simple design is virtually maintenance-free.

Other systems

Three other systems have been developed: the 'Multi-therm', 'Achilles' and ohmic heating. In the first two the food is heated by a combination of hot liquid and microwave energy. In ohmic heating a conducting fluid is heated directly by electrical energy (Chapter 18). Conversion efficiencies from electrical energy to heat of greater than 90% are claimed, and particulate feeds may be processed without shearing forces associated with some other types of heat exchangers. Indirect systems are automatically cleaned in place after 3–4 h of operation to remove accumulated deposits. The cleaning programme does not involve loss of sterile conditions, and processing resumes immediately afterwards.

12.3 Effect on foods

The purpose of heat sterilisation is to extend the shelf life of foods for storage at ambient temperatures, while minimising the changes in nutritional value and eating quality. Differences between the D and z values of micro-organisms, enzymes and sensory or nutritional components of foods are exploited to optimise processes for the retention of nutritional and sensory qualities (Swartzel, 1982). Preceding sections describe how this is achieved in practice by a reduction in size or cross-sectional area of containers, by agitation during processing or by aseptic processing. In this section the changes to foods caused by traditional canning techniques are compared with those caused by UHT processing.

12.3.1 Colour

The time–temperature combinations used in canning have a substantial effect on most naturally occurring pigments in foods. For example, in meats the red oxymyoglobin pigment is converted to brown metmyoglobin, and purplish myoglobin is converted to red–brown myohaemichromogen. Maillard browning and caramelisation also contribute to the colour of sterilised meats. However, this is an acceptable change in cooked meats. Sodium nitrite and sodium nitrate are added to some meat products to reduce the risk of growth of *C. botulinum*. The resulting red–pink coloration is due to nitric oxide myoglobin and metmyoglobin nitrite.

In fruits and vegetables, chlorophyll is converted to pheophytin, carotenoids are isomerised from 5, 6-epoxides to less intensely coloured 5, 8-epoxides, and anthocyanins are degraded to brown pigments. This loss of colour is often corrected using permitted synthetic colourants (Appendix C). Discolouration of canned foods during storage occurs, for example, when iron or tin react with anthocyanins to form a purple pigment, or when colourless leucoanthocyanins form pink anthocyanin complexes in some varieties of pears and quinces. In sterilised milk slight colour changes are due to caramelisation, Maillard browning and changes in the reflectivity of casein micelles.

In UHT processing, meat pigments change colour, but there is little caramelisation or Maillard browning. Carotenes and betanin are virtually unaffected, and chlorophyll and anthocyanins are better retained. There is an increase in whiteness in the colour of milk.

12.3.2 Flavour and aroma

In canned meats there are complex changes, for example pyrolysis, deamination and decarboxylation of amino acids, degradation, Maillard reactions and caramelisation of carbohydrates to furfural and hydroxymethylfurfural, and oxidation and decarboxylation of lipids. Interactions between these components produce more than 600 flavour compounds in ten chemical classes. In fruits and vegetables, changes are due to complex reactions which involve the degradation, recombination and volatilisation of aldehydes, ketones, sugars, lactones, amino acids and organic acids. In milk the development of a cooked flavour is due to denaturation of whey proteins to form hydrogen sulphide and the formation of lactones and methyl ketones from lipids. In aseptically sterilised foods the changes are again less severe, and the natural flavours of milk, fruit juices and vegetables are better retained. Changes to milk are discussed in detail by Burton (1988).

12.3.3 Texture or viscosity

In canned meats, changes in texture are caused by coagulation and a loss of waterholding capacity of proteins, which produces shrinkage and stiffening of muscle tissues. Softening is caused by hydrolysis of collagen, solubilisation of the resulting gelatin, and melting and dispersion of fats through the product. Polyphosphates (Appendix C) are added to some products to bind water. This increases the tenderness of the product and reduces shrinkage. In fruits and vegetables, softening is caused by hydrolysis of pectic materials, gelatinisation of starches and partial solubilisation of hemicelluloses, combined with a loss of cell turgor. Calcium salts may be added to blancher water (Chapter 10), or to brine or syrup, to form insoluble calcium pectate and thus to increase the firmness of the canned product. Different salts are needed for different types of fruit (for example calcium hydroxide for cherries, calcium chloride for tomatoes and calcium lactate for apples) owing to differences in the proportion of demethylated pectin in each product. Small changes in the viscosity of milk are caused by modification of K-casein, leading to an increased sensitivity to calcium precipitation and coagulation.

In aseptically processed milk and fruit juices the viscosity is unchanged. The texture of solid fruit and vegetable pieces is softer than the unprocessed food due to solubilisation of pectic materials and a loss of cell turgor but is considerably firmer than canned products. The relatively long time required for collagen hydrolysis and the relatively low temperature needed to prevent toughening of meat fibres are conditions found in canning but not in UHT processing. Toughening of meat is therefore likely under UHT conditions. The texture of meat purées is determined by size reduction and blending operations (Chapters 4 and 5) and is not substantially affected by aseptic processing.

Table 12.9 Loss of vitamins in canned and bottled foods (including losses due to preparation and blanching)

Food	Loss (%)									
	Carotene	Thiamin	Riboflavin	Niacin	Vitamin C	Panto- thenic acid	Vitamin B ₆	Folacin	Bio- tin	
<i>Low-acid foods</i>										
Carrots	0-9 (6)	67	38-60	32	75	54	80	59	40	
Beef	—	67	100	100	—	—	—	—	—	
Green beans	22-52	62	54-63	40	79	61	50	57	—	
Mackerel	4	60	39	29	—	—	46	—	—	
Milk	0	35	0	0	50-90	0	50	10-20	—	
Mushrooms	—	80	46	52	33	54	—	84	54	
Peas	0-30 (3)	75 (84)	47 (67)	71 (91)	67 (80)	80	69	59	78	
Potatoes	—	56	44	56	28	—	59	—	—	
Salmon	9	73	0	0	—	58	57	—	—	
Spinach	0-32 (9)	80 (84)	45 (47)	50 (50)	72 (79)	78	75	35	67	
Tomatoes	0 (2)	17 (22)	25 (25)	0 (1)	26 (26)	30	10	54	55	
<i>Acid foods</i>										
Apple	0-4	31	48	—	74	15	0	—	—	
Cherries (sweet)	41	57	64	46	68	—	6	—	—	
Peaches	65 (70)	49 (57)	39	39 (38)	56 (58)	71	21	—	—	
Pears	—	45	45	0	73	69	18	—	—	
Pineapple	25	7 (10)	30	0	57 (57)	12	—	—	—	

The values in parentheses indicate the vitamin loss after storage for 12 months at 10-15°C. Adapted from De Ritter (1982), Rolls (1982), Burger (1982) and March (1982).

Table 12.10 Changes in nutritive value of milk after UHT and in-bottle sterilisation

Nutrient	Loss (%) on processing	
	UHT	In-bottle
Thiamin	10	35
Ascorbic acid	25	90
Vitamin B ₁₂	10	90
Folic acid	10	50
Pantothenic acid	0	0
Biotin	0	0
β -carotene	0	0
Pyridoxine	10	50
Vitamin D	0	0
Whey proteins (denaturation)	12–40 ^a	87
Lysine	–	10
Cystine	–	13
Biological value	–	6

^aDirect UHT at 135°C for 2 s (12.3%) and indirect UHT at 135°C for 2 s (40.3%).

Adapted from Rolls (1982), Kiesker (1972) and Ford *et al.* (1969).

12.3.4 Nutritional value

Canning causes the hydrolysis of carbohydrates and lipids, but these nutrients remain available and the nutritional value of the food is not affected. Proteins are coagulated and, in canned meats, losses of amino acids are 10–20%. Reductions in lysine content are proportional to the severity of heating but rarely exceed 25%. The loss of tryptophan and, to a lesser extent, methionine, reduces the biological value of the proteins by 6–9%. Vitamin losses (Table 12.9) are mostly confined to thiamin (50–75%) and pantothenic acid (20–35%). In canned fruits and vegetables, significant losses may occur in all water-soluble vitamins, particularly ascorbic acid. However, there are large variations owing to differences in the types of food, the presence of residual oxygen in the container, and methods of preparation (peeling and slicing) or blanching (Chapters 3 and 10). In some foods, vitamins are transferred into the brine or syrup, which is also consumed. There is thus a smaller nutritional loss.

Sterilised soya–meat products may show an increase in nutritional value owing to a factor that decreases the stability of the trypsin inhibitor in soy beans. Aseptically processed meat and vegetable products lose thiamin and pyridoxine but other vitamins are largely unaffected. There are negligible vitamin losses in aseptically processed milk (Table 12.10) and lipids, carbohydrates and minerals are virtually unaffected. Riboflavin, pantothenic acid, biotin, nicotinic acid and vitamin B₆ are unaffected. The effect of processing conditions on vitamin content of canned foods are discussed in detail by Lamb *et al.* (1982), and changes in sterilised milk are discussed by Burton (1988). Ramesh (1999) has reviewed vitamin losses during UHT processing. Nutrient losses also occur during periods of prolonged storage, and these should also be considered when assessing the importance of sterilised foods in the diet.

12.4 Acknowledgements

Grateful acknowledgement is made for information supplied by the following: HRS Heat Exchangers Ltd, Watford, Hertfordshire WD1 2DW, UK; APV International Ltd,

Crawley, West Sussex RH10 2QB, UK; Unilever Ltd, London EC4P 4BQ, UK; A Johnson and Co. Ltd, Wokingham, Berkshire RG11 2PU, UK.

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13

Evaporation and distillation

In common with other unit operations that are intended to separate components of foods (Chapter 6), evaporation and distillation aim to separate specific components to increase the value of the food. In both types of operation, separation is achieved by exploiting differences in the vapour pressure (volatility) of the components and using heat to remove one or more from the bulk of the food.

13.1 Evaporation

Evaporation, or concentration by boiling, is the partial removal of water from liquid foods by boiling off water vapour. It increases the solids content of a food and hence preserves it by a reduction in water activity (Chapter 1). Evaporation is used to pre-concentrate foods (for example fruit juice, milk and coffee) prior to drying, freezing or sterilisation and hence to reduce their weight and volume. This saves energy in subsequent operations and reduces storage, transport and distribution costs. There is also greater convenience for the consumer (for example fruit drinks for dilution, concentrated soups, tomato or garlic pastes, sugar) or for the manufacturer (for example liquid pectin, fruit concentrates for use in ice cream or baked goods). Changes to food quality that result from the relatively severe heat treatment are minimised by the design and operation of the equipment. Evaporation is more expensive in energy consumption than other methods of concentration (membrane concentration (Chapter 6)) and freeze concentration (Chapter 22) but a higher degree of concentration can be achieved (Table 13.1).

13.1.1 Theory

During evaporation, sensible heat is transferred from steam to the food, to raise the temperature to its boiling point. Latent heat of vaporisation is then supplied by the steam to form bubbles of vapour, which leave the surface of the boiling liquid. The rate of evaporation is determined by both the rate of heat transfer into the food and the rate of

Table 13.1 A comparison of energy efficiency and degree of concentration in different methods of concentration

	Steam equivalent (cost per kilogram of water removed divided by equivalent cost of steam)	Maximum concentration possible (%)
Ultrafiltration	0.001	28
Reverse osmosis	0.028	30
Freeze concentration	0.090–0.386	40
Evaporation		
Triple effect without aroma recovery	0.370	80
Triple effect with aroma recovery	0.510	80

From Thijssen (1974).

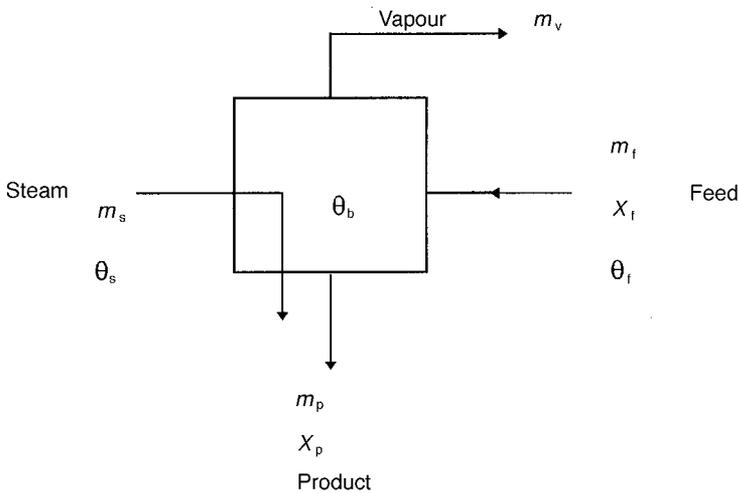


Fig. 13.1 Steady state operation of an evaporator: m_f (kg s^{-1}), mass transfer rate of feed liquor; m_p (kg s^{-1}), mass transfer rate of product; X_f , solids fraction of feed liquor; X_p , solids fraction of feed product; m_v (kg s^{-1}), mass transfer rate of vapour produced; m_s (kg s^{-1}), mass transfer rate of steam used; θ_f ($^{\circ}\text{C}$), initial feed temperature; θ_b ($^{\circ}\text{C}$), boiling temperature of food; θ_s ($^{\circ}\text{C}$), temperature of steam.

mass transfer of vapour from the food. These processes are represented schematically in Fig. 13.1.

Heat and mass balances

Heat and mass balances (Chapter 1) are used to calculate the degree of concentration, energy use and processing times in an evaporator. The mass balance states that ‘the mass of feed entering the evaporator equals the mass of product and vapour removed from the evaporator’. For the water component, this is given by:

$$m_f(1 - X_f) = m_p(1 - X_p) + m_v \quad \boxed{13.1}$$

For solutes, the mass of solids entering the evaporator equals the mass of solids leaving the evaporator:

$$m_f X_f = m_p X_p \quad \boxed{13.2}$$

$$\text{The total mass balance is } m_f = m_p + m_v \quad \boxed{13.3}$$

Assuming that there are negligible heat losses from the evaporator, the heat balance states that 'the amount of heat given up by the condensing steam equals the amount of heat used to raise the feed temperature to boiling point and then to boil off the vapour':

$$Q = m_s \lambda_s = m_f c_p (\theta_b - \theta_f) + m_v \lambda_v \quad \boxed{13.4}$$

where c ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$) = specific heat capacity of feed liquor, λ_s (J kg^{-1}) = latent heat of condensing steam, λ_v (J kg^{-1}) = latent heat of vapourisation of water (Table 13.2). That is:

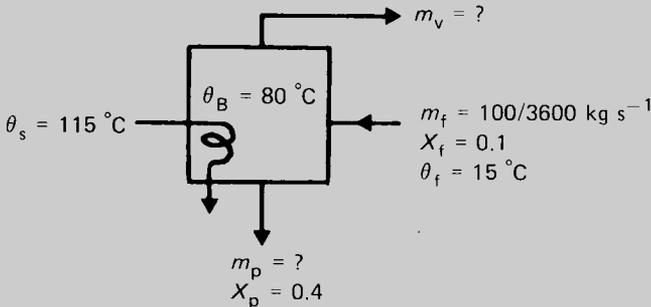
Heat supplied by steam = Sensible heat + Latent heat of vaporisation

The rate of heat transfer across evaporator walls and boundary films (Chapter 1) is found using equation (1.22). ($Q = UA(\theta_s - \theta_b)$.) For the majority of an evaporation process, the rate of heat transfer is the controlling factor and the rate of mass transfer only becomes important when the liquor becomes highly concentrated.

Sample problem 13.1

A single-effect, vertical short-tube evaporator (Section 13.1.2) is to be used to concentrate syrup from 10% solids to 40% solids at a rate of 100 kg h^{-1} . The feed enters at 15°C and is evaporated under a reduced pressure of 47.4 kPa (at 80°C). Steam is supplied at 169 kPa (115°C). Assuming that the boiling point remains constant and that there are no heat losses, calculate the quantity of steam used per hour and the number of tubes required. (Additional data: the specific heat of syrup is constant at $3.960 \text{ kJ kg}^{-1} \text{ K}^{-1}$, the specific heat of water is $4.186 \text{ kJ kg}^{-1} \text{ K}^{-1}$, the latent heat of vaporisation of the syrup is 2309 kJ kg^{-1} , the overall heat transfer coefficient is $2600 \text{ W m}^{-2} \text{ K}^{-1}$ and the latent heat of steam is 2217 kJ kg^{-1} at 115°C .)

Solution to Sample problem 13.1



To find the quantity of steam used per hour, we find that, from equation (13.2),

$$\frac{100}{3600} \times 0.1 = m_p \times 0.4$$

$$m_p = 0.0069 \text{ kg s}^{-1}$$

From equation (13.1),

$$\frac{100}{3600}(1 - 0.1) = 0.0069(1 - 0.4) + m_v$$

$$m_v = 0.0209 \text{ kg s}^{-1}$$

From a mass balance, we find the following table.

	mass (kg s ⁻¹)		
	Solids	Liquid	Total
Feed	0.00278	0.025	0.0278
Product	0.00276	0.00414	0.0069
Vapour			0.0209

From equation (13.4), the heat required for evaporation is

$$\begin{aligned} Q &= 0.0278 \times 3960(80 - 15) + 0.0209 \times 2309 \times 10^3 \\ &= 5.54 \times 10^4 \text{ J s}^{-1} \end{aligned}$$

Now heat supplied by 1 kg of steam per second = latent heat + sensible heat on cooling at 80°C

$$\begin{aligned} &= 2217 \times 10^3 + 1 \times 4186 \times (115 - 80) \\ &= 2.36 \times 10^6 \text{ J s}^{-1} \end{aligned}$$

On the assumption of a heat balance in which the heat supplied by the steam equals the heat required for evaporation,

$$\begin{aligned} \text{mass of steam} &= \frac{5.54 \times 10^4}{2.36 \times 10^6} \\ &= 0.023 \text{ kg s}^{-1} \\ &= 84.5 \text{ kg h}^{-1} \end{aligned}$$

To find the number of tubes, we have from equation (1.22), ($Q = UA\Delta t$) that

$$5.54 \times 10^4 = 2600 \times A(115 - 80)$$

Therefore

$$A = 0.61 \text{ m}^2$$

Now

$$\begin{aligned} \text{area of one tube} &= 0.025 \times 1.55 \times 3.142 \\ &= 0.122 \text{ m}^2 \end{aligned}$$

Thus,

$$\begin{aligned} \text{number of tubes} &= \frac{0.61}{0.122} \\ &= 5 \end{aligned}$$

Table 13.2 Latent heat of vaporisation of water

Temperature (°C)	Latent heat (J kg ⁻¹)
0	2.494×10^6
20	2.448×10^6
40	2.402×10^6
60	2.357×10^6
80	2.309×10^6
100	2.258×10^6

Sample problem 13.2

Milk containing 3.7% fat and 12.8% total solids is to be evaporated to a produce a product containing 7.9% fat. What is the yield of product from 100 kg of milk and what is the total solids concentration in the final product, assuming that there are no losses during the process?

Solution to Sample problem 13.2

$$\text{Mass of fat in 100 kg of milk} = 100 \times 0.037$$

If Y = yield of product:

$$\text{Mass of fat in the evaporated milk} = Y \times 0.079$$

As no fat is gained or lost during the process:

$$0.79 \times Y = 3.7$$

$$\text{Yield}(Y) = 46.8 \text{ kg}$$

$$\text{Mass of solids in the milk} = 100 \times 0.128$$

If Z = % total solids in the evaporated milk

$$\text{Solids in the product} = 46.8 \times (Z/100)$$

i.e.

$$0.4684 \times Z = 12.8$$

$$Z = 27.3\%$$

Related problems are given in Chapter 1 (Sample problems 1.2, 1.7 and 1.8).

Factors influencing the rate of heat transfer

The following factors influence the rate of heat transfer and hence determine processing times and the quality of concentrated products:

- *Temperature difference between the steam and boiling liquid.* There are two options to increase the temperature difference: to increase the pressure and temperature of the steam (Chapter 12, Table 12.6) or to reduce the temperature of the boiling liquid by evaporating under a partial vacuum. In commercial vacuum evaporators the boiling

point may be reduced to as low as 40°C. However, both methods increase the capital cost of equipment because of the extra strength required, and also the cost of energy needed for processing. The temperature difference becomes smaller as foods become more concentrated, owing to elevation of the boiling point, and the rate of heat transfer therefore falls as evaporation proceeds. In large evaporators, the boiling point of liquid at the base may be slightly raised as a result of increased pressure from the weight of liquid above (the hydrostatic head). In such cases measurement of the boiling point for processing calculations is made half-way up the evaporator.

- *Deposits on heat transfer surfaces.* The ‘fouling’ of evaporator surfaces reduces the rate of heat transfer. It depends on the temperature difference between the food and the heated surface and the viscosity and chemical composition of the food. For example, denaturation of proteins or deposition of polysaccharides cause the food to burn onto hot surfaces. Fouling is reduced in some types of equipment by continuously removing food from the evaporator walls (Section 13.1.2). Metal corrosion on the steam side of evaporation equipment would also reduce the rate of heat transfer, but it is reduced by anti-corrosion chemicals or surfaces. Both types of deposit are described in detail by Pulido (1984).
- *Boundary films.* A film of stationary liquid at the evaporator wall is often the main resistance to heat transfer. The thickness of the boundary film is reduced by promoting convection currents within the food or by mechanically induced turbulence (Section 13.1.2). The viscosity of many foods increases as concentration proceeds. This reduces the Reynolds number and hence reduces the rate of heat transfer (details are given in Chapter 1, Section 1.3). In addition, more viscous foods are in contact with hot surfaces for longer periods and, as a result, suffer greater heat damage.

Factors influencing the economics of evaporation

The main factors that influence the economics of evaporation are loss of concentrate or product quality (Section 13.2) and high energy consumption. Product losses are caused by *foaming*, due to proteins and carbohydrates in the food, which causes inefficient separation of vapour and concentrate, and *entrainment*, in which a fine mist of concentrate is produced during the violent boiling, and is carried out of the evaporator by the vapour. Most designs of equipment include disengagement spaces or separators to minimise entrainment.

A substantial amount of energy is needed to remove water from foods by boiling (2257 kJ per kilogram of water evaporated at 100°C). The economics of evaporation are therefore substantially improved by attention to the design and operation of equipment and careful planning of energy use. Smith (1997) describes an energy management system used in a sugar refinery that has resulted in substantial savings in energy consumption.

Energy can be saved by re-using heat contained in vapours produced from the boiling food by:

- *vapour recompression*, in which the pressure (and therefore the temperature) of vapour is increased, using a mechanical compressor or a Venturi-type steam jet. The resulting high pressure steam is re-used as a heating medium.
- *preheating*, in which vapour is used to heat the incoming feed liquor or condensed vapour is used to raise steam in a boiler.
- *multiple effect evaporation*, in which several evaporators (or ‘effects’) are connected together. Vapour from one effect is used directly as the heating medium in the next.

Table 13.3 Steam consumption with vapour recompression and multiple effect evaporation

Number of effects	Steam consumption (kg per kg of water evaporated)	
	Without vapour recompression	With vapour recompression
1	1.1	0.6
2	0.6	0.4
3	0.4	0.3

From Mannheim and Passy (1974).

However, the vapour can only be used to boil liquids at a lower boiling temperature. The effects must therefore have progressively lower pressures in order to maintain the temperature difference between the feed and the heating medium.

The number of effects used in a multiple effect system is determined by the savings in energy consumption (Table 13.3) compared with the higher capital investment required, and the provision of increasingly higher vacua in successive effects (Rumsey *et al.*, 1984). In the majority of applications, three to six effects are used but up to nine effects have been reported (Anon., 1981).

Different arrangements of multiple effect evaporators are shown in Fig. 13.2 using triple-effect evaporation as an example and the relative advantages and limitations of each arrangement are described in Table 13.4.

Table 13.4 Advantages and limitations of various methods of multiple effect evaporation

Arrangement of effects	Advantages	Limitations
Forward feed	Least expensive, simple to operate, no feed pumps required between effects, lower temperatures with subsequent effects and therefore less risk of heat damage to more viscous product	Reduced heat transfer rate as the feed becomes more viscous, rate of evaporation falls with each effect, best quality steam used on initial feed which is easiest to evaporate. Feed must be introduced at boiling point to prevent loss of economy (if steam supplies sensible heat, less vapour is available for subsequent effects)
Reverse feed	No feed pump initially, best-quality steam used on the most difficult material to concentrate, better economy and heat transfer rate as effects are not subject to variation in feed temperature and feed meets hotter surfaces as it becomes more concentrated thus partly offsetting increase in viscosity	Interstage pumps necessary, higher risk of heat damage to viscous products as liquor moves more slowly over hotter surfaces, risk of fouling
Mixed feed	Simplicity of forward feed and economy of backward feed, useful for very viscous foods	More complex and expensive
Parallel	For crystal production, allows greater control over crystallisation and prevents the need to pump crystal slurries	Most complex and expensive of the arrangements, extraction pumps required for each effect

Adapted from Brennan *et al.* (1990).

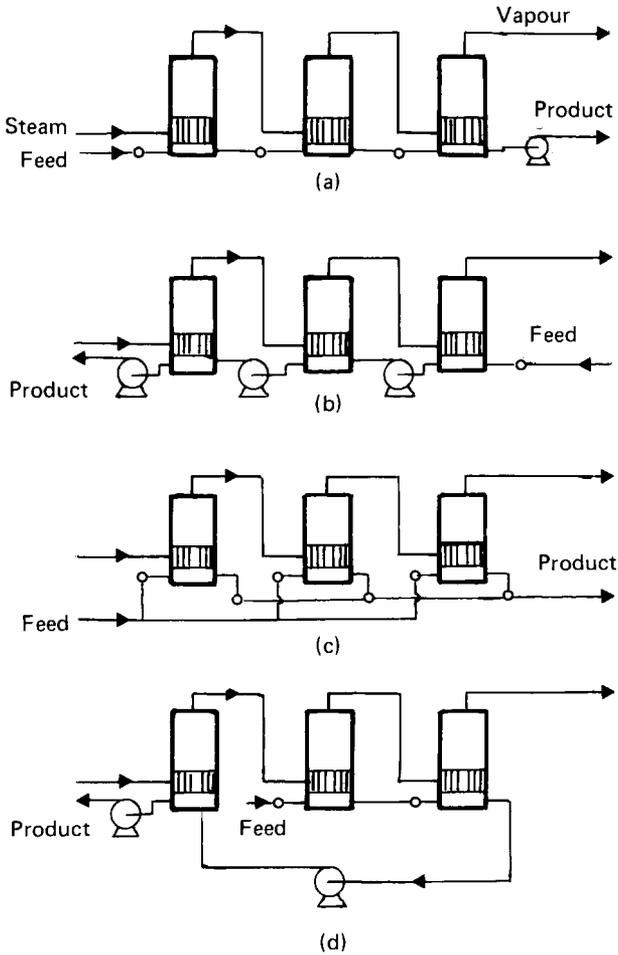


Fig. 13.2 Arrangement of effects in multiple effect evaporation: (a) forward; (b) reverse; (c) parallel; (d) mixed.
(After Brennan *et al.* (1990).)

13.1.2 Equipment

Evaporators consist of:

- a heat exchanger (termed a *calandria*) which transfers heat from steam to the food
- a means of separating the vapours produced
- a mechanical or steam ejector vacuum pump. Mechanical pumps have lower operating costs but higher capital costs than steam ejector pumps.

Separation in an evaporator is achieved by exploiting the difference in volatility between water and solutes. Ideally it should selectively remove water without changing the solute composition, so that the original product is obtained on dilution. This is approached in some equipment but, the closer to the ideal that is achieved, the higher the cost. As with other unit operations the selection of a particular method is therefore a compromise between the cost of production and the quality required in the product. The selection of an evaporator should include the following considerations:

- operating capacity (as kilograms of water removed per hour)
- degree of concentration required (as percentage of dry solids in the product)
- heat sensitivity of the product in relation to the residence time and temperature of evaporation
- the requirement for facilities to recover volatiles
- ease of cleaning
- reliability and simplicity of operation
- size of the evaporator in relation to its capacity
- capital and operating costs in relation to capacity and product quality (Mannheim and Passy, 1974).

Energy consumption is a major factor in evaporation, and significant developments have taken place in computer control of evaporators (for example Anon. (1986), also Chapter 2). The most widespread evaporators for juice concentration are falling film evaporators (see below) and an example of these is the 'thermally accelerated short-time evaporator' (TASTE) (Kennedy *et al.*, 1983). Under manual operation, the steam flow is set at a constant rate and the juice flow is manually adjusted to obtain the required concentration in the final product. This may fluctuate by a several °Brix due to changes in feed composition or other variables in the process and requires skill and experience by the operator to correct the deviation from the required concentration. This results in both off-specification products and wastage of energy. Chen *et al.* (1981) describe computer control systems, involving control of steam and juice temperatures and flowrates to improve the economy of TASTE evaporators.

In some applications it may be more cost effective to combine two types of evaporator, for example initial concentration of the bulk liquor in a low cost evaporator followed by final concentration of the smaller volume of heat sensitive liquor in a more expensive, but less damaging evaporator as the second effect. The majority of evaporator designs operate continuously but batch boiling pans are used for the preparation of small quantities of materials, or in applications where flexibility is required for frequent changes of product.

Natural circulation evaporators

Open- or closed-pan evaporators are hemispherical pans, heated directly by gas or electrical resistance wires or heated indirectly by steam passed through internal tubes or an external jacket. For vacuum operation, they are fitted with a lid. A stirrer or paddle is used to increase the rate of heat transfer and to prevent food from burning onto the pan (see Chapter 5, Fig. 5.8). They are similar in appearance to jacketed mixing vessels. They have relatively low rates of heat transfer (Table 13.5) and low energy efficiencies, and they cause damage to heat-sensitive foods. However, they have low capital costs, are relatively easy to construct and maintain and are flexible for applications where frequent changes of product are likely, or when used for relatively low or variable production rates. They have therefore found wide application in the preparation of ingredients such as sauces and gravies or in the manufacture of jam and other preserves (see, for example, Darrington, 1982).

The *short-tube evaporator* is an example of a tube-and-shell heat exchanger, also used in pasteurisation (Chapter 11) and heat sterilisation (Chapter 12). It consists of a vessel (or shell) which contains a vertical, or less commonly horizontal bundle of tubes. The vertical arrangement of tubes promotes natural convection currents and therefore higher rates of heat transfer (Fig. 13.3). Feed liquor is heated by steam condensing on the outside

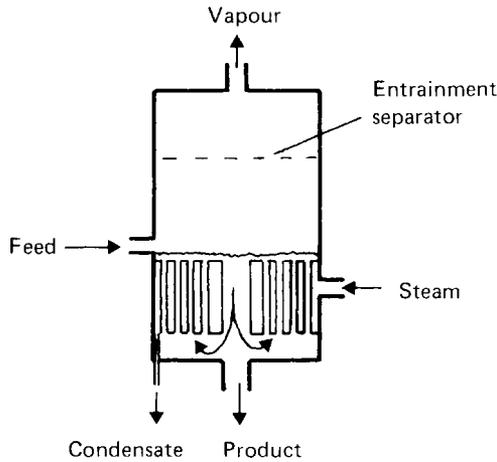


Fig. 13.3 Vertical short-tube evaporator.
(After Karel (1975).)

of the tubes and rises through the tubes, boils and recirculates through a central downcomer tube. *External calandria evaporators* are tube-and-shell heat exchangers which are fitted with an external pipe for recirculation of the product. This increases convection currents and rates of heat transfer, and the calandria is easily accessible for cleaning. They are suitable for concentrating heat-sensitive foods, including dairy products and meat extracts, when operated under partial vacuum.

These evaporators have low construction and maintenance costs, high flexibility and higher rates of heat transfer than open or closed pans, when used with relatively low-viscosity liquids (Table 13.5). They are generally unsuited to high-viscosity liquors as there is poor circulation of liquor and a high risk of food burning onto the tube walls. They are used for concentrating syrups, salt and fruit juices.

Long-tube evaporators consist of a vertical bundle of tubes, each up to 5 cm in diameter, contained within a steam shell 3–15 m high. Liquor is heated almost to boiling point before entering the evaporator. It is then further heated inside the tubes and boiling commences. The expansion of steam forces a thin film of rapidly concentrating liquor up the walls of each tube (Fig. 13.4). The concentrate is separated from the vapour and removed from the evaporator, passed to subsequent effects in a multiple-effect system, or recirculated. Vapour is re-used in multiple-effect or vapour recompression systems (Section 13.1.1).

For low-viscosity foods (for example milk), the thin film of liquor is forced up the evaporator tubes and this arrangement is therefore known as a *climbing-film evaporator*. For more viscous foods, or those that are very heat sensitive, (for example yeast extracts, fruit juices (Anon., 1981) and in starch processing), the feed is introduced at the top of the tube bundle in a *falling-film evaporator*. The force of gravity supplements the forces arising from expansion of the steam, to produce very high liquor flow rates (up to 200 m s^{-1} at the end of 12 m tubes) and short residence times (typically 5–30 s). Multiple-effect systems, capable of evaporating 45 000 l of milk per hour, have been described (Anon., 1986). Both types of long-tube evaporator are characterised by high heat transfer coefficients (Table 13.5) and efficient energy use (0.3–0.4 kg of steam per kilogram of water evaporated in multiple-effect systems). Falling film evaporators are now the most commonly used in the food industry and are described in detail by Burkart and Wiegand (1987).

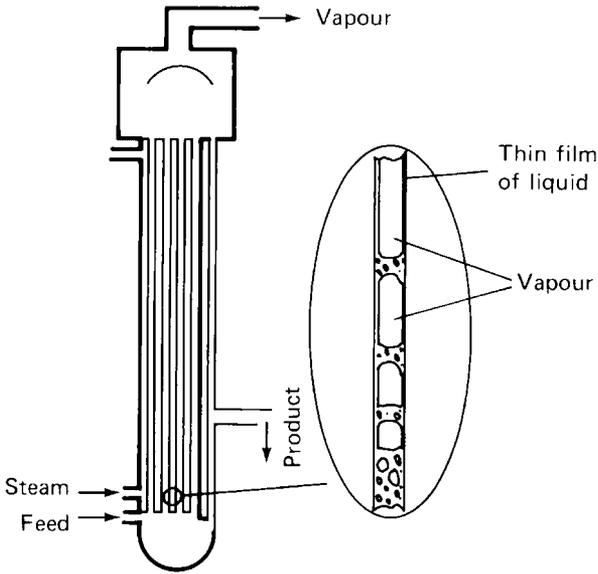


Fig. 13.4 Climbing-film evaporator.

Forced circulation evaporators

In forced-circulation evaporators a pump or scraper assembly moves the liquor, usually in thin layers, and thus maintains high heat transfer rates and short residence times (Table 13.5). This also results in more compact equipment and higher production rates but increases both the capital and the operating costs of the equipment.

Plate evaporators are similar in construction to the heat exchangers used for pasteurisation and ultra high-temperature (UHT) sterilisation (Chapters 11 and 12). However, in this case the climbing- and falling-film principle is used to concentrate liquids in the spaces between plates. The number of climbing- or falling-film sections fitted within a single machine depends on the production rate and degree of concentration required. The mixture of vapour and concentrate is separated outside the evaporator. Despite the high capital investment, these types of evaporator have high rates of heat transfer, short residence times and high energy efficiencies (Table 13.5). They are compact, capable of high throughputs and easily dismantled for maintenance and inspection. They are more suitable for heat-sensitive foods of higher viscosity ($0.3\text{--}0.4\text{ N s m}^{-2}$) including yeast extracts, dairy products, fruit juices, low alcohol drinks and meat extracts. Their advantages, compared to other falling film evaporators, are described by Olsson (1988).

The *expanding-flow evaporator* uses similar principles to the plate evaporator but has a stack of inverted cones instead of a series of plates. Feed liquor flows to alternate spaces between the cones from a central shaft and evaporates as it passes up through channels of increasing flow area (hence the name of the equipment). Steam is fed down alternate channels. The vapour-concentrate mixture leaves the cone assembly tangentially and is separated by a special design of shell which induces a cyclone effect. This evaporator has a number of advantages including compactness, short residence times and a high degree of flexibility achieved by changing the number of cones.

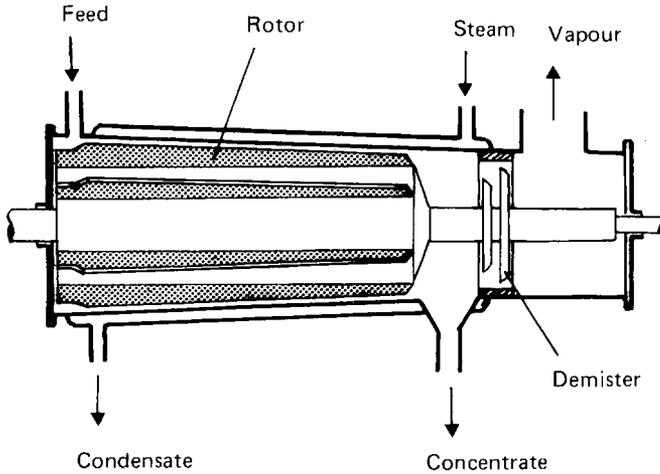


Fig. 13.5 Mechanical thin film evaporator.
(After Leniger and Beverloo (1975).)

Mechanical (or agitated) thin-film evaporators

Scraped- or wiped-surface evaporators are characterised by differences in the thickness of the film of food being processed. Wiped-film evaporators have a film thickness of approximately 0.25 mm whereas in scraped-film evaporators it is up to 1.25 mm. Both types consist of a steam jacket surrounding a high-speed rotor, fitted with short blades along its length (Fig. 13.5). The design is similar to a scraped-surface aseptic steriliser (Chapter 12). Feed liquor is introduced between the rotor and the heated surface and evaporation takes place rapidly as a thin film of liquor is swept through the machine by the rotor blades. The blades keep the film violently agitated and thus promote high rates of heat transfer and prevent the product from burning onto the hot surface (Anon., 1981). The residence time of the liquor is adjusted between 0.5 s and 100 s depending on the type of food and the degree of concentration required.

This type of equipment is highly suited to viscous (up to 20 N s m^{-2}) heat-sensitive foods or to those that are liable to foam or foul evaporator surfaces (for example fruit pulps and juices, tomato paste, meat extracts, honey, cocoa mass, coffee and dairy products). However, the capital costs are high owing to the precise alignment required between the rotor and wall. Operating costs are also high as only single effects are possible, which reduces the throughput and gives poor steam economy. It is therefore used for 'finishing' highly viscous products after concentration in other equipment where there is less water to be removed, the product is valuable and there is a substantial risk of heat damage.

A second design of mechanical thin-film evaporator is the *Centri-therm evaporator* which, although similar in appearance to the expanding flow evaporator, operates using a different principle. Here, liquor is fed from a central pipe to the undersides of rotating hollow cones. It immediately spreads out to form a layer approximately 0.1 mm thick. Steam condenses on the other side of each cone, and rapidly evaporates the liquor. In contrast with the expanding-flow evaporator, in which liquid is moved by vapour pressure, the Centri-therm employs centrifugal force to move the liquor rapidly across the heated surface of the cone. Residence times are 0.6–1.6 s (Lewicki and Kowalczyk,

Table 13.5 Comparison of residence times and heat transfer coefficients in selected evaporators

Type of evaporator	Number of stages	Residence time (approximate)	OHTC ($\text{W m}^{-2} \text{K}^{-1}$)	
			Low viscosity	High viscosity
Open or vacuum pan	Single	30 min to several hours	500–1000	< 500
Vertical short tube	Single	–	570–2800	–
Climbing film	Single	10–60 sec	2250–6000	< 300
Falling film	Single	5–30 sec	2000–3000	–
Plate	Three	2–30 sec	2000–3000	–
Expanding flow	Two	0.5–30 sec	2500	–
Agitated film	Single	20–30 sec	2000–3000	1700
Centri-Therm	Single	1–10 sec	8000	–

Adapted from Mannheim and Passy (1974) and Earle (1983).

1980), even with concentrated liquors (up to 20 N s m^{-2}). Very high heat transfer coefficients and short residence times are possible (Table 13.5). This is due in part to the thin layers of liquor but also to the droplets of condensed steam which are flung from the rotating cones as fast as they are formed. There is therefore no boundary film of condensate to impede heat transfer. The equipment produces a concentrate which, when rediluted, has sensory and nutritional qualities that are virtually unchanged from those of the feed material. It is used for coffee and tea extracts, meat extract, fruit juices (Fischer *et al.*, 1983) and enzymes for use in food processing.

13.2 Effect on foods

Aroma compounds that are more volatile than water are thus lost during evaporation. This reduces the sensory characteristics of most concentrates; in fruit juices this results in a loss of flavour, although in some foods the loss of unpleasant volatiles improves the product quality (for example in cocoa (Anon., 1981) and milk). Some volatiles can be recovered and retained in the product:

- by volatile recovery by vapour condensation and fractional distillation
- by stripping volatiles from the feed liquor with inert gas and adding them back after evaporation (see also the spinning cone column in Section 13.3).

These methods are described in more detail in Section 13.3. The advantages and limitations of each procedure have been reviewed by Mannheim and Passy (1972) and Thijssen (1970). Flash coolers, in which the food is sprayed into a vacuum chamber, are used to cool a viscous product rapidly and hence to reduce heat damage.

Evaporation darkens the colour of foods, partly because of the increase in concentration of solids, but also because the reduction in water activity promotes chemical changes, (for example Maillard browning (Chapter 1)). As these changes are time and temperature dependent, short residence times and low boiling temperatures produce concentrates which have a good retention of sensory and nutritional qualities. A comparison of nutrient losses in milk preserved by evaporation and UHT sterilisation is shown in Table 13.6. Vitamins A and D and niacin are unaffected. Additional vitamin losses occur during storage (for example 50% loss of vitamin C in marmalade over 12 months at 18°C (Lincoln and McCay, 1945) and 10% loss of thiamin over 24 months in peanut butter at 18°C).

Table 13.6 Vitamin losses in concentrated and UHT sterilised milk

Product	Loss (%)				
	Thiamin	Vitamin B ₆	Vitamin B ₁₂	Folic acid	Ascorbic acid
Evaporated milk	20	40	80	25	60
Sweetened condensed milk	10	< 10	30	25	25
UHT sterilised milk	< 10	< 10	< 10	< 10	< 25

From Porter and Thompson (1976).

13.3 Distillation

Although common in the chemical industry, distillation in food processing is mostly confined to the production of alcoholic spirits and separation of volatile flavour and aroma compounds (for example, production of essential oils by steam distillation).

When a food that contains components having different degrees of volatility is heated, those that have a higher vapour pressure (more volatile components) are separated first. These are termed the 'distillate' and components that have a lower volatility are termed 'bottoms' or residues. Although batch distillation (in 'pot stills') remains in use in some whisky and other spirit distilleries, most industrial distillation operations use more economical continuous distillation columns (Fig. 13.6a,b) (Kent and Evers, 1994). Feed liquor flows continuously through the column and as it is heated, volatiles are produced and separated at the top of the column as distillate and the residue is separated at the base. In order to enhance the separation of these components and equilibrium conditions between the liquid and vapour phases, a proportion of the distillate is added back to the top of the column (reflux) and a portion of the bottoms is vapourised in a reboiler and added to the bottom of the column. Columns are filled with either a packing material (typically ceramic, plastic or metal rings) or fitted with perforated trays, both of which increase the contact between liquid and vapour phases.

A more recent development is the use of a 'spinning cone column' to remove volatile components from liquids. It is used to recover flavours from beer, coffee, tomato products and fruit juices, to produce low-alcohol wines and beers and to remove off-flavours. The equipment consists of a column containing a series of rotating inverted cones, which are intermeshed with stationary cones attached to the column wall. Steam or nitrogen is supplied to the base of the column and the feed liquor enters at the top. Thin turbulent films are produced over the large surface area of the cones and rapid separation takes place. The gas passes out of the top of the column and volatile aroma compound are condensed and collected. Because separation is achieved by mechanical energy, rather than heat, there is less damage to flavours and lower energy consumption. The equipment is also considerably smaller than a packed column having an equivalent throughput (Schofield, 1995).

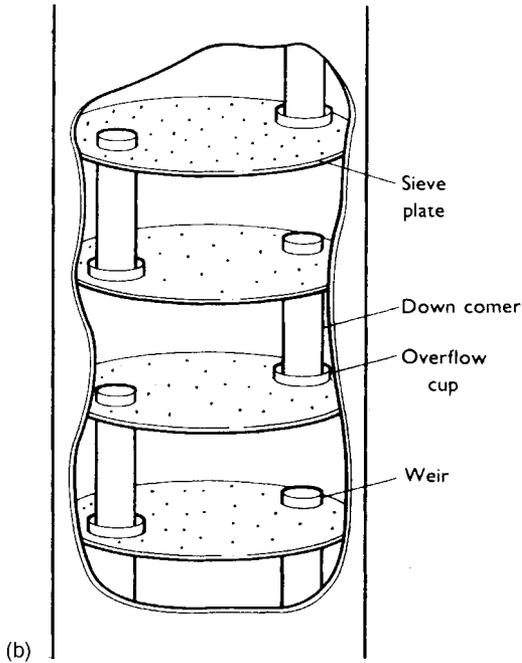
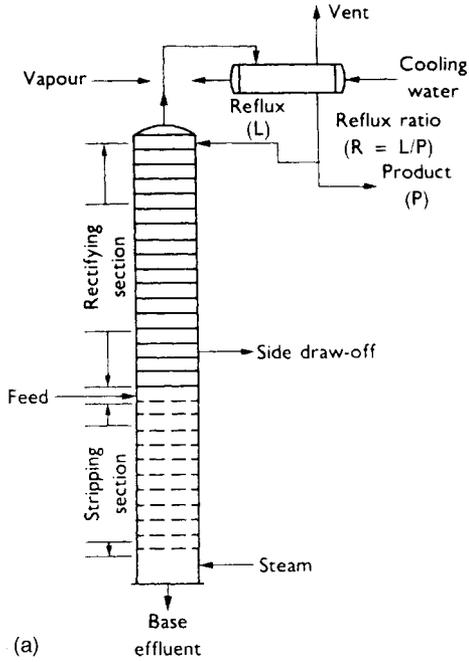


Fig. 13.6 (a) Continuous distillation column and (b) internal plates in the column to promote cross-flow.
(From Panek and Boucher (1989).)

13.4 Acknowledgements

Grateful acknowledgement is made for information supplied by APV Nordic, Anhydro Ltd, DK-2860 Soborg-Copenhagen, Denmark; Brierley, Collier & Hartley Equipment Ltd, Rochdale, Lancashire OL11 4EX, UK.

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14

Extrusion

Extrusion is a process which combines several unit operations including mixing, cooking, kneading, shearing, shaping and forming. Extruders are classified according to the method of operation (cold extruders or extruder-cookers) and the method of construction (single- or twin-screw extruders). The principles of operation are similar in all types: raw materials are fed into the extruder barrel and the screw(s) then convey the food along it. Further down the barrel, smaller flights restrict the volume and increase the resistance to movement of the food. As a result, it fills the barrel and the spaces between the screw flights and becomes compressed. As it moves further along the barrel, the screw kneads the material into a semi-solid, plasticised mass. If the food is heated above 100°C the process is known as *extrusion cooking* (or *hot extrusion*). Here, frictional heat and any additional heating that is used cause the temperature to rise rapidly. The food is then passed to the section of the barrel having the smallest flights, where pressure and shearing is further increased. Finally, it is forced through one or more restricted openings (dies) at the discharge end of the barrel. As the food emerges under pressure from the die, it expands to the final shape and cools rapidly as moisture is flashed off as steam. A variety of shapes, including rods, spheres, doughnuts, tubes, strips, squirls or shells can be formed. Typical products include a wide variety of low density, expanded snackfoods and ready-to-eat (RTE) puffed cereals (Table 14.1). Developments using combined supercritical fluid technology (Chapter 6) with extruders to produce a new range of puffed products, pasta and confectionery are described by Rizvi *et al.* (1995). Extruded products may be subsequently processed further by drying (Chapter 15), frying (Chapter 17) or packaging (Chapters 24, 25). Many extruded foods are also suitable for coating or enrobing (Chapter 23). Further details of extrusion technology are given by O'Connor (1987).

Cold extrusion, in which the temperature of the food remains at ambient is used to mix and shape foods such as pasta and meat products. Low pressure extrusion, at temperatures below 100°C, is used to produce, for example, liquorice, fish pastes, surimi and pet foods (Table 14.1 and Section 14.3).

Extrusion cooking is a high-temperature short-time (HTST) process which reduces microbial contamination and inactivates enzymes. However, the main method of

Table 14.1 Examples of extruded foods

Types of product	Examples
Cereal-based products	Expanded snackfoods RTE and puffed breakfast cereals Soup and beverage bases, instant drinks Weaning foods Pre-gelatinised and modified starches, dextrins Crispbread and croutons Pasta products Pre-cooked composite flours
Sugar-based products	Chewing gum Liquorice Toffee, caramel, peanut brittle Fruit gums
Protein-based products	Texturised vegetable protein (TVP) Semi-moist and expanded petfoods and animal feeds and protein supplements Sausage products, frankfurters, hot dogs Surimi Caseinates Processed cheese

Adapted from Harper (1979), Harper (1987), Heldman and Hartel (1997), Jones (1990) and Best (1994).

preservation of both hot- and cold-extruded foods is by the low water activity of the product (0.1–0.4) (Chapter 1), and for semi-moist products in particular, by the packaging materials that are used.

Extrusion has gained in popularity for the following reasons:

- *Versatility*. A very wide variety of products are possible by changing the ingredients, the operating conditions of the extruder and the shape of the dies. Many extruded foods cannot be easily produced by other methods.
- *Reduced costs*. Extrusion has lower processing costs and higher productivity than other cooking or forming processes. Some traditional processes, including manufacture of cornflakes and frankfurters, are more efficient and cheaper when replaced by extrusion (Section 14.3).
- *High production rates and automated production*. Extruders operate continuously and have high throughputs. For example, production rates of up to 315 kg h^{-1} for snackfoods, 1200 kg h^{-1} for low-density cereals and 9000 kg h^{-1} for dry expanded petfoods are possible (Mans, 1982). Details of automatic control of extruders are described by Olkku *et al.* (1980) and Bailey *et al.* (1995).
- *Product quality*. Extrusion cooking involves high temperatures applied for a short time and the limited heat treatment therefore retains many heat sensitive components.
- *No process effluents*. Extrusion is a low-moisture process that does not produce process effluents. This eliminates water treatment costs and does not create problems of environmental pollution.

Extrusion can be seen as an example of a size enlargement process, in which granular or powdered foods are re-formed into larger pieces. Other examples of size enlargement include forming or moulding (Chapter 5) and agglomeration of powders (Chapter 15). Extruders are also used in the plastics industry to produce packaging materials (Chapter 24).

14.1 Theory

Because extrusion involves simultaneous mixing, kneading and cooking, it causes a large number of complex changes to a food, including hydration of starches and proteins, homogenisation, gelation, shearing, melting of fats, denaturation or re-orientation of proteins, plastification and expansion of the food structure. For many years the empirical knowledge of extruder operators outstripped scientific theory of the sequence and nature of these interactions and their effects. However, computer modelling of fluid flow behaviour and heat transfer inside the extruder barrel has more recently led to a greater understanding of the operation of extruders (Kulshreshtha *et al.* (1995), Tan and Hofer (1995), Eley *et al.* (1997) and Schoner and Moreira (1997). The two factors that most influence the nature of the extruded product are the rheological properties of the food and the operating conditions of the extruder.

14.1.1 Rheological properties of the food

The properties of the feed material have an important influence on the texture and colour of the product; the most important factors are:

- the type of feed materials
- their moisture content
- the physical state of the materials
- their chemical composition, particularly the amounts and types of starches, proteins, fats and sugars
- the pH of the moistened material.

The composition of the feed material, its moisture content and particle size all influence the viscosity of the product in the extruder. From equations (14.1) and (14.2) below, it can be seen that viscosity is a crucial factor that determines the operating conditions of the extruder and hence the product quality. Different types of feed material produce completely different products when the same operating conditions are used in the same extruder. This is because of differences in the type and amounts of starch, proteins, moisture and other added ingredients (for example oil or emulsifier), which result in different viscosities and hence different flow characteristics. Similarly, addition of acids to adjust the pH of the feed material causes changes to starch gelatinisation and unfolding of protein molecules. This in turn changes the viscosity and hence the structure and strength of the extruded product. Differences in sugar content or pH also produce variations in colour due to different extents of Maillard browning reactions.

During extrusion cooking of starch-based foods, added water causes the starch granules to swell and absorb water to become hydrated. Smaller particles, such as flours or grits, are hydrated and cooked more rapidly than larger particles and this in turn also alters the product quality. The increased moisture content and elevated temperatures cause the starch to gelatinise and a viscous plasticised mass is produced (Mercier, 1980). Gelatinisation of starch usually causes an increase in viscosity, but in extrusion cookers the intense shearing action can also break macro-molecules down to smaller units, resulting in a reduction in viscosity.

As the product leaves the die, it is in a glassy state. It expands rapidly and as it cools, the temperature falls below the glass transition state and strands and matrices form that set the structure and determine the product texture (Blanshard, 1995). Results of detailed research on the changes to starch are described by Guy (1993).

The changes in starch solubility under different conditions of temperature and shear rate are monitored by measuring the *Water Absorption Index* (WAI) and the *Water Solubility Characteristic* (WSC). The WSC decreases as the WAI increases. The WAI of cereal products generally increases with the severity of processing, reaching a maximum at 180–200°C.

Soy proteins, gluten or caseinate molecules unfold in the hot moist conditions to produce a uniform, viscous plasticised mass. The shearing action prevents re-alignment of the molecules until they emerge from the die. Then the expansion and cooling cause the proteins to polymerise, cross-link and re-orient to form a characteristic fibrous structure and set the final texture of the product. The *nitrogen solubility index* is a measure of the extent of protein denaturation. It decreases during extrusion cooking, and feed materials should therefore have largely undenatured proteins.

14.1.2 Operating characteristics

The most important operating parameters in an extruder are:

- temperature
- pressure
- diameter of the die apertures
- shear rate.

The shear rate is influenced by the internal design of the barrel, its length and the speed and geometry of the screw(s).

Most research to model extruders has been done with single-screw machines (Fig. 14.1 and Section 14.2) because twin-screw extruders are substantially more complex. In operation, the single-screw extruder acts as a type of pump, dragging the food through the barrel and increasing the pressure and temperature before the food is forced through the die. For optimum pumping, the food should stick to the barrel and slip freely from the screw surface (Heldman and Hartel, 1997). However, if food slips on the barrel it does not move through the extruder and is simply mixed. For this reason, the barrel wall is often grooved to minimise slipping.

A simplified model for the operation of an extruder, developed by Harper (1981), assumes that the temperature of the food is constant, fluid flow is Newtonian and laminar

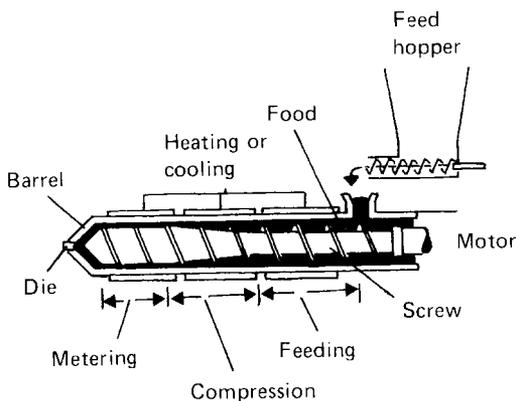


Fig. 14.1 A single-screw extruder.
(Courtesy of Werner and Pfeiderer Ltd.)

(Chapter 1), there is no slip at the barrel wall and no leakage between the screw and the barrel. With these assumptions, the flow through a single screw extruder is calculated using equation (14.1):

$$Q = G_1 N F_d + G_2 / \mu \cdot \Delta P / L \cdot F_p \quad \boxed{14.1}$$

where $Q (\text{m}^3 \text{s}^{-1})$ = volumetric flow rate in the metering section (Fig. 14.1), $N (\text{rpm})$ = screw speed, $\mu (\text{N s m}^{-2})$ = viscosity of the fluid in the metering section, $\Delta P (\text{Pa})$ = pressure increase in the barrel, G_1 and G_2 = constants that depend on screw and barrel geometry, $L (\text{m})$ = length of extruder channel and F_d and F_p = shape factors for flow due to drag and pressure respectively.

The first part of the equation represents fluid flow down the barrel caused by pumping and drag against the barrel wall, whereas the second part represents backward flow from high pressure to low pressure, caused by the increase in pressure in the barrel. Clearly, the amount of pressure in the barrel depends in part on the size of the dies; if the barrel is completely open at the die end, there will be no pressure build-up and the extruder will simply act as a screw conveyor. Conversely, if the die end is completely closed, the pressure will increase until backward flow equals drag flow and no further movement will occur. The extruder would become a mixer. In between these two extremes, the size of the die greatly affects the performance of the extruder. The ratio of pressure to drag flow is known as the *throttling factor* (a) which varies from zero (open die hole) to 1 (die hole is closed). In practice, most extruders operate with a values of between 0.2 and 0.5 (Heldman and Hartel, 1997).

The flow through the die is found using equation (14.2):

$$Q = K' \cdot \Delta P / \mu \quad \boxed{14.2}$$

where $Q (\text{m}^3 \text{s}^{-1})$ = volumetric flow rate through the die (Fig 14.1), $\mu (\text{N s m}^{-2})$ = viscosity of the fluid in the die, $\Delta P (\text{Pa})$ = pressure drop across the die (from inside the barrel to atmospheric pressure) and K' = a flow resistance factor that depends on the number, shape and size of the die holes, usually found experimentally.

The operating conditions for the extruder can be found by calculating the flow rate and die pressure drop that satisfy both equations. This is shown diagrammatically in Fig. 14.2. The position of the operating point is determined by the type of die, depth of flights on the screw, length and speed of the screw.

It should be noted that the above formulae are based on simple models that do not take account of, for example, leakage of food between the flights and the barrel, a partially empty barrel, changes in temperature and the effects of non-Newtonian fluids. One such fluid is a starch slurry which becomes gelatinised during extrusion and its rheological properties change as it moves through the extruder. It is important that the screw speed (and hence the residence time) is balanced with the extent of heating to obtain the required characteristics in the final product, but this may be very difficult to model as changes in non-Newtonian fluids are significantly more complicated. In practice, therefore, the assumptions made in the formulae may limit their usefulness for predicting flow behaviour or operating conditions, but may be used as a starting point for experimental studies. Most extruder manufacturers use a combination of more sophisticated models and practical experience of the relationships between die shape, extruder construction and characteristics of the product to design their equipment. The situation with twin-screw extruders is even more complex: changes to the degree of inter-meshing of the screws (Section 14.2) or the direction of rotation dramatically alter the flow characteristics in the extruder and make modelling equations very complex.

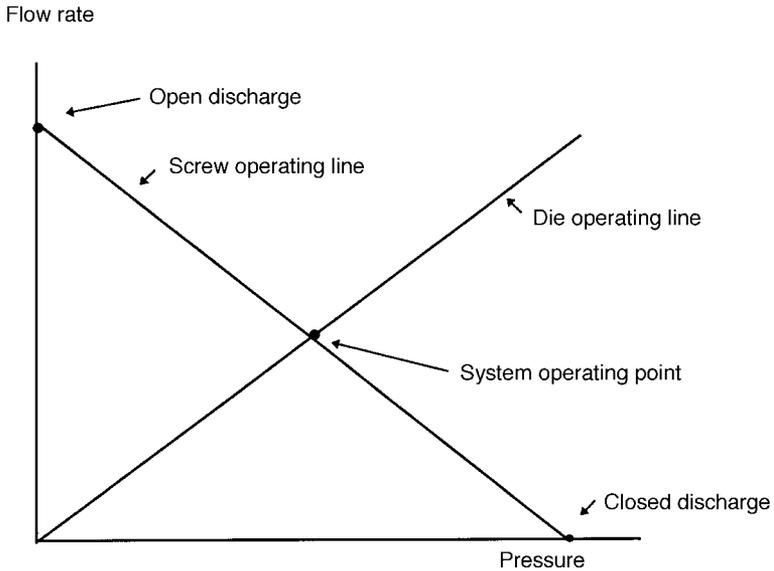


Fig. 14.2 Determination of operating point for a single screw extruder. (Adapted from Miller (1990).)

The rate of heat transfer between a heated barrel jacket and the food during extrusion cooking is found using equation (1.22) in Chapter 1. Related sample problems are found in Chapter 1 (Sample problems 1.7 and 1.8).

14.2 Equipment

14.2.1 Single-screw extruders

The equipment (Fig. 14.1) consists of a cylindrical screw that rotates in a grooved cylindrical barrel, made from hard alloys or hardened stainless steel to withstand the frictional wear. The length to diameter ratio of the barrel is between 2:1 and 25:1 (Hauck, 1993). The pitch and diameter of the screw, the number of flights and the clearance between the flights and the barrel can each be adjusted to change the performance of the extruder. The screw is driven by a variable speed electric motor that is sufficiently powerful to pump the food against the pressure generated in the barrel. The screw speed is one of the main factors that influences the performance of the extruder: it affects the residence time of the product, the amount of frictional heat generated, heat transfer rates and the shearing forces on the product. Typical screw speeds are 150–600 rpm, depending on the application. Compression is achieved in the extruder barrel by back pressure, created by the die and by:

- increasing the diameter of the screw and decreasing the screw pitch
- using a tapered barrel with a constant or decreasing screw pitch
- placing restrictions in the screw flights.

Die pressures vary from around 2000×10^3 Pa for low viscosity products to $17\,000 \times 10^3$ Pa for expanded snackfoods (Heldman and Hartel, 1997).

Single-screw extruders can be classified according to the extent of shearing action on the food into:

Table 14.2 Operating data for different types of extruder

Parameter	High shear	Medium shear	Low shear
Net energy input to product (kWh kg ⁻¹)	0.10–0.16	0.02–0.08	0.01–0.04
Barrel length:diameter (L/D)	2–15	10–25	5–22
Screw speed (rpm)	> 300	> 200	> 100
Maximum barrel temperature (°C)	110–180	55–145	20–65
Maximum product temperature (°C)	149	79	52
Maximum barrel pressure (kPa)	4000–17 000	2000–4000	550–6000
Product moisture (%)	5–8	15–30	25–75
Product density (kg/m ³)	32–160	160–500	320–800

Adapted from Hauck (1993) and Harper (1979).

- *High shear.* High speeds and shallow flights create high pressures and temperatures that are needed to make breakfast cereals and expanded snackfoods.
- *Medium shear.* For breadings, texturised proteins and semi-moist petfoods.
- *Low shear.* Deep flights and low speeds create low pressures for forming pasta, meat products and gums.

Operating data for different types of extruder are given in Table 14.2.

In extrusion cooking, much of the energy from the extruder motor is lost as friction and rapidly heats the food (between 50 and 100% of total energy input (Harper, 1987)). Additional heating can be achieved using a steam-jacketed barrel and/or by a steam-heated screw (in some applications the jacket is also used to cool the product using cold water). In other designs, electric induction heating elements are used to heat the barrel directly. Some products also require the extruder die to be heated to maintain the viscosity and degree of expansion, whereas others require the die to be cooled to reduce the amount of expansion. The temperature and pressure profiles in different sections of a high-shear cooking extruder are shown in Fig. 14.3.

Single-screw extruders have lower capital and operating costs and require less skill to operate and maintain than twin-screw machines do. They are used for straightforward cooking and forming applications, when the flexibility of a twin-screw machine is not needed.

14.2.2 Twin-screw extruders

The screws in twin-screw extruders rotate within a ‘figure of 8’ shaped bore in the barrel. Screw length to diameter ratios are between 10:1 and 25:1 (Harper, 1987). Extruders are classified according to the direction of rotation and the way in which the screws intermesh. Co-rotating intermeshing screws, which are self-wiping (the flights of one screw sweep food from the adjacent screw) are most commonly found in food-processing applications (Fig. 14.4). The spacing between the flights can be adjusted so that large spaces initially convey the material to the cooking section and then smaller spaces compress the plasticised mass before extrusion through an inter-changeable die. One of the main advantages of twin-screw extruders is the greater flexibility of operation that is possible by changing the degree of intermeshing of the screws, the number of flights or the angle of pitch of the screw. ‘Kneading discs’ can also be fitted to the screws so that

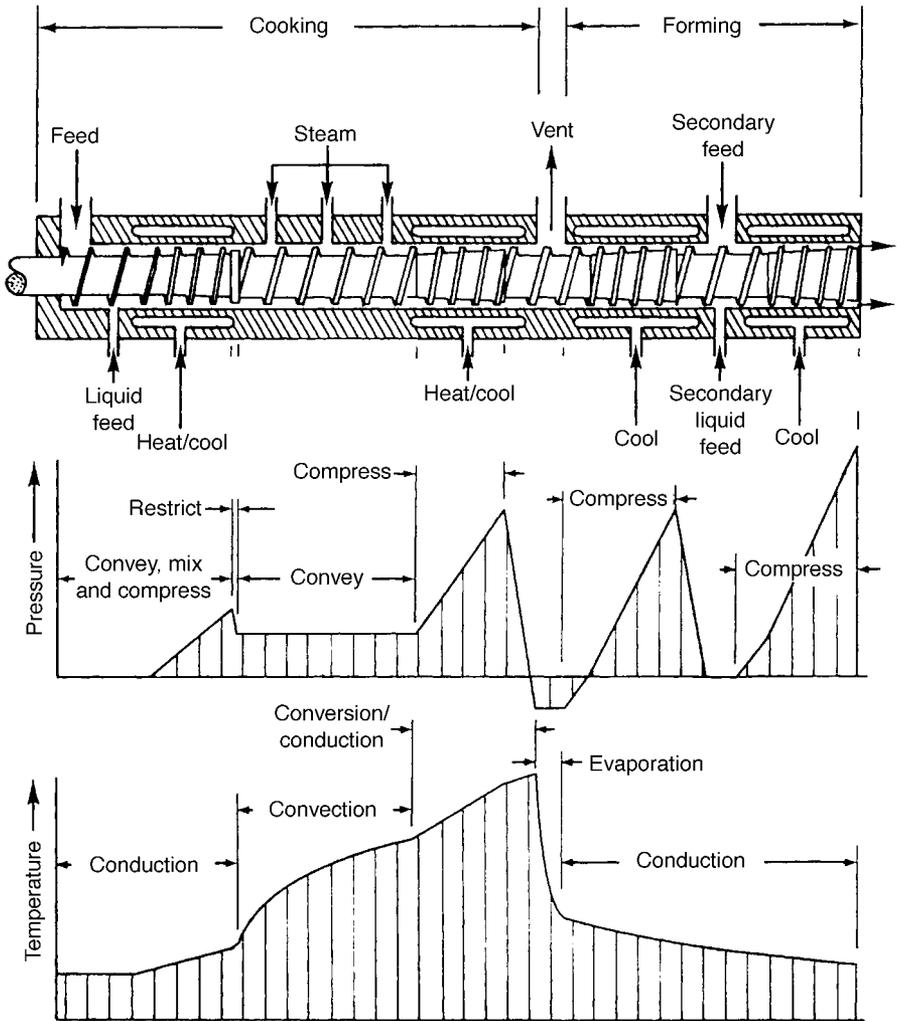


Fig. 14.3 Changes in temperature and pressure in a high shear cooking extruder for expanded food products.
(From Miller (1990).)

the product passes between and through the discs to increase the kneading action. Their operating characteristics are described by Frame (1994).

Twin-screw extruders have the following advantages:

- The throughput is independent of feedrate, and fluctuations in production rate can be accommodated by the positive displacement action of the screws. In contrast, a single screw must be full of material to operate effectively. The positive displacement also produces higher rates of heat transfer and better control of heat transfer than a single screw does.
- Twin-screw machines handle oily, sticky or very wet materials, or other products that slip in a single screw. The limitations for single- and twin-screw machines are respectively 4% and 20% fat, 10% and 40% sugar, and 30% and 65% moisture. There is therefore greater flexibility in operation using different raw materials.

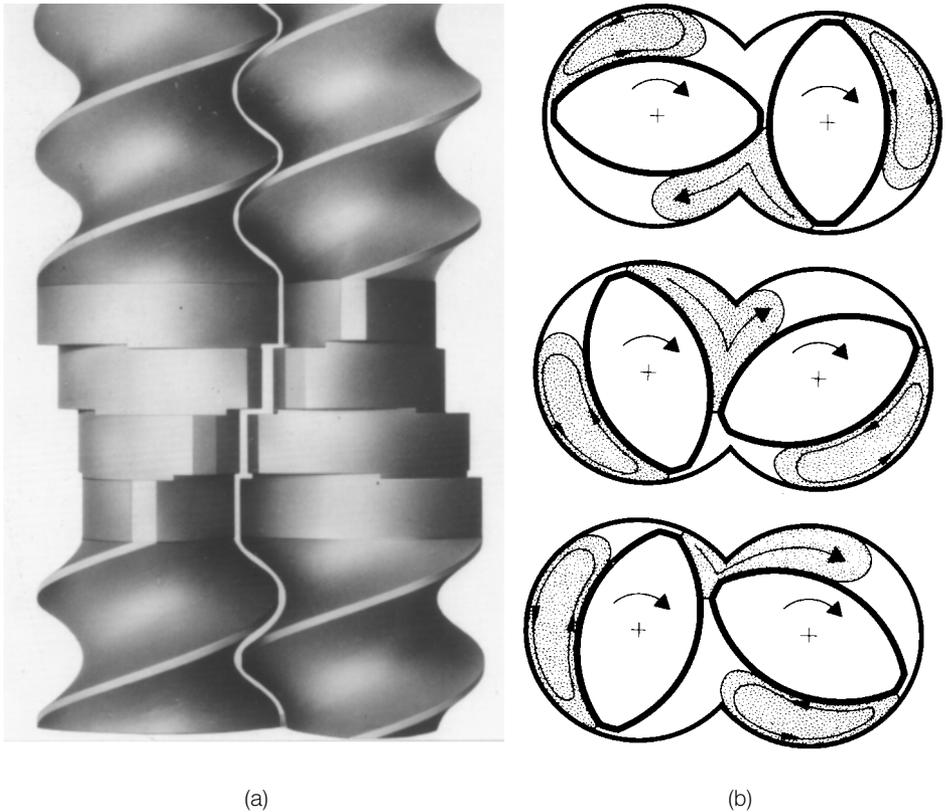


Fig. 14.4 Kneading elements of a co-rotating twin-screw extruder showing dough mixing: (a) sealing profile; (b) movement of material. (Courtesy of Werner and Pfleiderer Ltd.)

- Forward or reverse conveying is used to control the pressure in the barrel. For example, in the production of liquorice and fruit gums, the food is heated and compressed by forward conveying, the pressure is released by reverse conveying, to vent excess moisture or to add additional flavour ingredients, and the food is then recompressed for extrusion.
- A short discharge section develops the pressure required for extrusion and thus subjects a smaller part of the machine to wear than in single-screw extruders.
- A mixture of particle sizes, from fine powders to grains, may be used, whereas a single screw is limited to a specific range of granular particle sizes.

The main limitations of twin-screw extruders are the relatively high capital and maintenance costs (up to twice the cost of single-screw equipment) and the greater constraints on operating ranges (Harper, 1987). The complex gearbox that is needed to drive the twin screws results in limitations on the maximum torque, pressure and thrust that can be achieved.

14.2.3 Ancillary equipment

Powders and granular feed materials are first blended with water, steam or other liquids in a preconditioner, to moisten them before feeding into the extruder (Fig. 14.5). This

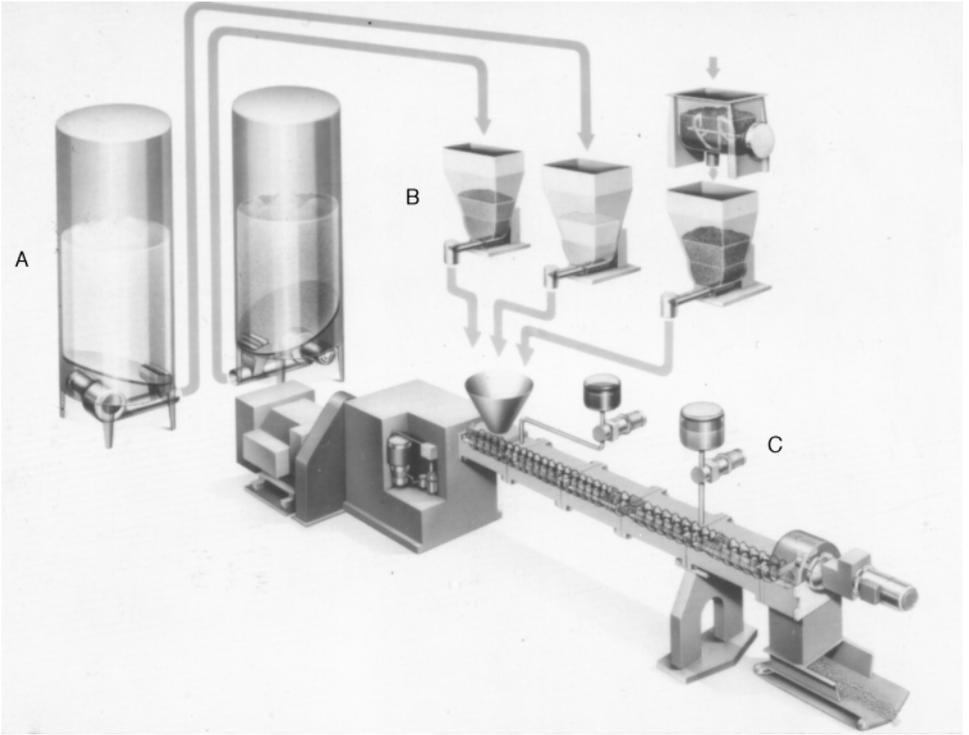


Fig. 14.5 Ancillary equipment with a twin-screw extruder: (A) pre-conditioners; (B) feed hoppers; (C) positive displacement pumps.
(Courtesy of Werner and Pfeiderer Ltd.)

produces a more uniform feed material that can be more accurately metered and provides more uniform extrusion conditions. The residence time in either batch or continuous preconditioners is closely controlled to ensure that each particle is uniformly blended with the liquid, and for steam conditioning, that there is uniform temperature equilibration. Preconditioning with steam or hot water for up to 4.5 mins increases the feed temperature and moisture content, gelatinises starch and denatures proteins. This improves the extruder efficiency, lowers specific energy consumption and reduces equipment wear and maintenance costs (Bailey *et al.*, 1995).

Extruders are fitted with feed hoppers that have screw augers or vibrating feeders to load material at a uniform rate into the barrel. The weight of product on a feeder (or loss in weight of the hopper) is used to automatically control the feedrate. Other control methods include speed control of variable speed motors, the ratio of fluid feedrate to dry material feedrate and barrel temperature. Bailey *et al.* (1995) describe a computerised system of process control that is able to control the extrusion process, the start-up and shut-down sequences, alarm recognition, storage of formulations and presentation of colour displays of the process to the operator. The control system continuously monitors over one hundred process alarm conditions, including the product formulation in relation to the operating conditions. It visually alerts the operator if non-specified conditions exist, and in extreme cases, controls an orderly shutdown or an emergency stop. Another system for control of a twin-screw extruder is described by Lu *et al.* (1993) (also Chapter 2).

Liquids and slurries are pumped into the extruder barrel by positive displacement pumps, with flow measuring devices fitted in-line to control the feedrate. Dies are produced with different shaped holes and are readily inter-changeable. Shapes may be simple, such as round holes to produce rods, square holes for bars or slots to produce sheets; or they may have more complex patterns for specially shaped products. Extruders may also be fitted with a special die to continuously inject a filling into an outer shell. This is known as *co-extrusion* and is used, for example, to produce filled confectionery.

After material leaves the die, it is cut into the required lengths by a series of knives that rotate across the face of the die. The speed of rotation is adjusted to the throughput to produce the correct length. Alternatively, the product may be transported by conveyor to a separate guillotine for cutting.

14.3 Applications

14.3.1 Cold extrusion

In this process, the product is extruded without cooking or distortion of the food. The extruder has a deep-flighted screw, which operates at a low speed in a smooth barrel, to knead and extrude the material with little friction. It is used to produce pasta, hot dogs, pastry doughs and some types of confectionery. Typical operating conditions are shown in Table 14.2 for low shear conditions.

14.3.2 Extrusion cooking

High pressures and temperatures are used to form expanded products. The rapid release of pressure as the food emerges from the die causes instantaneous expansion of steam and gas in the material, to form a low-density product. Hot extrusion is a HTST process, which minimises the loss of nutrients and reduces microbial contamination. The moisture content of some products, for example snackfoods, crispbread and breakfast cereals, is further reduced after extrusion by drying (Chapters 14 and 18).

Confectionery products

HTST extrusion cooking is used to produce a gelatinised, chewy product such as fruit gums and liquorice, from a mixture of sugar, glucose and starch. The heat gelatinises the starch, dissolves the sugar and vaporises excess water which is vented from the machine. Colourings and flavours are added to the plasticised material and, after mixing, it is cooled and extruded. The product texture can be adjusted from soft to elastic by control over the formulation and processing conditions, the shape can be changed by changing the die, and a variety of flavours and colours may be added. These different combinations permit a very large range of potential products, including liquorice, toffee, fudge, boiled sweets, creams, and chocolate, each produced by the same equipment (Best, 1994). Product uniformity is high, no after-drying is required, and there is a rapid start-up and shut-down.

Hard-boiled sweets are produced from granulated sugar and corn syrup. The temperature in the extruder is raised to 165°C to produce a homogeneous, decrystallised mass. Acids, flavours and colour are added to the sugar mass, and the moisture content is reduced to 2% as the product emerges from the die into a vacuum chamber. It is then fed to stamping or forming machines to produce the required shape. Compared with traditional methods which use boiling pans (Chapter 13), energy consumption in an

extruder operating at 1000 kg h^{-1} is reduced from 971 to 551 kJ per kilogram of sugar mass, and steam consumption is reduced from 0.485 to 0.193 kg per kilogram of sugar mass (Huber, 1984).

Cereal products

Crispbread

Wheat flour, milk powder, corn starch, sugar and water are mixed and the product is extruded at a high temperature and pressure. The crispbread is then toasted to reduce the moisture content further and to brown the surface. Savings compared with oven baking are up to 66% in energy consumption, as less moisture is removed, and up to 60% in capital costs and floor space, as large ovens are unnecessary (Vincent, 1984).

A lower pressure and/or larger die aperture are used to produce *prefoms* or *half-products* from pre-gelatinised cereal doughs. These small, hard, dense pellets are suitable for extended storage and transport to other processors, where the final product is produced by frying, toasting or puffing. When the half-products are heated in air or oil, they are softened and develop the necessary physical properties for expansion. The residual moisture in the pellets then turns to steam, to expand the product rapidly to its final shape.

Breakfast cereals

In traditional cornflake manufacture, large maize kernels (grits) were needed, as the size of the individual grit determined the size of the final cornflake. Grits were then pressure cooked, dried, tempered to ensure a uniform moisture distribution, flaked, toasted and sprayed with a vitamin solution. The total processing time exceeded 5 h. Dough pellets are now produced in a low-pressure extruder. The size of the pellets determines the size of the cornflakes. They are then flaked, toasted and sprayed as before. The advantages of extrusion cooking are:

- a reduction in raw material costs (19.4%) as maize grits of any size may be used, a reduction in energy consumption (100%), capital expenditure (44%) and labour costs (14.8%) (Darrington, 1987)
- rapid processing to produce cornflakes within minutes of start-up
- close control over the size and quality of the final product
- flexibility to change the product specification easily (Slater, 1984).

Details of the manufacture of ready-to-eat breakfast cereals are given by Bailey *et al.* (1995) and are shown in Fig. 14.6. Each stage of feed material preparation, extrusion, drying, separation of flakes that are broken or stuck together (in the 'scalper') and coating is linked by a programmable logic controller (Chapter 2).

Protein-based foods

Texturised vegetable protein (TVP)

Extrusion cooking destroys the enzymes present in soybeans, including a urease which reduces the shelf life, a lipoxidase which causes off flavours by oxidation of soya oil and also a trypsin inhibitor which reduces protein digestibility. This improves the acceptability, digestibility and shelf life of the product. Defatted soya flour, soya concentrate or isolate are moistened and the pH is adjusted. A lower pH (5.5) increases chewiness in the final product, whereas a higher pH (8.5) produces a tender product and more rapid rehydration. Colours, flavours and calcium chloride firming agent are added, and the material is plasticised in an extruder at 60–104°C. It is then extruded to form

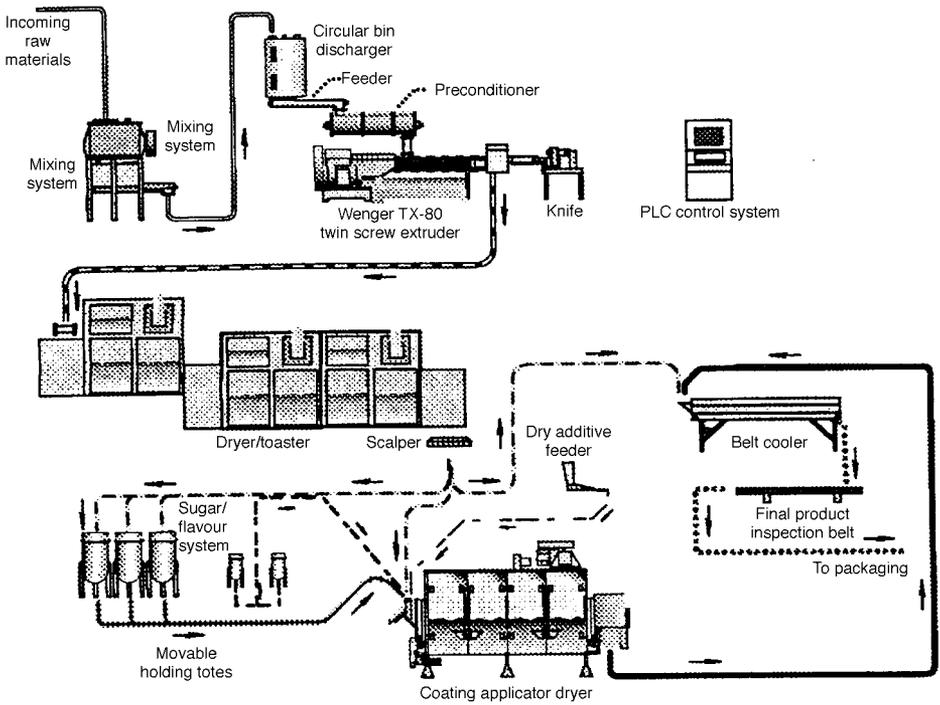


Fig. 14.6 Production of ready-to-eat breakfast cereal.
(From Bailey *et al.* (1995).)

expanded texturised strands, which are cooled and dried to 6–8% moisture content. Details of the production of different texturised soya products are given by Smith and Ben-Gera (1980).

Meat and fish products

Application of extruders to meat and fish products has mostly focused on production of extruded snacks or shelf-stable starch pellets that incorporate previously under-utilised by-products from meat, fish or prawns. Additionally, the manufacture of shiozuri surimi from ground, minced fish has been investigated using extruders operating at a die temperature of 6–27°C. A detailed description of surimi processing and the application of the process to red meats and poultry is given by Knight *et al.* (1991).

Other developments

A number of more recent applications of extrusion are described by Jones (1990), including the use of extruders as enzymatic reactors with thermostable α -amylase to produce modified starches (Chapter 7). Caseinates are also subjected to partial hydrolysis in an extruder with selected proteases and the products are reported to have very good bacteriological quality, improved colour, flavour and water absorption properties. Another application is the direct production of oligosaccharide mixtures from potato starch, without the use of enzymes, that are suitable for dietetic and infant food. Oil can be extracted more efficiently from soybean flour by first using dry extrusion (10–14% moisture) at 135°C followed immediately by pressing in a continuous screw press (Chapter 6). The process is said to produce very high quality oil, similar to a refined,

deodorised product, together with an oilcake, containing 50% protein and 90% inactivation of trypsin inhibitors, that is suitable for human consumption.

Extruders are also beginning to be used for decontamination of spices and for sterilisation of cocoa nibs prior to roasting for chocolate manufacture. In the latter application, it is reported that extrusion cooking results in a 1000-fold reduction in micro-organisms and removal of off-flavours that eliminates the need for a time consuming and expensive conching stage (also Chapter 23).

14.4 Effect on foods

14.4.1 Sensory characteristics

Production of characteristic textures is one of the main features of extrusion technology. The extent of changes to starch, determined by the operating conditions and feed materials (Section 14.1), produce the wide range of product textures that can be achieved. The HTST conditions in extrusion cooking have only minor effects on the natural colour and flavour of foods. However, in many foods the colour of the product is determined by the synthetic pigments (Appendix C) added to the feed material as water- or oil-soluble powders, emulsions or lakes. Fading of colour due to product expansion, excessive heat or reactions with proteins, reducing sugars or metal ions may be a problem in some extruded foods. Added flavours are mixed with ingredients before cold extrusion, but this is largely unsuccessful in extrusion cooking as the flavours are volatilised when the food emerges from the die. Micro-encapsulated flavours are more suitable but expensive. Flavours are therefore more often applied to the surface of extruded foods in the form of sprayed emulsions or viscous slurries. However, this may cause stickiness in some products and hence require additional drying.

14.4.2 Nutritional value

Vitamin losses in extruded foods vary according to the type of food, the moisture content, the temperature of processing and the holding time. Generally, losses are minimal in cold extrusion. The HTST conditions in extrusion cooking, and the rapid cooling as the product emerges from the die, cause relatively small losses of most vitamins and essential amino acids. For example at an extruder temperature of 154°C there is a 95% retention of thiamin and little loss of riboflavin, pyridoxine, niacin or folic acid in cereals. However, losses of ascorbic acid and β -carotene are up to 50%, depending on the time that the food is held at the elevated temperatures (Harper, 1979), and loss of lysine, cystine and methionine in rice products varies between 50 and 90% depending on processing conditions (Seiler, 1984). In soy flour the changes to proteins depend on the formulation and processing conditions. High temperatures and the presence of sugars cause Maillard browning and a reduction in protein quality. Lower temperatures and low concentrations of sugars result in an increase in protein digestibility, owing to rearrangement of the protein structure. Destruction of anti-nutritional components in soya products improves the nutritive value of texturised vegetable proteins.

14.5 Acknowledgements

Grateful acknowledgement is made for information supplied by: Werner and Pfeiderer

(UK) Ltd, Stockport SK6 6AG, UK; Vincent Processes Ltd, Shaw, Newbury, Berkshire RG13 2NT, UK; Baker Perkins Ltd, Peterborough PE3 6TA, UK.

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B. Heat processing using hot air

15

Dehydration

Dehydration (or drying) is defined as ‘the application of heat under controlled conditions to remove the majority of the water normally present in a food by evaporation’ (or in the case of freeze drying (Chapter 22) by sublimation). This definition excludes other unit operations which remove water from foods (for example mechanical separations and membrane concentration (Chapter 6), evaporation (Chapter 13) and baking (Chapter 16)) as these normally remove much less water than dehydration.

The main purpose of dehydration is to extend the shelf life of foods by a reduction in water activity (Chapter 1). This inhibits microbial growth and enzyme activity, but the processing temperature is usually insufficient to cause their inactivation. Therefore any increase in moisture content during storage, for example due to faulty packaging, will result in rapid spoilage. The reduction in weight and bulk of food reduces transport and storage costs. For some types of food, dehydration provides a convenient product for the consumer or more easily handled ingredients for food processors. Drying causes deterioration of both the eating quality and the nutritional value of the food. The design and operation of dehydration equipment aim to minimise these changes by selection of appropriate drying conditions for individual foods. Examples of commercially important dried foods are coffee, milk, raisins, sultanas and other fruits, pasta, flours (including bakery mixes), beans, pulses, nuts, breakfast cereals, tea and spices. Examples of important dried ingredients that are used by manufacturers include egg powder, flavourings and colourings, lactose, sucrose or fructose powder, enzymes and yeasts.

15.1 Theory

Dehydration involves the simultaneous application of heat and removal of moisture from foods.¹ Factors that control the rates of heat and mass transfer are described in Chapter 1.

1. Except for osmotic dehydration, in which foods are soaked in concentrated solutions of sugar or salt to remove water using the difference in osmotic pressure as the driving force for moisture transfer. This method is used to produce ‘crystallised’ or sugared fruits and with salt it is used in some countries as a pre-treatment for fish and vegetables before drying. Further details are given by Torreggiani (1993).

PSYCHROMETRIC CHART (10-120 °C)

Based on a barometric pressure of 101.325 kPa

Sensible/total heat ratio for water added at 30 °C

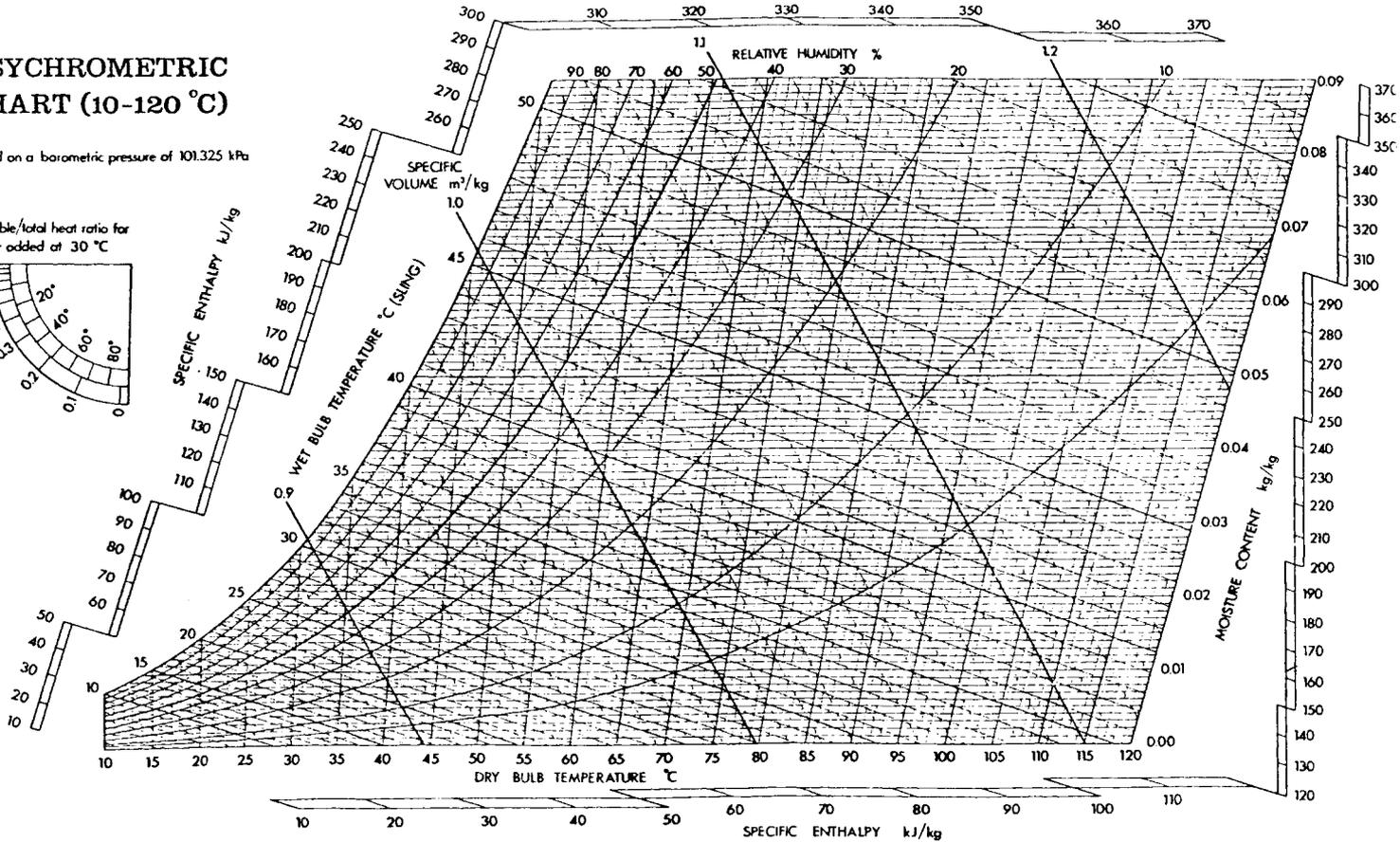
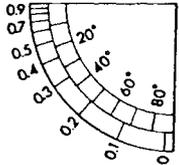


Fig. 15.1 Psychrometric chart (10–120°C) based on barometric pressure of 101.325 kPa. (Courtesy of Chartered Institution of Building Service Engineers.)

Dehydration by heated air or heated surfaces is described in this chapter. Microwave, dielectric and radiant driers are described in Chapter 18 and freeze drying is described in Chapter 22.

There are a large number of factors that control the rate at which foods dry, which can be grouped into the following categories:

- those related to the processing conditions
- those related to the nature of the food
- those related to the drier design.

The effects of processing conditions and type of food are described below and differences in drier design are summarised in Section 15.2.

15.1.1 Drying using heated air

Psychrometrics

There are three inter-related factors that control the capacity of air to remove moisture from a food:

1. the amount of water vapour already carried by the air
2. the air temperature
3. the amount of air that passes over the food.

The amount of water vapour in air is expressed as either *absolute humidity*² (termed *moisture content* in Fig. 15.1) or *relative humidity*³ (RH) (in per cent). Psychrometry is the study of inter-related properties of air–water vapour systems. These properties are conveniently represented on a *psychrometric chart* (Fig. 15.1).

Heat from drying air is absorbed by food and provides the latent heat needed to evaporate water from the surface. The temperature of the air, measured by a thermometer bulb, is termed the *dry-bulb* temperature. If the thermometer bulb is surrounded by a wet cloth, heat is removed by evaporation of water from the cloth and the temperature falls. This lower temperature is called the *wet-bulb temperature*. The difference between the two temperatures is used to find the relative humidity of air on the psychrometric chart. An increase in air temperature, or reduction in RH, causes water to evaporate more rapidly from a wet surface and therefore produces a greater fall in temperature. The *dew point* is the temperature at which air becomes saturated with moisture (100% RH) and any further cooling from this point results in condensation of the water from the air. Adiabatic cooling lines are the parallel straight lines sloping across the chart, which show how absolute humidity decreases as the air temperature increases.

Mechanism of drying

The third factor that controls the rate of drying, in addition to air temperature and humidity, is the air velocity. When hot air is blown over a wet food, water vapour diffuses through a boundary film of air surrounding the food and is carried away by the moving air (Fig. 15.2). A water vapour pressure gradient is established from the moist interior of the food to the dry air. This gradient provides the ‘driving force’ for water removal from the food.

2. Equals the mass of water vapour per unit mass of dry air (in kilograms per kilogram).
3. Defined as ‘the ratio of the partial pressure of water vapour in the air to the pressure of saturated water vapour at the same temperature, multiplied by 100’.

Sample problems 15.1

Using the psychrometric chart (Fig 15.1), calculate the following

1. the absolute humidity of air which has 50% RH and a dry-bulb temperature of 60°C;
2. the wet-bulb temperature under these conditions;
3. the RH of air having a wet-bulb temperature of 45°C and a dry-bulb temperature of 75°C;
4. the dew point of air cooled adiabatically from a dry-bulb temperature of 55°C and 30% RH;
5. the change in RH of air with a wet-bulb temperature of 39°C, heated from a dry-bulb temperature of 50°C to a dry-bulb temperature of 86°C;
6. the change in RH of air with a wet-bulb temperature of 35°C, cooled adiabatically from a dry-bulb temperature of 70°C to 40°C.

Solutions to Sample problems 15.1

1. 0.068 kg per kilogram of dry air (find the intersection of the 60°C and 50% RH lines, and then follow the chart horizontally right to read off the absolute humidity);
2. 47.5°C (from the intersection of the 60°C and 50% RH lines, extrapolate left parallel to the wet-bulb lines to read off the wet-bulb temperature);
3. 20% (find the intersection of the 45°C and 75°C lines and follow the sloping RH line upwards to read off the % RH);
4. 36°C (find the intersection of the 55°C and 30% RH lines and follow the wet-bulb line left until the RH reaches 100%);
5. 50–10% (find the intersection of the 39°C wet-bulb and the 50°C dry-bulb temperatures, and follow the horizontal line to the intersection with the 86°C dry-bulb line; read the sloping RH line at each intersection (this represents the changes that take place when air is heated prior to being blown over food));
6. 10–70% (find the intersection of the 35°C wet-bulb and the 70°C dry-bulb temperatures, and follow the wet-bulb line left until the intersection with the 40°C dry-bulb line; read sloping RH line at each intersection (this represents the changes taking place as the air is used to dry food; the air is cooled and becomes more humid as it picks up moisture from the food)).

The boundary film acts as a barrier to both heat transfer and water vapour removal during drying. The thickness of the film is determined primarily by the air velocity; if the velocity is low, the boundary film is thicker and this reduces both the heat transfer coefficient and the rate of removal of water vapour. Water vapour leaves the surface of the food and increases the humidity of the surrounding air, to cause a reduction in the water vapour pressure gradient and hence the rate of drying. Therefore the faster the air, the thinner the boundary film and hence the faster the rate of drying. In summary, the three characteristics of air that are necessary for successful drying when the food is moist are:

1. a moderately high dry-bulb temperature
2. a low RH
3. a high air velocity.

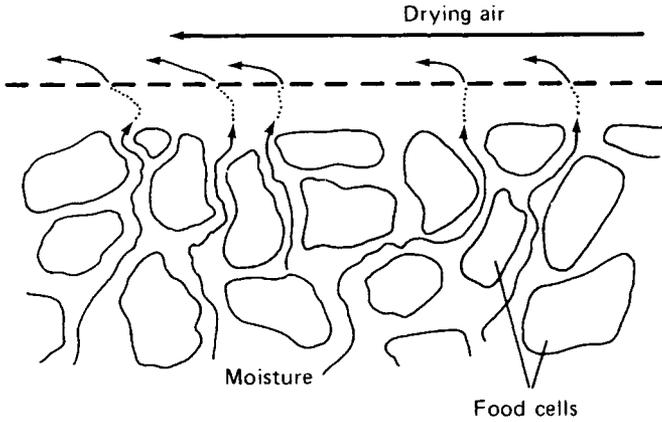


Fig. 15.2 Movement of moisture during drying.

Constant-rate period

When food is placed into a drier, there is a short initial settling down period as the surface heats up to the wet-bulb temperature (A–B in Fig. 15.3(a)). Drying then commences and, provided water moves from the interior of the food at the same rate as it evaporates from the surface, the surface remains wet. This is known as the *constant-rate period* and continues until a certain *critical moisture content* is reached (B–C in Fig. 15.3(a) and (b)). The surface temperature of the food remains close to the wet-bulb temperature of the drying air until the end of the constant-rate period, due to the cooling effect of the evaporating water. In practice, different areas of the food surface dry out at different rates and, overall, the rate of drying declines gradually towards the end of the ‘constant’-rate period.

Falling-rate period

When the moisture content of the food falls below the critical moisture content, the rate of drying slowly decreases until it approaches zero at the *equilibrium moisture content* (that is the food comes into equilibrium with the drying air). This is known as the *falling-rate period*. Non-hygroscopic foods (Chapter 1) have a single falling-rate period (C–D in Fig. 15.3(a) and (b)), whereas hygroscopic foods have two or more periods. In the first period, the plane of evaporation moves from the surface to inside the food, and water vapour diffuses through the dry solids to the drying air. The second period occurs when the partial pressure of water vapour is below the saturated vapour pressure, and drying is by desorption.

During the falling-rate period(s), the rate of water movement from the interior to the surface falls below the rate at which water evaporates to the surrounding air, and the surface therefore dries out (assuming that the temperature, humidity and air velocity are unchanged). If the same amount of heat is supplied by the air, the surface temperature rises until it reaches the dry-bulb temperature of the drying air. Most heat damage to food can therefore occur in the falling-rate period and the air temperature is controlled to balance the rate of drying and extent of heat damage. Most heat transfer is by convection from the drying air to the surface of the food, but there may also be heat transfer by radiation. If the food is dried in solid trays, there will also be conduction through the tray to the food. Calculation of heat transfer is therefore often very complex in drying systems.

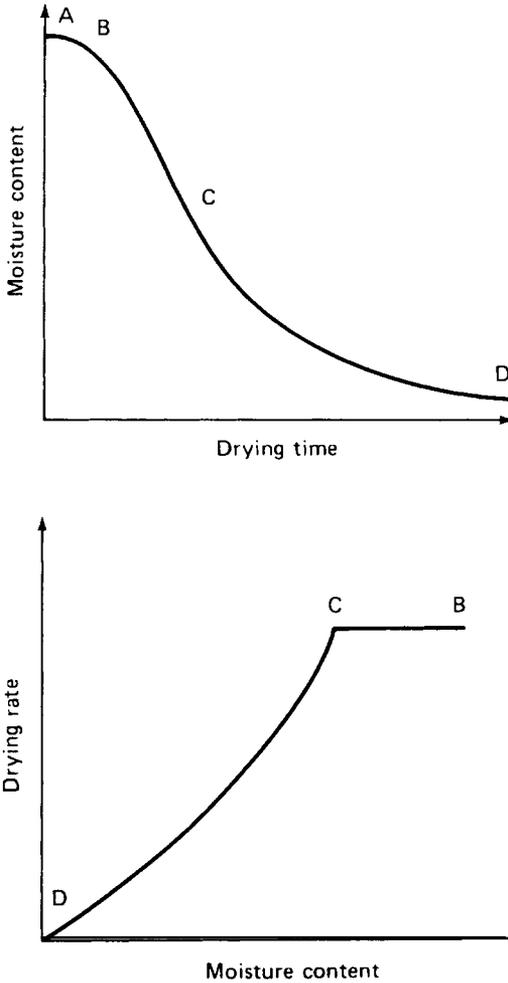


Fig. 15.3 (a) and (b) Drying curves. The temperature and humidity of the drying air are constant and all heat is supplied to the food surface by convection.

The falling-rate period is usually the longest part of a drying operation and, in some foods (for example grain drying) the initial moisture content is below the critical moisture content and the falling-rate period is the only part of the drying curve to be observed. During the falling-rate period, the factors that control the rate of drying change. Initially the important factors are similar to those in the constant-rate period, but gradually the rate of water movement (mass transfer) becomes the controlling factor. Water moves from the interior of the food to the surface by the following mechanisms:

- liquid movement by capillary forces, particularly in porous foods
- diffusion of liquids, caused by differences in the concentration of solutes at the surface and in the interior of the food
- diffusion of liquids which are adsorbed in layers at the surfaces of solid components of the food
- water vapour diffusion in air spaces within the food caused by vapour pressure gradients.

During drying, one or more of the above mechanisms may be taking place and their relative importance can change as drying proceeds. For example, in the first part of the falling-rate period, liquid diffusion may be the main mechanism, whereas in later parts, vapour diffusion may be more important. It is therefore sometimes difficult to predict drying times in the falling-rate period. The mechanisms that operate depend mostly on the temperature of the air and the size of the food pieces. They are unaffected by the RH of the air (except in determining the equilibrium moisture content) and the velocity of the air. The size of food pieces has an important effect on the drying rate in both the constant-rate and falling-rate periods. In the constant-rate period, smaller pieces have a larger surface area available for evaporation whereas in the falling-rate period, smaller pieces have a shorter distance for moisture to travel through the food. Calculation of drying rates is further complicated if foods shrink during the falling-rate period.

Other factors which influence the rate of drying include:

- The *composition and structure* of the food has an influence on the mechanism of moisture removal. For example, the orientation of fibres in vegetables (e.g. celery) and protein strands in meat allow more rapid moisture movement along their length than across the structure. Similarly, moisture is removed more easily from intercellular spaces than from within cells. Rupturing cells by blanching or size reduction increases the rate of drying but may adversely affect the texture of the rehydrated product. Additionally, high concentrations of solutes such as sugars, salts, gums, starches, etc., increase the viscosity and lower the water activity (Chapter 1) and thus reduce the rate of moisture movement.
- The *amount of food* placed into a drier in relation to its capacity (in a given drier, faster drying is achieved with smaller quantities of food).

In practice, the rate at which foods dry may differ from the idealised drying curves described above for these reasons.

Calculation of drying rate

In commercial operation, it is necessary to estimate how quickly a food will dry in a particular drier in order to calculate the amount of production that can be achieved per hour or per day. Where simple drying behaviour is found and data on critical and equilibrium moisture contents or thermal properties of foods are known, drying times can be estimated by calculation. However, this data is not available for many foods and results of pilot scale drying trials are used to estimate drying times.

The moisture content of a food may be expressed on a wet weight basis⁴ or a dry weight basis.⁵ In the calculations described below, a dry weight basis is used throughout.

The rate of heat transfer is found using:

$$Q = h_s A (\theta_a - \theta_s) \quad \boxed{15.1}$$

The rate of mass transfer is found using:

$$-m_c = K_g A (H_s - H_a) \quad \boxed{15.2}$$

4. Mass of water per unit mass of wet food.

5. Mass of water per unit mass of dry solids in the food.

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Since, during the constant-rate period, an equilibrium exists between the rate of heat transfer to the food and the rate of mass transfer in the form of moisture loss from the food, these rates are related by:

$$-m_c = \frac{h_c A}{\lambda} (\theta_a - \theta_s) \quad (15.3)$$

where Q (J s^{-1}) = rate of heat transfer, h_c ($\text{W m}^{-2} \text{K}^{-1}$) = surface heat transfer coefficient for convective heating, A (m^2) = surface area available for drying, θ_a ($^\circ\text{C}$) = average dry bulb temperature of drying air, θ_s ($^\circ\text{C}$) = average wet bulb temperature of drying air, m_c (kg s^{-1}) = change of mass with time (drying rate), K_g ($\text{kg m}^{-2} \text{s}^{-1}$) = mass transfer coefficient, H_s ($\text{kg moisture per kg dry air}$) = humidity at the surface of the food (saturation humidity), H_a ($\text{kg moisture per kg dry air}$) = humidity of air and λ (J kg^{-1}) = latent heat of vaporisation at the wet bulb temperature.

The surface heat transfer coefficient (h_c) is related to the mass flow rate of air using the following equations: for parallel air flow:

$$h_c = 14.3G^{0.8} \quad (15.4)$$

and for perpendicular air flow:

$$h_c = 24.2G^{0.37} \quad (15.5)$$

where G ($\text{kg m}^{-2} \text{s}^{-1}$) = mass flow rate of air per unit area.

For a tray of food, in which water evaporates only from the upper surface, the drying time is found using:

$$-m_c = \frac{h_c}{\rho \lambda x} (\theta_a - \theta_s) \quad (15.6)$$

where ρ (kg m^{-3}) = bulk density of food and x (m) = thickness of the bed of food. The drying time in the constant rate period is found using:

$$t = \frac{\rho \lambda x (M_i - M_c)}{h_c (\theta_a - \theta_s)} \quad (15.7)$$

where t (s) is the drying time, M_i (kg per kg of dry solids) = initial moisture content, and M_c (kg per kg of dry solids) = critical moisture content.

For water evaporating from a spherical droplet in a spray drier (Section 15.2.1), the drying time is found using:

$$t = \frac{r^2 \rho_l \lambda}{3h_c (\theta_A - \theta_S)} \frac{M_i - M_f}{1 + M_i} \quad (15.8)$$

where ρ (kg m^{-3}) = density of the liquid, r (m) = radius of the droplet, M_f (kg per kg of dry solids) = final moisture content.

The following equation is used to calculate the drying time from the start of the falling-rate period to the equilibrium moisture content using a number of assumptions concerning, for example, the nature of moisture movement and the absence of shrinkage of the food:

$$t = \frac{\rho x (M_c - M_e)}{K_g (P_s - P_a)} \ln \left(\frac{M_c - M_e}{M - M_e} \right) \quad (15.9)$$

where M_e (kg per kg of dry solids) = equilibrium moisture content, M (kg per kg of dry solids) = moisture content at time t from the start of the falling-rate period, P_s (Torr) =

saturated vapour pressure at the wet bulb temperature and P_a (Torr) = partial water vapour pressure.

Derivations of the above equations are described by Karel (1975), Brennan *et al.* (1990), Barbosa-Canovas (1996) and Hall (1979).

Sample problem 15.2

A conveyor drier (Section 15.2.1) is required to dry peas from an initial moisture content of 78% to 16% moisture (wet-weight basis), in a bed 10 cm deep which has a voidage of 0.4. Air at 85°C with a relative humidity of 10% is blown perpendicularly through the bed at 0.9 m s⁻¹. The drier belt measures 0.75 m wide and 4 m long. Assuming that drying takes place from the entire surface of the peas and there is no shrinkage, calculate the drying time and energy consumption in both the constant- and the falling-rate periods. (Additional data: the equilibrium moisture content of the peas is 9%, the critical moisture content 300% (dry-weight basis), the average diameter 6 mm, the bulk density 610 kg m⁻³, the latent heat of evaporation 2300 kJ kg⁻¹, the saturated water vapour pressure at wet-bulb temperature 61.5 Torr and the mass transfer coefficient 0.015 kg m⁻² s⁻¹.)

Solution to Sample problem 15.2

In the constant-rate period, from equation (15.5),

$$\begin{aligned} h_c &= 24.2(0.9)^{0.37} \\ &= 23.3 \text{ W m}^{-2} \text{ K}^{-1} \end{aligned}$$

From Fig. 15.1 for $\theta_a = 85^\circ\text{C}$ and RH = 10%,

$$\theta_s = 42^\circ\text{C}$$

To find the area of the peas,

$$\begin{aligned} \text{volume of a sphere} &= \frac{4}{3} \pi r^3 \\ &= 4/3 \times 3.142(0.003)^3 \\ &= 339 \times 10^{-9} \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{volume of the bed} &= 0.75 \times 4 \times 0.1 \\ &= 0.3 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{volume of peas in the bed} &= 0.3(1 - 0.4) \\ &= 0.18 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{number of peas} &= \frac{\text{volume of peas in bed}}{\text{volume each pea}} \\ &\equiv \frac{0.18}{339 \times 10^{-9}} \\ &\equiv 5.31 \times 10^5 \end{aligned}$$

$$\begin{aligned} \text{area of sphere} &= 4\pi r^2 \\ &= 4 \times 3.142(0.003)^2 \\ &= 113 \times 10^{-6} \text{ m}^2 \end{aligned}$$

and

$$\begin{aligned}\text{total area of peas} &= 5.31 \times 10^5 \times 113 \times 10^{-6} \\ &= 60 \text{ m}^2\end{aligned}$$

From equation (15.3),

$$\begin{aligned}\text{drying rate} &= \frac{23.3 \times 60}{2.3 \times 10^6} (85 - 42) \\ &= 0.026 \text{ kg s}^{-1}\end{aligned}$$

From a mass balance,

$$\begin{aligned}\text{volume of bed} &= 0.03 \text{ m}^3 \\ \text{bulk density} &= 610 \text{ kg m}^{-3}\end{aligned}$$

Therefore,

$$\begin{aligned}\text{mass of peas} &= 0.3 \times 610 \\ &= 183 \text{ kg} \\ \text{initial solids content} &= 183 \times 0.22 \\ &= 40.26 \text{ kg}\end{aligned}$$

Therefore,

$$\begin{aligned}\text{initial mass water} &= 183 - 40.26 \\ &= 142.74 \text{ kg}\end{aligned}$$

After constant-rate period, solids remain constant and

$$\begin{aligned}\text{mass of water} &= 96.6 - 40.26 \\ &= 56.34 \text{ kg}\end{aligned}$$

Therefore,

$$(142.74 - 56.34) = 86.4 \text{ kg water lost}$$

at a rate of 0.026 kg s^{-1}

$$\text{Drying time} = \frac{86.4}{0.026} = 3323 = 55.4 \text{ min}$$

Therefore,

$$\begin{aligned}\text{energy required} &= 0.026 \times 2.3 \times 10^6 \\ &= 6 \times 10^4 \text{ J s}^{-1} \\ &= 60 \text{ kW}\end{aligned}$$

In the falling-rate period, from Section 15.1.1,

$$\text{RH} = \frac{P_A}{P_0} \times 100$$

$$10 = \frac{P}{61.5} \times 100$$

Therefore,

$$P = 6.15 \text{ Torr}$$

The moisture values are

$$M_c = \frac{75}{25} = 3$$

$$M_f = \frac{16}{84} = 0.19$$

$$M_e = \frac{9}{91} = 0.099$$

From equation (15.9),

$$\begin{aligned} t &= \frac{(3 - 0.099)610 \times 0.1}{0.015(61.5 - 6.15)} \ln \left(\frac{3 - 0.099}{0.19 - 0.099} \right) \\ &= 737.7 \text{ s} \\ &= 12.3 \text{ min} \end{aligned}$$

From a mass balance, at the critical moisture content, 96.6 kg contains 25% solids = 24.16 kg. After drying in the falling-rate period, 84% solids = 24.16 kg. Therefore,

$$\begin{aligned} \text{total mass} &= \frac{100}{84} \times 24.16 \\ &= 28.8 \text{ kg} \end{aligned}$$

and

$$\begin{aligned} \text{mass loss} &= 96.6 - 28.8 \\ &= 67.8 \text{ kg} \end{aligned}$$

Thus,

$$\begin{aligned} \text{average drying rate} &= \frac{67.8}{737.7} \\ &= 0.092 \text{ kg s}^{-1} \end{aligned}$$

and

$$\begin{aligned} \text{average energy required} &= 0.092 \times 2.3 \times 10^6 \\ &= 2.1 \times 10^5 \text{ J s}^{-1} \\ &= 210 \text{ kW} \end{aligned}$$

15.1.2 Drying using heated surfaces

Slurries of food are deposited on a heated steel drum. Heat is conducted from the hot surface, through the food, and moisture is evaporated from the exposed surface. The main resistance to heat transfer is the thermal conductivity of the food (Chapter 1, Table 1.5). Additional resistance arises if the partly dried food lifts off the hot surface, forming a barrier layer of air between the food and the drum. Knowledge of the rheological properties of the food is therefore necessary to determine the thickness of the layer and the way in which it is applied to the heated surface. Equation 1.22 (in Chapter 1) is used to calculate drying rate.

Sample problem 15.3

A single-drum drier (Section 15.2.2) 0.7 m in diameter and 0.85 m long operates at 150°C and is fitted with a doctor blade to remove food after $\frac{3}{4}$ rev. It is used to dry a 0.6 mm layer of 20% w/w solution of gelatin, pre-heated to 100°C, at atmospheric pressure. Calculate the speed of the drum required to produce a product with a moisture content of 4 kg of solids per kilogram of water. (Additional data: the density of gelatin feed is 1020 kg m⁻³ and the overall heat transfer coefficient 1200 W m⁻² K⁻¹; assume that the critical moisture content of the gelatin is 450% (dry weight basis).)

Solution to Sample problem 15.3

First,

$$\begin{aligned}\text{drum area} &= \pi DL \\ &= 3.142 \times 0.7 \times 0.85 \\ &= 1.87 \text{ m}^2\end{aligned}$$

Therefore

$$\begin{aligned}\text{mass of food on the drum} &= (1.87 \times 0.75) 0.0006 \times 1020 \\ &= 0.86 \text{ kg}\end{aligned}$$

From a mass balance (initially the food contains 80% moisture and 20% solids),

$$\begin{aligned}\text{mass of solids} &= 0.86 \times 0.2 \\ &= 0.172 \text{ kg}\end{aligned}$$

After drying, 80% solids = 0.172 kg. Therefore

$$\begin{aligned}\text{mass of dried food} &= \frac{100}{80} \times 0.172 \\ &= 0.215 \text{ kg}\end{aligned}$$

$$\begin{aligned}\text{mass loss} &= 0.86 - 0.215 \\ &= 0.645 \text{ kg}\end{aligned}$$

From equation (15.1)

$$\begin{aligned}Q &= 1200 \times 1.87 (150 - 100) \\ &= 1.12 \times 10^5 \text{ J s}^{-1}\end{aligned}$$

$$\begin{aligned}\text{drying rate} &= \frac{1.12 \times 10^5}{2.257 \times 10^6} \text{ kg s}^{-1} \\ &= 0.05 \text{ kg s}^{-1}\end{aligned}$$

and

$$\begin{aligned}\text{residence time required} &= \frac{0.645}{0.05} \\ &= 13 \text{ s.}\end{aligned}$$

As only three-quarters of the drum surface is used, 1 rev should take $(100/75) \times 13 = 17.3$ s. Therefore speed = 3.5 rev min⁻¹.

15.2 Equipment

15.2.1 Hot-air driers

The cost of fuel for heating air is the main economic factor affecting drying operations and commercial driers have a number of features that are designed to reduce heat losses or save energy. Examples from Brennan (1992) include:

- insulation of cabinets and ducting
- recirculation of exhaust air through the drying chamber, provided a high outlet temperature can be tolerated by the product and the reduction in evaporative capacity is acceptable
- recovering heat from the exhaust air to heat incoming air using heat exchangers or thermal wheels (Chapter 1) or fore-warming the feed material
- use of direct flame heating by natural gas and low nitrogen oxide burners to reduce product contamination by the products of combustion
- drying in two stages (e.g fluidised beds followed by bin drying or spray drying followed by fluidised bed drying)
- pre-concentrating liquid foods to the highest solids content possible using multiple effect evaporation (Chapter 13). Energy use per unit mass of water removed in evaporators can be several orders of magnitude less than that required for dehydration
- automatic control of air humidity by computer control.

Further details are given by Zagorzycki (1983), Masters (1972), Grikitis (1986), Heldman and Hartel (1997) and Driscoll (1995) (see also Chapter 2).

The criteria for selection of drying equipment and potential applications are described in Table 15.1. The relative costs of different drying methods from data by Sapakie and Renshaw (1984) are as follows: forced-air drying, 198; fluidised-bed drying, 315; drum drying, 327; continuous vacuum drying, 1840; freeze drying, 3528. Tragardh (1981) compared relative energy consumption (in kilowatt hours per kilogram of water removed) as follows: roller drying, 1.25; pneumatic drying, 1.8; spray drying, 2.5; fluidised-bed drying, 3.5.

Bin driers

Bin driers are large, cylindrical or rectangular containers fitted with a mesh base. Hot air passes up through a bed of food at relatively low velocities (for example 0.5 m s^{-1} per square metre of bin area). They have a high capacity and low capital and running costs, and are mainly used for 'finishing' (to 3–6% moisture content) after initial drying in other types of driers. They improve the operating capacity of initial driers by removing the food when it is in the falling-rate period, when moisture removal is most time consuming. The deep bed of food permits variations in moisture content to be equalised and acts as a store to smooth out fluctuations in the product flow between drying and packaging operations. The driers may be several metres high and it is therefore important that foods are sufficiently strong to withstand compression and thus retain spaces between the pieces to permit the passage of hot air through the bed (Table 15.1).

Cabinet driers (tray driers)

These consist of an insulated cabinet fitted with shallow mesh or perforated trays, each of which contains a thin (2–6 cm deep) layer of food. Hot air is blown at $0.5\text{--}5 \text{ m s}^{-1}$ through a system of ducts and baffles to promote uniform air distribution over and/or through each tray. Additional heaters may be placed above or alongside the trays to

Table 15.1 Characteristics of driers

Type of drier	Characteristics of the food						Drying conditions			Examples of products
	Batch or continuous	Solid/liquid	Initial moisture content	Heat sensitive	Size of pieces	Should be mechanically strong	Drying rate	Final moisture content	Typical maximum evaporative capacity (kg h ⁻¹)	
Bin	B	S	Low		Int	Yes	Slow	Low	–	Vegetables
Cabinet	B	S	Mod		Int		Mod	Mod	55–75	Fruits, vegetables
Conveyor/band	C	S	Mod		Int		Mod	Mod	1820	Breakfast cereals, fruit products, confectionery, vegetables, biscuits, nuts
Drum	C	S	Mod		Sm		Mod	Mod	410	Slurries, corn syrup, instant potato, gelatin
Foam mat	C	L	–	Yes	–		Fast	Fast	–	Fruit juices
Fluidised bed	B/C	S	Mod		Sm	Yes	Mod	Low	910	Peas, diced or sliced vegetables, grains, powders or extruded foods, fruits, desiccated coconut, herbs
Kiln	B	S	Mod		Int		Slow	Mod	–	Apple rings, slices, hops
Microwave/dielectric	B/C	S	Low		Sm		Fast	Low	–	Bakery products
Pneumatic/ring	C	S	Low	Yes	Sm	Yes	Fast	Low	15 900	Starches, gravy or soup powder, mashed potato
Radiant	C	S	Low		Sm		Fast		–	Bakery products
Rotary	B/C	S	Mod	Yes	Sm	Yes	Mod	Mod	1820–5450	Cocoa beans, nuts, pomace, cooked cereals
Spin flash	C	L	Mod	Yes	Int/Sm		Fast	Low	7800	Pastes, filter cakes, sludges, viscous liquids
Spray	C	S	–		–		Fast	Mod	15 900	Powders, instant coffee, powdered milk
Sun/solar	B	S	Mod		Int		Slow	Mod	–	Fruits, vegetables
Trough	C	S	Mod		Int		Mod	Mod	–	Peas, diced vegetables
Tunnel	C	S	Mod		Int		Mod	Mod	–	Vegetables, fruits
Vacuum band/shelf	C	L	–		–		Fast	Low	18 200	Juices, meat extracts, chocolate crumb

Key: S = Solid, L = Liquid, Mod = Moderate, Int = Intermediate to large (granules, pellets, pieces), Sm = Small (powders).

Data from Barr and Baker (1997).

Table 15.2 Comparison of small and large scale drying technologies

Type of drier	Cost (\$US)	Capacity (kg wet food/24 h)	Investment (\$US per kg dry capacity)	Fuel efficiency	Labour requirement
'Brace' solar drier	50	10	50	n/a	v.low
Solar cabinet drier	70	30	23	n/a	v.low
'McDowell' drier	170	40	43	v.poor	low
Wood burning cabinet drier	340	80	43	v.poor	low
ITDG batch drier	3 400	240	140	poor	high
ITDG semi-continuous drier	6 800	360	190	medium	v.high
Cabinet drier (small)	85 000	500	1 700	good	high
Cabinet drier (large)	170 000	2 500	680	good	medium
Tunnel drier (12 carriage)	145 000	6 000	240	good	low
Band drier	800 000	48 000	170	v.good	v.low

From Axtell and Bush (1991).

increase the rate of drying. Tray driers are used for small-scale production (1–20 t day⁻¹) or for pilot-scale work. They have low capital and maintenance costs and are flexible in operation for different foods. However, they have relatively poor control and produce more variable product quality as food dries more rapidly on trays nearest to the heat source. A low cost, semi-continuous mechanism which overcomes this problem by periodically replacing the lowest tray in the stack has been developed by Intermediate Technology Development Group (Axtell and Bush, 1991 and Axtell and Russell, 2000). A comparison of the technology with solar driers and large scale systems is shown in Table 15.2.

Tunnel driers

Layers of food are dried on trays, which are stacked on trucks programmed to move semi-continuously through an insulated tunnel, having one or more types of air flow described in Table 15.3. Food is finished in bin driers. Typically a 20 m tunnel contains 12–15 trucks with a total capacity of 5000 kg of food. This ability to dry large quantities of food in a relatively short time made tunnel drying widely used, especially in the USA. However, the method has now been largely superseded by conveyor drying and fluidised-bed drying as a result of their higher energy efficiency, reduced labour costs and better product quality.

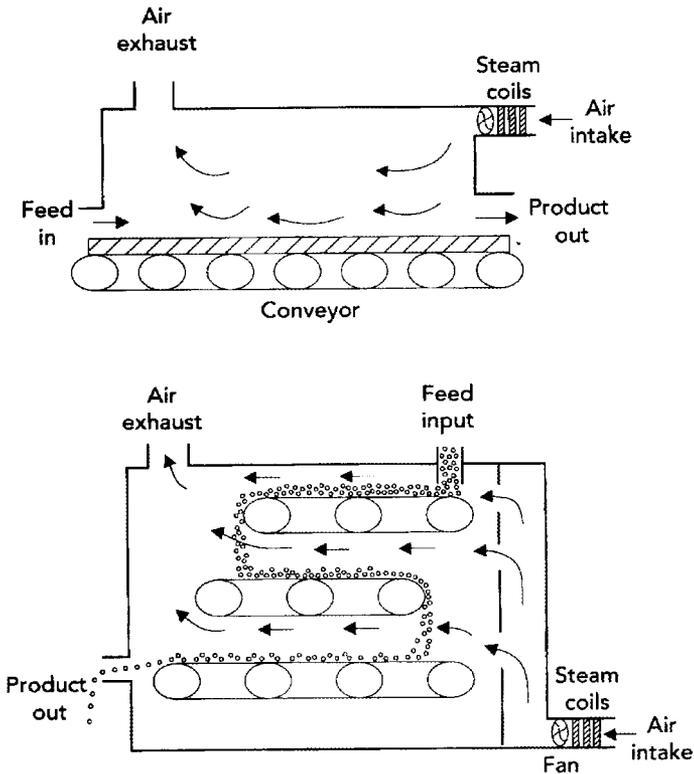
Conveyor driers (belt driers)

Continuous conveyor driers are up to 20 m long and 3 m wide. Food is dried on a mesh belt in beds 5–15 cm deep. The air flow is initially directed upwards through the bed of food and then downwards in later stages to prevent dried food from blowing out of the bed. Two- or three-stage driers (Fig. 15.4) mix and re-pile the partly dried food into deeper beds (to 15–25 cm and then 250–900 cm in three-stage driers). This improves uniformity of drying and saves floor space. Foods are dried to 10–15% moisture content and then finished in bin driers. This equipment has good control over drying conditions and high production rates. It is used for large scale drying of foods (for example up to 5.5 t h⁻¹). Driers may have computer controlled independent drying zones and automatic loading and unloading to reduce labour costs.

A second application of conveyor driers is *foam mat drying* in which liquid foods are formed into a stable foam by the addition of a stabiliser (Appendix C) and aeration with nitrogen or air. The foam is spread on a perforated belt to a depth of 2–3 mm and dried

Table 15.3 Advantages and limitations of parallel flow, counter-current flow, centre-exhaust and cross-flow drying

Type of air flow	Advantages	Limitations
Parallel or co-current type: food → air flow →	Rapid initial drying. Little shrinkage of food. Low bulk density. Less damage to food. No risk of spoilage	Low moisture content difficult to achieve as cool moist air passes over dry food
Counter-current type: food → air flow ←	More economical use of energy. Low final moisture content as hot air passes over dry food	Food shrinkage and possible heat damage. Risk of spoilage from warm moist air meeting wet food
Centre-exhaust type: food → air flow →↑←	Combined benefits of parallel and counter-current driers but less than cross-flow driers	More complex and expensive than single-direction air flow
Cross-flow type: food → air flow ↑↓	Flexible control of drying conditions by separately controlled heating zones, giving uniform drying and high drying rates	More complex and expensive to buy, operate and maintain

**Fig. 15.4** (a) Conveyor drier and (b) three-stage conveyor drier.

(From Heldman and Hartel (1997).)

rapidly in two stages by parallel and then counter-current air flows (Table 15.3). Foam mat drying is approximately three times faster than drying a similar thickness of liquid. The thin porous mat of dried food is then ground to a free-flowing powder which has good rehydration properties. Rapid drying and low product temperatures result in a high-

quality product, but a large surface area is required for high production rates, and capital costs are therefore high.

A further variation is trough driers (or belt-trough driers) in which small, uniform pieces of food are dried in a mesh conveyor belt which hangs freely between rollers, to form the shape of a trough. Hot air is blown through the bed of food, and the movement of the conveyor mixes and turns the food to bring new surfaces continually into contact with the drying air. The mixing action also moves food away from the drying air, and this allows time for moisture to move from inside the pieces to the dry surfaces. The surface moisture is then rapidly evaporated when the food again contacts the hot air. These driers have high drying rates (for example 55 min for diced vegetables, compared with 5 h in a tunnel drier), high energy efficiencies, good control and minimal heat damage to the product. They operate in two stages, to 50–60% moisture and then to 15–20% moisture before finishing in bin driers.

Fluidised-bed driers

The main features of a fluidised-bed drier are a distributor to evenly distribute the air at a uniform velocity around the bed of material; a plenum chamber below the distributor to produce an homogenous region of air and prevent localised high velocities; and a disengagement or 'freeboard' region above the bed to allow disentrainment of particles thrown up by the air. Air from the fluidised bed is usually fed into cyclones to separate out fine particles, which are then added back to the product or agglomerated (Bahu, 1997). Above the distributor, mesh trays contain a bed of particulate foods up to 15 cm deep. Hot air is blown through the bed, causing the food to become suspended and vigorously agitated (fluidised), exposing the maximum surface area of food for drying (Fig. 15.5). A sample calculation of the air velocity needed for fluidisation is described in Chapter 1 (Sample problem 1.6). These driers are compact and have good control over drying conditions and high drying rates.

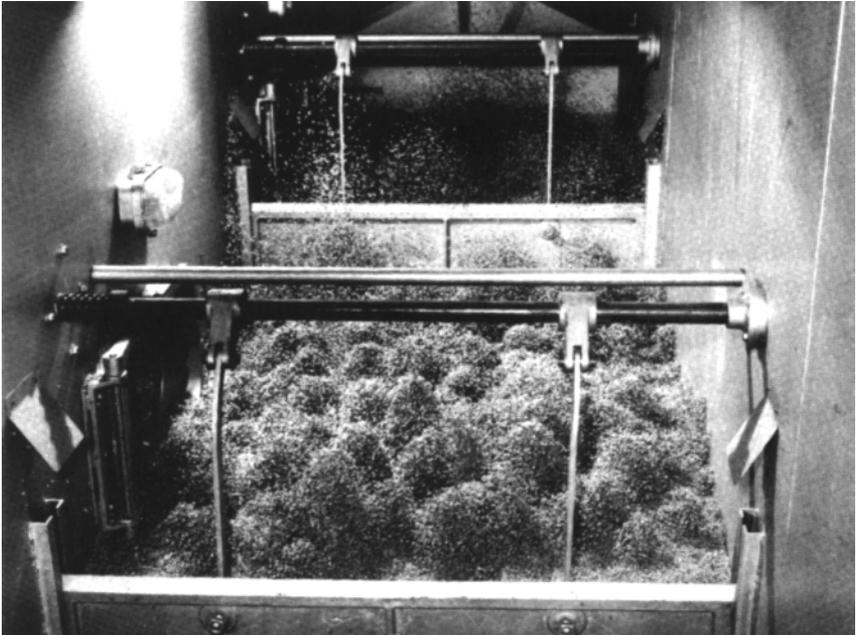


Fig. 15.5 Fluidised-bed drying.
(Courtesy of Petrie and McNaught Ltd.)

In batch operation, the product is thoroughly mixed by fluidisation and this leads to a uniform moisture content. In continuous operation the trays vibrate to move the food under gravity from one tray to the next. There is a greater range of moisture contents in the dried product, and bin driers are used for finishing. The main applications are for small, particulate foods that are capable of being fluidised without excessive mechanical damage, including yeast, desiccated coconut, grain, herbs, instant coffee, sugar and tea (Bahu, 1997).

In a development of the fluidised-bed drier, named the 'Torbed' drier, a fluidised bed of particles is made to rotate around a torus-shaped chamber by hot air blown directly from a burner (Fig. 15.6). The drier has very high rates of heat and mass transfer and substantially reduced drying times. Larger pieces require a period of moisture equilibration before final drying. The drier has microprocessor control and is suitable for agglomeration and puff drying in addition to roasting, cooking and coating applications.

Another development of the fluidised bed principle is the *Spin-flash drier* in which a drying chamber is fitted with a rotor at the base. Hot air enters tangentially and this, together with the action of the rotor, causes a turbulent rotating flow of air up through the chamber. Food pieces, such as crab meat paste, cocoa cake or gums, enter the chamber and become coated in dry powder. The lumps fall to the base where they are fluidised by the air and rotated by the rotor. As they dry the lumps break up and release powder, which is carried up the wall of the chamber and removed through a classification orifice that is changeable for different product particle size ranges. In the *centrifugal fluidised-bed drier* particulate food is filled into a drying chamber which rotates at high speed. Hot air is forced through the bed

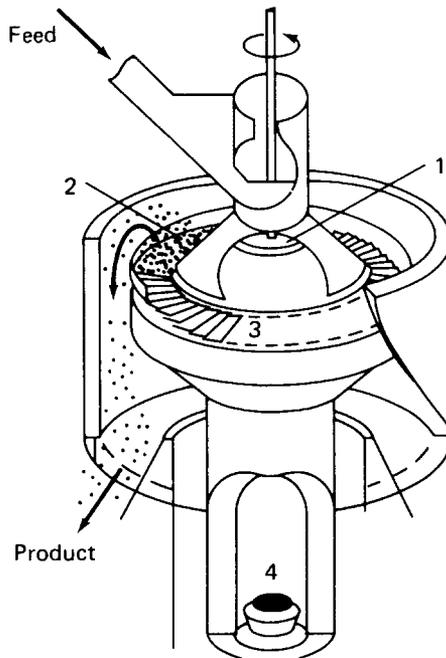


Fig. 15.6 Torbed drier: (1) rotating disc distributor to deliver raw material evenly into processing chamber; (2) rotating bed of particles; (3) fixed blades with hot gas passing through at high velocity; (4) burner assembly.

(Courtesy of Torrttech Ltd.)

of food at a velocity that is high enough to overcome the centrifugal force and fluidise the particles. This higher air velocity increases the rate of drying (Cohen and Yang, 1995). Further details of the different types of fluidised-bed driers are given by Bahu (1997).

Kiln driers

These are two-storey buildings in which a drying room with a slatted floor is located above a furnace. Hot air and the products of combustion from the furnace pass through a bed of food up to 20 cm deep. They have been used traditionally for drying apple rings in the USA and hops in Europe, but there is limited control over drying conditions and drying times are relatively long. High labour costs are also incurred by the need to turn the product regularly, and by manual loading and unloading. However the driers have a large capacity and are easily constructed and maintained at low cost.

Pneumatic driers

In these driers, moist powders or particulate foods, usually less than 40% moisture and particle size ranges of 10–500 μm , are metered into metal ducting and suspended in hot air. In vertical driers the air-flow is adjusted so that lighter and smaller particles, which dry more rapidly, are carried to a cyclone separator more rapidly than are heavier and wetter particles, which remain suspended to receive the additional drying required. For products that require longer residence times, the ducting is formed into a continuous loop (*pneumatic ring driers*) and the product is recirculated until it is adequately dried. High temperature short-time ring driers (or *flash driers*) are used to expand the starch in potatoes or carrots to give a rigid, porous structure, which improves both subsequent conventional drying and rehydration rates. Drying takes place within 2–10 s and these driers are therefore suitable for foods that lose moisture rapidly from the surface. Evaporative cooling of the particles prevents heat damage to give high quality products.

Pneumatic driers have relatively low capital and maintenance costs, high drying rates and close control over drying conditions, which make them suitable for heat sensitive foods. Outputs range from 10 kg h⁻¹ to 25 t h⁻¹ (Barr and Baker, 1997). They are often used after spray drying to produce foods which have a lower moisture content than normal (for example special milk or egg powders and potato granules). In some applications the simultaneous transportation and drying of the food may be a useful method of materials handling (Chapter 26).

Rotary driers

A slightly inclined (up to 5°) rotating metal cylinder is fitted internally with flights to cause the food to cascade through a stream of parallel or counter-current (Table 15.3) hot air as it moves through the drier. The large surface area of food exposed to the air produces high drying rates and a uniformly dried product. The method is especially suitable for foods that tend to mat or stick together in belt or tray driers. However, the damage caused by impact and abrasion in the drier restricts this method to relatively few foods (for example nuts and cocoa beans). To overcome this problem, a variation of the design, named a *Rotary louvre drier*, in which longitudinal louvres are positioned to form an inner drum, has been introduced. The food particles form a partially fluidised rolling bed on the base of this drum and hot air passes through the louvres and the food (Barr and Baker, 1997).

Spray driers

A fine dispersion of pre-concentrated food (40–60% moisture) is first 'atomised' to form fine droplets and then sprayed into a co- or counter-current flow of heated air (Table 15.3)

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at 150–300°C in a large drying chamber. One of the following types of atomiser is used:

- *Centrifugal atomiser*. Liquid is fed to the centre of a rotating disc or bowl having a peripheral velocity of 90–200 m s⁻¹. Droplets, 50–60 μm in diameter, are flung from the edge to form a uniform spray.
- *Pressure nozzle atomiser*. Liquid is forced at a high pressure (700–2000 × 10³ Pa) through a small aperture to form droplet sizes of 180–250 μm. Grooves on the inside of the nozzle cause the spray to form into a cone shape and therefore to use the full volume of the drying chamber.
- *Two-fluid nozzle atomiser*. Compressed air creates turbulence which atomises the liquid. The operating pressure is lower than the pressure nozzle, but a wider range of droplet sizes is produced.
- *Ultrasonic nozzle atomiser*. A two-stage atomiser in which liquid is first atomised by a nozzle atomiser and then using ultrasonic energy to induce further cavitation.

Nozzle atomisers are susceptible to blockage by particulate foods, and abrasive foods gradually widen the apertures and increase the average droplet size.

Studies of droplet drying, including methods for calculating changes in size, density and trajectory of the droplets are described by Charm (1978), Kerkhof and Schoeber (1974) and Masters (1972).

Rapid drying (1–10 s) takes place because of the very large surface area of the droplets. The feed rate is controlled to produce an outlet air temperature of 90–100°C, which corresponds to a wet-bulb temperature (and product temperature) of 40–50°C to produce little heat damage to the food. The dry powder is collected at the base of the drier and removed by a screw conveyor or a pneumatic system with a cyclone separator. There are a large number of designs of atomiser, drying chamber, air heating and powder collecting systems which arise from the different requirements of the very large variety of food materials that are spray dried (for example milk, egg, coffee, cocoa, tea, potato, ice cream mix, butter, cream, yoghurt and cheese powder, coffee whitener, fruit juices, meat and yeast extracts, encapsulated flavours (Heath, 1985) and wheat and corn starch products). Detailed designs are described by Masters (1972), Masters (1997) and Kjaergaard (1974). Spray driers may also be fitted with fluidised bed facilities to finish powders taken from the drying chamber. Spray driers vary in size from small pilot-scale models for low-volume high-value products such as enzymes and flavours, to large commercial models capable of producing 10 000 kg of dried milk per hour (Byrne, 1986).

The main advantages are rapid drying, large-scale continuous production, low labour costs and relatively simple operation and maintenance. The major limitations are high capital costs and the requirement for a relatively high-feed moisture content to ensure that the food can be pumped to the atomiser. This results in higher energy costs (to remove the moisture) and higher volatile losses. Conveyor-band driers and fluidised-bed driers are beginning to replace spray driers as they are more compact and energy efficient (Ashworth, 1981). Development work with *ultrasonic drying* has indicated a potential alternative to spray drying. Small droplets are first produced in a liquid by ultrasound (Chapter 4) and then heated to remove the water. Drying takes place very rapidly (sometimes within seconds) and the dried residue is collected. The process works well with low-fat solutions, but less well with oily or fatty foods, which do not dry easily (Cohen and Yang, 1995).

Sun and solar drying

Sun drying (without drying equipment) is the most widely practised agricultural processing operation in the world; more than 250 000 000 t of fruits and grains are dried

by solar energy per annum. In some countries, foods are simply laid out in fields or on roofs or other flat surfaces and turned regularly until dry. More sophisticated methods (solar drying) collect solar energy and heat air, which in turn is used for drying. Solar driers are classified into:

- direct natural-circulation driers (a combined collector and drying chamber)
- direct driers with a separate collector
- indirect forced-convection driers (separate collector and drying chamber).

Both solar and sun drying are simple inexpensive technologies, in terms of both capital input and operating costs. Energy inputs and skilled labour are not required and in sun drying, very large amounts of crop can be dried at low cost. The major disadvantages are relatively poor control over drying conditions and lower drying rates than those found in artificial driers, which results in products that have lower quality and greater variability. In addition, drying is dependent on the weather and the time of day and requires a larger labour force than other methods. There are a large number of different designs of solar driers, described in detail by Brenndorfer *et al.* (1985) and Imrie (1997). Small solar driers have been investigated at research institutions, particularly in developing countries, for many years but their often low capacity (Table 15.2) and insignificant improvement to drying rates and product quality, compared to hygienic sun drying, have restricted their commercial use to only three or four applications worldwide. Larger solar driers with photo-voltaic powered fans and having a capacity of 200–400 kg/batch, have been developed by Hohenheim University to a commercial scale of operation. Several hundred driers are now in use in Mediterranean countries to dry fruit to export standards for European markets (Axtell and Russell, 2000). Potential developments using solar energy are likely to include their use in pre-heating air to gain reductions in energy consumption in fuel-fired driers.

15.2.2 Heated-surface (or contact) driers

Driers in which heat is supplied to the food by conduction have two main advantages over hot-air drying:

1. It is not necessary to heat large volumes of air before drying commences and the thermal efficiency is therefore high.
2. Drying may be carried out in the absence of oxygen to protect components of foods that are easily oxidised.

Typically heat consumption is 2000–3000 kJ per kilogram of water evaporated compared with 4000–10 000 kJ per kilogram of water evaporated for hot-air driers. However, foods have a low thermal conductivity (Chapter 1, Table 1.5) which becomes lower as the food dries and a thin layer of food is therefore needed to conduct heat rapidly, without causing heat damage.

Drum driers (roller driers)

Slowly rotating hollow steel drums are heated internally by pressurised steam to 120–170°C. A thin layer of food is spread uniformly over the outer surface by dipping, spraying, spreading or by auxiliary feed rollers. Before the drum has completed one revolution (within 20 s–3 min), the dried food is scraped off by a ‘doctor’ blade which contacts the drum surface uniformly along its length. Driers may have a single drum (Fig. 15.7(a)), double drums (Fig. 15.7(b)) or twin drums. The single drum is widely used as it

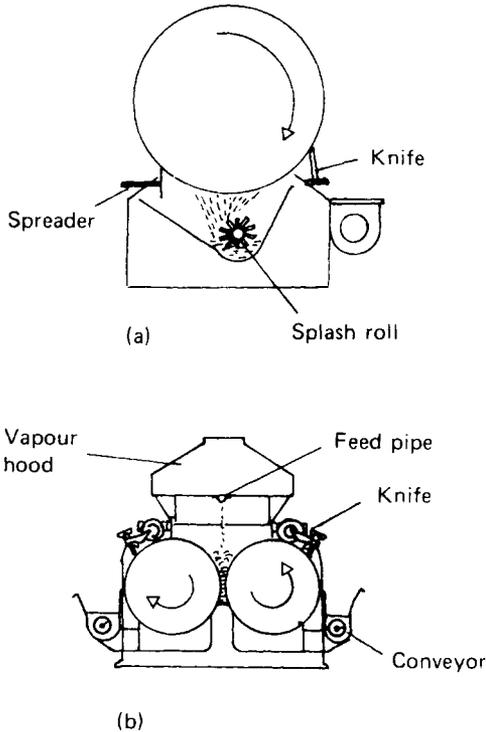


Fig. 15.7 Drum driers: (a) single drum and (b) double drum.
(Courtesy of APV Mitchell Ltd.)

has greater flexibility, a larger proportion of the drum area available for drying, there is easier access for maintenance and no risk of damage caused by metal objects falling between the drums.

Drum driers have high drying rates and high energy efficiencies and they are suitable for slurries in which the particles are too large for spray drying. Drum drying is used to produce potato flakes, pre-cooked cereals, molasses, some dried soups and fruit purees, and whey or distillers' solubles for animal feed formulations. However, the high capital cost of the machined drums and heat damage to sensitive foods caused by high drum temperatures have caused a move to spray drying for many bulk dried foods.

Developments in drum design to improve the sensory and nutritional qualities of dried food include the use of auxiliary rolls to remove and reapply food during drying, the use of high-velocity air to increase the drying rate or the use of chilled air to cool the product. Drums may be enclosed in a vacuum chamber to dry food at lower temperatures, but the high capital cost of this system restricts its use to high-value heat-sensitive foods.

In *ball-drying*, a drying chamber is fitted with a slowly rotating screw and contains ceramic balls that are heated by hot air, blown into the chamber. Particulate foods are dried mainly by conduction as a result of contact with the hot balls and are moved through the drier by the screw, to be discharged at the base. The drying time is controlled by the speed of the screw and the temperature of the heated balls (Cohen and Yang, 1995).

Vacuum band and vacuum shelf driers

A food slurry is spread or sprayed onto a steel belt (or 'band') which passes over two hollow drums, within a vacuum chamber at 1–70 Torr. The food is dried by the first

Table 15.4 Types of contact drier

Type of drier	Batch (B) or continuous (C)	Vacuum (V) or atmospheric (A)	Feed	Production rate	Typical applications
Vacuum tray	B	V	Any	Low	Fruit pieces, meat or vegetable extracts
Vacuum band	C	V	Pastes, solids	Low-medium	Chocolate crumb, meat or vegetable extracts, fruit juices
Plate	C	V or A	Free-flowing solids	Low-medium	Tea, coffee
Thin-film	C	V or A	Liquids	Low-medium	Tomato concentrate, gelatin
Drum	C	V or A	Liquids	Low-medium	Instant potato, corn syrup, baby foods
Rotating batch	B	V	Free-flowing solids	Low-medium	Gravy mix, pectin
Horizontally agitated	B or C	V or A	Liquids, pastes, powders	Low-high	Chocolate crumb, corn meal, confectionery
Indirect rotary	C	A	Free-flowing solids	Medium-very high	Brewer's grain, starch
Vertical agitated	B	V or A	Liquids, pastes, powders	Low-medium	Plant extracts, food colours, glucose, starch

From Oakley (1997).

Table 15.5 Summary of some novel drying techniques

Technique	Applications	Advantages	Limitations
Microwave and dielectric drying (Chapter 18)	High value products	Low temperature, batch or continuous operation, good quality products	Slow, expensive
Microwave augmented freeze drying (Chapter 22)	High value products	Low temperature, rapid, good quality products	Expensive
Centrifugal fluidised-bed drying	Small particles, vegetable pieces, powders	Rapid, easy to control	Loss of product integrity, noisy
Ball drying	Small particles, vegetable pieces	Low temperature, rapid, continuous operation, good quality products	Loss of product integrity, difficult to control
Ultrasonic drying	Liquids	Rapid	Requires low fat liquids
Explosive puff drying	Produces honeycomb structure in small particles	Rapid, good rehydration of products	Loss of product integrity, high levels of heat

Adapted from Cohen and Yang (1995).

steam-heated drum, and then by steam-heated coils or radiant heaters located over the band. The dried food is cooled by the second water-cooled drum and removed by a doctor blade. Vacuum shelf driers consist of hollow shelves in a vacuum chamber. Food is placed in thin layers on flat metal trays which are carefully made to ensure good contact with the shelves. A partial vacuum of 1–70 Torr is drawn in the chamber and steam or hot water is passed through the shelves to dry the food. Rapid drying and limited heat damage to the food make both methods suitable for heat-sensitive foods. However, care is necessary to prevent the dried food from burning onto trays in vacuum shelf driers, and shrinkage reduces the contact between the food and heated surfaces of both types of equipment. They have relatively high capital and operating costs and low production rates and are used mainly to produce puff-dried foods.

Explosion puff drying involves partially drying food to a moderate moisture content and then sealing it into a pressure chamber. The pressure and temperature in the chamber are increased and then instantly released. The rapid loss of pressure causes the food to expand and develop a fine porous structure. This permits faster final drying and rapid rehydration. Sensory and nutritional qualities are well retained. The technique was first applied commercially to breakfast cereals and now includes a range of fruit and vegetable products. A comparison of different contact driers is given in Table 15.4.

Other developments in drying technologies are described by Cohen and Yang (1995) and are summarised in Table 15.5.

15.3 Effect on foods

All products undergo changes during drying and storage that reduce their quality compared to the fresh material and the aim of improved drying technologies is to minimise these changes while maximising process efficiency. The main changes to dried

Table 15.6 Approximate ratios for drying, shrinkage and rehydration of selected vegetables

Vegetable	Drying ratio	Overall shrinkage ratio	Rehydration ratio
Cabbage	11.5	21.0	10.5
Carrots, sliced	7.5	12.0	7.0
Onions, sliced	7.0	8.0	5.5
Peppers, green	17.0	22.0	8.0
Spinach	13.0	13.5	5.0
Tomato flakes	14.0	20.0	5.0

foods are to the texture and loss of flavour or aroma, but changes in colour and nutritional value are also significant in some foods.

15.3.1 Texture

Changes to the texture of solid foods are an important cause of quality deterioration. The nature and extent of pre-treatments (for example, calcium chloride added to blancher water (Chapter 10), the type and extent of size reduction (Chapter 4), and peeling (Chapter 3)) each affect the texture of rehydrated fruits and vegetables. The loss of texture in these products is caused by gelatinisation of starch, crystallisation of cellulose (see also glass transition, Chapter 1, Section 1.1), and localised variations in the moisture content during drying, which set up internal stresses. These rupture, crack, compress and permanently distort the relatively rigid cells, to give the food a shrunken shrivelled appearance. On rehydration the product absorbs water more slowly and does not regain the firm texture of the fresh material. There are substantial variations in the degree of shrinkage and rehydration with different foods (Table 15.6).

Drying pieces of meat is not common in many countries owing to the severe changes in texture compared with other methods of preservation. These are caused by aggregation and denaturation of proteins and a loss of water-holding capacity, which leads to toughening of muscle tissue.

In general, rapid drying and high temperatures cause greater changes to the texture of foods than do moderate rates of drying and lower temperatures. As water is removed during drying, solutes move from the interior of the food to the surface. The mechanism and rate of movement are specific for each solute and depend on the type of food and the drying conditions used. Evaporation of water causes concentration of solutes at the surface. High air temperatures (particularly with fruits, fish and meats), cause complex chemical and physical changes to solutes at the surface, and the formation of a hard impermeable skin. This is termed *case hardening* and it reduces the rate of drying to produce a food with a dry surface and a moist interior. It is minimised by controlling the drying conditions to prevent excessively high moisture gradients between the interior and the surface of the food.

The textural characteristics of powders are related to their bulk density and the ease with which they are rehydrated. The bulk density of powders depends on the size of the dried particles and on whether they are hollow or solid. This is determined by the nature and composition of the food and the drying conditions (for example the uniformity of droplet size, temperature, solids content and degree of aeration of the feed liquid). Low-fat foods (for example fruit juices, potato and coffee) are more easily formed into free-flowing powders than are whole milk or meat extracts. Powders are 'instantised' by

Table 15.7 Bulk density and moisture content of selected powdered foods

Food	Bulk density (kg m ⁻³)	Moisture content (%)
Cocoa	480	3–5
Coffee (ground)	330	7
Coffee (instant)	330	2.5
Coffee creamer	470	3
Corn starch	560	12
Egg, whole	340	2–4
Milk, powdered, skimmed	640	2–4
Milk, instant, skimmed	550	2–4
Salt, granulated	960	0.2
Sugar, granulated	800	0.5
Wheat flour	450	12

Adapted from Watt and Merrill (1975) and Peleg (1983).

treating individual particles so that they stick together to form free-flowing agglomerates or aggregates, in which there are relatively few points of contact. The surface of each particle is easily wetted when the powder is rehydrated and the agglomerates break up to allow particles to sink below the surface and disperse rapidly through the liquid. These characteristics are respectively termed *wettability*, *sinkability*, *dispersibility* and *solubility*. For a powder to be considered ‘instant’, it should complete these four stages within a few seconds. Further details of the properties and handling of powders are given by Lewis (1996).

Agglomeration can be achieved by remoistening particles in low-pressure steam in an agglomerator, and then redrying. Fluidised-bed, jet, disc, cone or belt agglomerators are described by Schubert (1980). Alternatively, ‘straight-through’ agglomeration is achieved either directly during spray drying or a relatively moist powder is agglomerated and dried in an attached fluidised-bed drier (Masters, 1972). Non-agglomeration methods employ a binding agent (for example lecithin) to bind particles together. This method was previously used for foods with a relatively high fat content (for example whole milk powder) but it has now largely been replaced by agglomeration procedures (Pisecky *et al.*, 1983).

The convenience of instantised powders for retail markets outweighs the additional expense of production, packaging and transport, but many powdered foods are also used as ingredients in other processes, and these are required to possess a high bulk density and a wider range of particle sizes. Small particles fill the spaces between larger ones and thus exclude air to promote a longer storage life. The characteristics of some powdered foods are described in Table 15.7.

15.3.2 Flavour and aroma

Heat not only vaporises water during drying but also causes loss of volatile components from the food and as a result most dried foods have less flavour than the original material. The extent of volatile loss depends on the temperature and moisture content of the food and on the vapour pressure of the volatiles and their solubility in water vapour. Volatiles which have a high relative volatility and diffusivity are lost at an early stage in drying. Foods that have a high economic value due to their characteristic flavours (for example herbs and spices) are dried at low temperatures (Mazza and LeMaguer, 1980).

The open porous structure of dried food allows access of oxygen, which is a second important cause of aroma loss due to oxidation of volatile components and lipids during storage. The rate of deterioration is determined by the storage temperature and the water activity (Chapter 1) of the food. In dried milk the oxidation of lipids produces rancid flavours owing to the formation of secondary products including δ -lactones. Most fruits and vegetables contain only small quantities of lipid, but oxidation of unsaturated fatty acids to produce hydroperoxides, which react further by polymerisation, dehydration or oxidation to produce aldehydes, ketones and acids, causes rancid and objectionable odours. Some foods (for example carrot) may develop an odour of 'violets' produced by the oxidation of carotenes to β -ionone (Rolls and Porter, 1973). These changes are reduced by:

- vacuum or gas packing
- low storage temperatures
- exclusion of ultraviolet or visible light
- maintenance of low moisture contents
- addition of synthetic antioxidants (Appendix C)
- preservation of natural anti-oxidants.

The technical enzyme, glucose oxidase (Chapter 7), is also used to protect dried foods from oxidation. A package which is permeable to oxygen but not to moisture and which contains glucose and the enzyme is placed on the dried food inside a container, to remove oxygen from the head space during storage. Milk powders are also stored under an atmosphere of nitrogen with 10% carbon dioxide (Chapter 20). The carbon dioxide is absorbed into the milk and creates a small partial vacuum in the head space. Air diffuses out of the dried particles and is removed by re-gassing after 24 h.

Flavour changes, due to oxidative or hydrolytic enzymes are prevented in fruits by the use of sulphur dioxide, ascorbic acid or citric acid, by pasteurisation of milk or fruit juices and by blanching of vegetables. Other methods which are used to retain flavours in dried foods include:

- recovery of volatiles and their return to the product during drying
- mixing recovered volatiles with flavour fixing compounds, which are then granulated and added back to the dried product (for example dried meat powders)
- addition of enzymes, or activation of naturally occurring enzymes, to produce flavours from flavour precursors in the food (for example onion and garlic are dried under conditions that protect the enzymes that release characteristic flavours).

15.3.3 Colour

There are a number of causes of colour loss or change in dried foods; drying changes the surface characteristics of a food and hence alters its reflectivity and colour. In fruits and vegetables, chemical changes to carotenoid and chlorophyll pigments are caused by heat and oxidation during drying and residual polyphenoloxidase enzyme activity causes browning during storage. This is prevented by blanching or treatment of fruits with ascorbic acid or sulphur dioxide. For moderately sulphured fruits and vegetables the rate of darkening during storage is inversely proportional to the residual sulphur dioxide content. However, sulphur dioxide bleaches anthocyanins, and residual sulphur dioxide is also linked to health concerns. Its use in dried products is now restricted in many countries.

The rate of Maillard browning in stored milk and fruit products depends on the water activity of the food and the temperature of storage. The rate of darkening increases markedly at high drying temperatures, when the moisture content of the product exceeds 4–5%, and at storage temperatures above 38°C (Lea, 1958).

15.3.4 Nutritional value

Large differences in reported data on the nutritional value of dried foods are due to wide variations in the preparation procedures, the drying temperature and time, and the storage conditions. In fruits and vegetables, losses during preparation usually exceed those caused by the drying operation. For example Escher and Neukom (1970) showed that losses of vitamin C during preparation of apple flakes were 8% during slicing, 62% from blanching, 10% from pureeing and 5% from drum drying.

Vitamins have different solubilities in water and as drying proceeds, some (for example riboflavin) become supersaturated and precipitate from solution, so losses are small (Table 15.8). Others, for example ascorbic acid, are soluble until the moisture content of the food falls to very low levels and these react with solutes at higher rates as drying proceeds. Vitamin C is also sensitive to heat and oxidation and short drying times, low temperatures, low moisture and oxygen levels during storage are therefore necessary to avoid large losses. Thiamin is also heat sensitive, but other water-soluble vitamins are more stable to heat and oxidation, and losses during drying rarely exceed 5–10%, excluding blanching losses.

Oil-soluble nutrients (for example essential fatty acids and vitamins A, D, E and K) are mostly contained within the dry matter of the food and they are not concentrated during drying. However, water is a solvent for heavy metal catalysts that promote oxidation of unsaturated nutrients. As water is removed, the catalysts become more reactive, and the rate of oxidation accelerates (Fig. 1.15 in Chapter 1). Fat-soluble vitamins are lost by interaction with the peroxides produced by fat oxidation. Losses during storage are reduced by lowering the oxygen concentration and the storage temperature and by exclusion of light.

The biological value and digestibility of proteins in most foods does not change substantially as a result of drying. However, milk proteins are partially denatured during drum drying, and this results in a reduction in solubility of the milk powder and loss of clotting ability. A reduction in biological value of 8–30% is reported, depending on the temperature and residence time in the drier (Fairbanks and Mitchell, 1935). Spray drying does not affect the biological value of milk proteins. At high storage temperatures and at

Table 15.8 Vitamin losses in selected dried foods

Food	Loss (%)						
	Vitamin A	Thiamin	Vitamin B ₂	Niacin	Vitamin C	Folic acid	Biotin
Fruits ^a	6	55	0	10	56		
Fig (sun-dried)	–	48	42	37	–	–	–
Whole milk (spray dried)	–	–	–	–	15	10	10
Whole milk (drum-dried)	–	–	–	–	30	10	10
Pork		50–70					
Vegetables ^b	5	< 10	< 10				

^aFruits mean loss from fresh apple, apricot, peach and prune.

^bVegetables mean loss from peas, corn, cabbage and beans (drying stage only).

Adapted from Rolls (1982) and Calloway (1962).

moisture contents above approximately 5%, the biological value of milk protein is decreased by Maillard reactions between lysine and lactose. Lysine is heat sensitive and losses in whole milk range from 3–10% in spray drying and 5–40% in drum drying (Rolls and Porter, 1973).

15.4 Rehydration

Water that is removed from a food during dehydration cannot be replaced in the same way when the food is rehydrated (that is, rehydration is not the reverse of drying); loss of cellular osmotic pressure, changes in cell membrane permeability, solute migration, crystallisation of polysaccharides and coagulation of cellular proteins all contribute to texture changes and volatile losses and are each irreversible (Rahman and Perera, 1999). Heat reduces the degree of hydration of starch and the elasticity of cell walls, and coagulates proteins to reduce their water-holding capacity. The rate and extent of rehydration may be used as an indicator of food quality; those foods that are dried under optimum conditions suffer less damage and rehydrate more rapidly and completely than poorly dried foods.

15.5 Acknowledgements

Grateful acknowledgement is made for information supplied by: APV Anhydro AS, Drying and Evaporation, DK-2860 Soborg, Denmark; Petrie and McNaught Ltd, Rochdale, UK; Proctor and Schwartz Inc., Glasgow, Scotland; Torftech Ltd, Mortimer, Reading, Berkshire, UK; Chartered Institute of Building Services Engineers, 222 Balham High Road, London SW12 9BS, UK; Drytec Ltd, Tonbridge, Kent TN9 1RA, UK.

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Baking and roasting

Baking and roasting are essentially the same unit operation: they both use heated air to alter the eating quality of foods. The terminology differs in common usage; baking is usually applied to flour-based foods or fruits, and roasting to meats, nuts and vegetables. In this chapter the term *baking* is used to include both operations. A secondary purpose of baking is preservation by destruction of micro-organisms and reduction of the water activity at the surface of the food. However, the shelf life of most baked foods is short unless it is extended by refrigeration or packaging.

16.1 Theory

Baking involves simultaneous heat and mass transfer; heat is transferred into the food from hot surfaces and air in the oven and moisture is transferred from the food to air that surrounds it and then removed from the oven (Chapter 1, Section 1.2 and Fig. 1.4).

In an oven, heat is supplied to the surface of the food by a combination of infrared radiation from the oven walls, by convection from circulating air and by conduction through the pan or tray on which the food is placed. Infrared radiation (Chapter 18) is absorbed into the food and converted to heat. Air, other gases and moisture vapour in the oven transfer heat by convection. The heat is converted to conductive heat at the surface of the food. A boundary film of air acts as a resistance to heat transfer into the food and to movement of water vapour from the food. The thickness of the boundary layer is determined mostly by the velocity of the air and the surface properties of the food (Chapters 1 and 15) and in part controls the rates of heat and mass transfer. Convection currents promote uniform heat distribution throughout the oven, and many commercial designs are fitted with fans to supplement natural convection currents and to reduce the thickness of boundary films. This increases heat transfer coefficients and improves the efficiency of energy utilisation.

Heat passes through the food by conduction in most cases, although convection currents are established during the initial heating of cake batters (Mizukoshi, 1990). The low thermal conductivity of foods (Chapter 1, Table 1.5) causes low rates of conductive

heat transfer and is an important influence on baking time. Conduction of heat through baking pans or trays increases the temperature difference at the base of the food and increases the rate of baking compared to the surface crust. The size of the pieces of food is an important factor in baking time as it determines the distance that heat must travel to bake the centre of the food adequately. Methods of heat transfer and resistances to heat and mass transfer are discussed further in Chapter 1. The technology of breadmaking is described in detail by Cauvain and Young (1998) and the technology of cake making by Bennion and Bamford (1997).

When a food is placed in a hot oven, the low humidity of air in the oven creates a moisture vapour pressure gradient, which causes moisture at the surface of the food to evaporate and this in turn creates movement of moisture from the interior of the food to the surface. The extent of moisture loss is determined by the nature of the food, movement of air in the oven and the rate of heat transfer. When the rate of moisture loss from the surface exceeds the rate of movement from the interior, the zone of evaporation moves inside the food, the surface dries out, its temperature rises to the temperature of the hot air (110–240°C) and a crust is formed. Because baking takes place at atmospheric pressure and moisture escapes freely from the food, the internal temperature of the food does not exceed 100°C. These changes are similar to those in hot-air drying (Chapter 15), but the more rapid heating and higher temperatures used in baking cause complex changes to the components of the food at the surface (Section 16.3). These changes both enhance eating qualities and retain moisture in the bulk of the food. In contrast with dehydration, where the aim is to remove as much water as possible with minimal changes in sensory quality, in baking the heat-induced changes at the surface of the food and retention of moisture in the interior of some products (cake, bread, meats, etc.) are desirable quality characteristics. In other products, such as biscuits and crispbread, loss of moisture from the interior is required to produce the desired crisp texture.

The types of mass and heat transfer in different parts of a food during baking are described in Table 16.1.

Equations for the calculation of heat transfer during baking are described in Chapter 1 and a relevant sample problem is given in Chapter 18.

Energy consumption during baking is of the order of 450–650 kJ per kilogram of food. Most of the heat is used to heat the food, to evaporate water, to form the crust, to superheat water vapour (steam) that is transported through the crust and to heat the dry crust. Commercial ovens are insulated with up to 30 cm of mineral wool, refractory tiles or similar materials, and heat losses are therefore minimised. Other energy conservation devices are described in Section 16.2 and Chapter 1 (Section 1.4.4).

Table 16.1 Mass and heat transfer during baking

Zone in the food	Type of mass transfer	Type of heat transfer
Boundary layer	Vapour diffusion	Conduction, convection, radiation
Crust	Vapour diffusion	Conduction, vapour movement (convection)
Evaporation zone	Vapour diffusion, surface diffusion, capillary flow	Conduction, movement of vapour and liquid water
Interior	Capillary flow	Conduction

Adapted from Hallstrom and Skjoldebrand (1983).

16.2 Equipment

Detailed descriptions of the different stages in baking are described by Manley (1998). Equipment used to prepare foods prior to baking is described in Chapter 5 (mixing and forming). In this chapter, fuel fired and electric ovens are described. Microwave and dielectric ovens are described in Chapter 18. Nearly all of the oven designs below now incorporate advanced energy saving features and microprocessor controls (Chapter 2). Pre-programmed baking controls enable operators to select a product code without the need to remember baking settings. Microprocessor control of the sequence, duration, temperature and humidity of baking prevents operator error and the use of incorrect baking conditions. Additionally, ovens at different sites can be programmed identically to achieve product uniformity from all factories. Changes to control settings or introduction of new products can be made using a diskette or from a central office by either a direct modem connection to the oven or via a communications network using a central computer.

Ovens are classified into direct or indirect heating types.

16.2.1 Direct heating ovens

In directly heated ovens, air and the products of combustion are recirculated by natural convection or by fans. The temperature in the oven is controlled automatically, by adjustment of air and fuel flow rates to the burners. Natural gas is commonly used, but propane, butane, fuel oil or solid fuels are also found (Chapter 1). Gas is burned in ribbon burners located above and below conveyor belts in continuous ovens, and at the base of the cabinet in batch ovens. Safety features are incorporated to extinguish the burners automatically if abnormal baking conditions arise, and pressure-relief panels are fitted to the top of the ovens to protect personnel should a gas explosion occur.

The advantages of direct heating ovens include:

- short baking times
- high thermal efficiencies
- good control over baking conditions (using the fan speed and the rate of fuel consumption)
- rapid start-up, as it is only necessary to heat the air in the oven.

However, care is necessary to prevent contamination of the food by undesirable products of combustion, and gas burners require regular servicing to maintain combustion efficiency. Microwave and dielectric ovens (Chapter 18) are another example of direct-heating ovens.

16.2.2 Indirect heating ovens

Steam tubes are either heated directly by burning fuel or supplied with steam from a remote boiler (Fig. 16.1). The steam tubes then heat air in the baking chamber. Heated air is commonly recirculated through the baking chamber and through a separate heat exchanger (Fig. 16.2). Alternatively, combustion gases are passed through banks of radiator tubes in the baking chamber, or fuel is burned between a double wall and the combustion products are exhausted from the top of the oven. Electric ovens are heated by induction heating radiator plates or bars. In batch ovens, the walls and base are heated whereas in continuous ovens, heaters are located above, alongside and below a conveyor

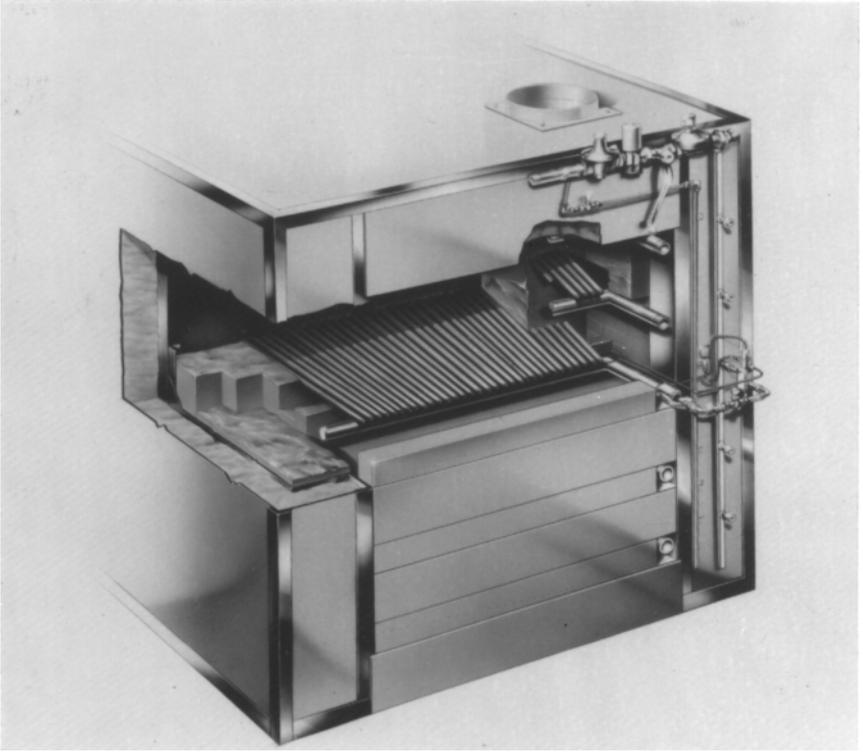


Fig. 16.1 Indirectly heated batch oven.
(Courtesy of Thomas Collins Ltd.)

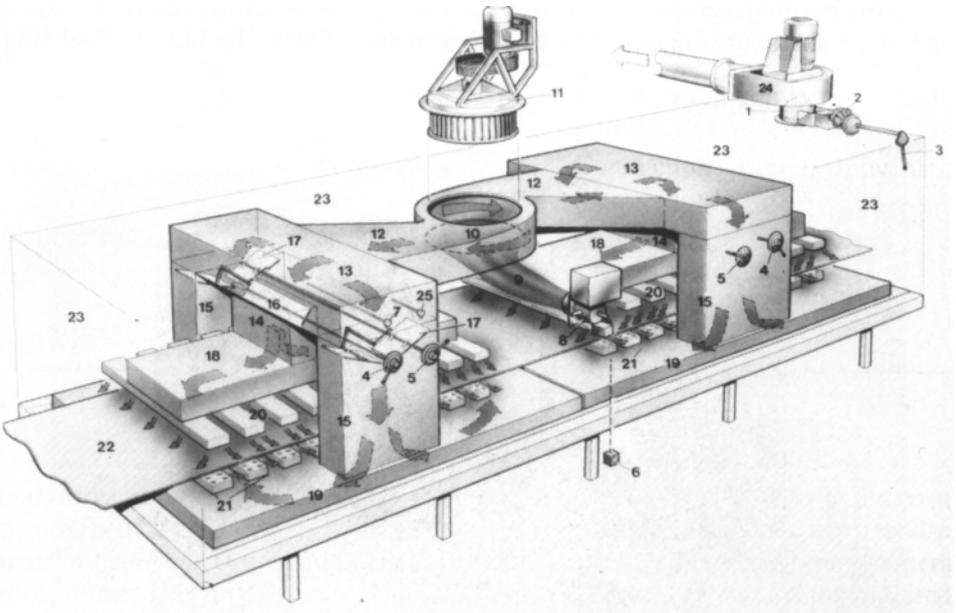


Fig. 16.2 Indirectly heated continuous oven.
(Courtesy of Spooner Industries Ltd.)

belt. Most ovens have 25 mm thick ceramic tiles fitted to the hearth to promote even heat distribution.

Forced-convection hot-air systems have shorter start-up times and a faster response to temperature control than do radiant ovens, because only the air is heated. Conventional heating, forced-convection heating, infrared heating and combined heating methods are compared by Malkki *et al.* (1984). Steam-heated batch ovens are also used for cooking meat products. Similar designs are fitted with smoke generators for smoking meats, cheeses and fish. These are described in detail by Toth and Potthast (1984). The techniques used in smoking are discussed by Lee (1983).

16.2.3 Batch ovens

In the *Peel oven*, food is loaded into a baking chamber, either on trays or singly, by means of a long-handled shovel (a *peel*) which gives its name to the oven. More recent designs include the *multi-deck oven* (Fig. 16.3) which is widely used for baked goods, meats and confectionery products. Some designs have a 'modular' construction to allow expansion of production by duplication of modules, without having to replace the entire plant. The main disadvantages of batch ovens are higher labour costs and lack of uniformity in baking times, caused by the delay in loading and unloading.

16.2.4 Continuous and semi-continuous ovens

Rotary-hearth ovens (Fig. 16.4(a)), *reel ovens* (Fig. 16.4(b)) and *multi-cycle tray ovens* (Fig. 16.4(c)) all circulate the food through the oven on trays, and loading and unloading take place though the same door. The operation is semi-continuous when the oven must be stopped to remove the food. The movement of food through the oven, with or without

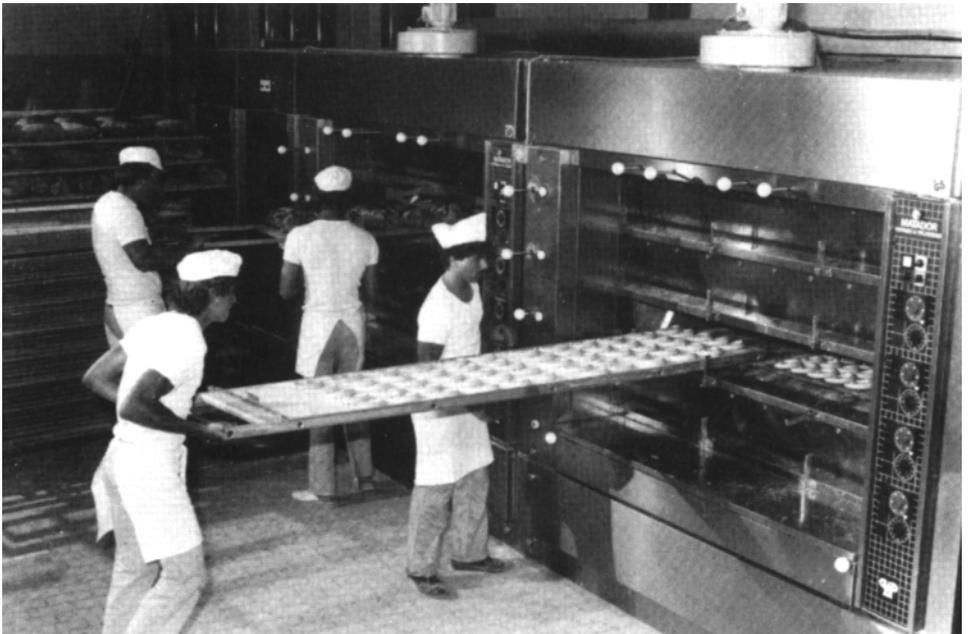


Fig. 16.3 Multi-deck oven.
(Courtesy of Werner and Pfeiderer Ltd.)

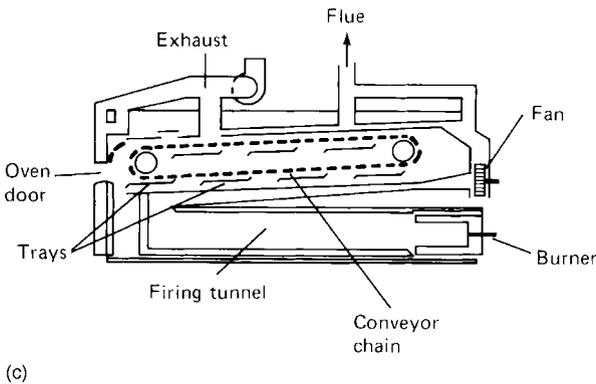
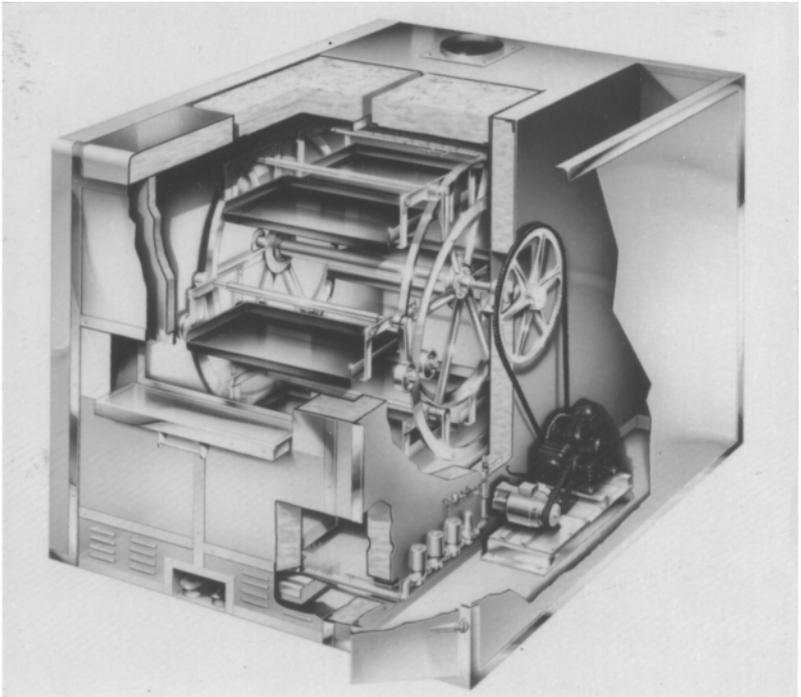
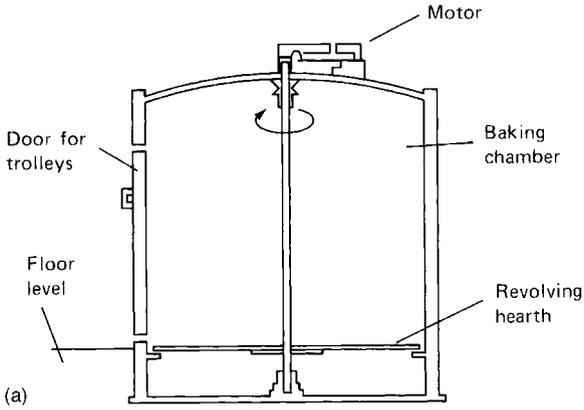


Fig. 16.4 Ovens: (a) revolving hearth oven; (b) reel oven (courtesy of Thomas Collins Ltd); (c) multi-cycle tray oven. (After Matz (1972).)



Fig. 16.5 Tunnel oven.
(Courtesy of Werner and Pfeiderer Ltd.)

fans to circulate the air, ensures more uniform heating. *Rotary-hearth ovens* have short baking times but take up a large floor space. *Reel ovens* move the product vertically through the oven and also horizontally from front to back. This permits a larger baking area for a given floor space and more uniform temperature distribution through the oven. The disadvantages of these ovens include the absence of zones of heating, and difficulty in automating loading and unloading. In many applications they are now replaced by tray and tunnel ovens. *Tray ovens* have a similar design to tunnel ovens but have metal trays permanently fixed to a chain conveyor. Each tray holds several baking pans and is pulled through the oven in one direction, then lowered onto a second rack, returned through the oven and unloaded (Fig. 16.4(c)).

Tunnel ovens consist of a metal tunnel (up to 120 m long and 1.5 m wide) (Fig. 16.5) through which food is conveyed either on steel plates (in a *travelling-hearth* type oven) or on a solid, perforated or woven metal belt in the *band* type oven. The oven is divided into heating zones and the temperature and humidity are controlled independently in each zone by heaters and dampers. These retain or remove moisture by adjusting the proportions of fresh and recirculated air in the oven. Vapour (and in direct heating ovens, the products of combustion) are extracted separately from each zone. Many designs are equipped with heat recovery systems (Fig. 16.6).

Microprocessor control of the belt speed, heater output and position of dampers automatically adjusts the baking conditions in each zone, to produce foods of a pre-determined colour or moisture content. Details of automatic colour monitoring of baked products are given in Chapter 3 (Section 3.2.2). Microprocessors also provide management information of production rates, energy efficiency and maintenance requirements (Chapter 2). Some ovens are fitted with programmable cycles in which temperature and

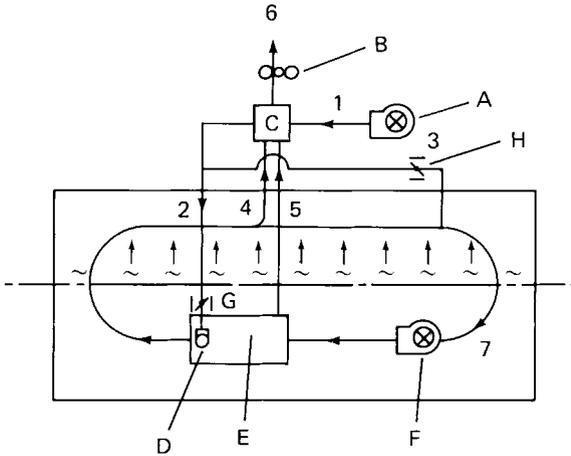


Fig. 16.6 Heat recovery for convection oven: (A) supply air fan; (B) exhaust fan; (C) heat recovery heat exchanger; (D) burner; (E) oven chamber heat exchanger (not in direct-fired ovens); (F) oven chamber air recirculating fan; (G) combustion air control damper; (H) zone integrity air control damper; (1) cold supply air; (2) hot combustion air; (3) hot-zone integrity air; (4) oven exhaust air plus product evaporation; (5) hot-oven heat exchanger exhaust; (6) cooled combined exhaust; (7) recirculating oven chamber air.
(Courtesy of Baker Perkins Ltd.)

time of heating, relative humidity, cooling time and air speed are programmed independently for each of 20 or more products. This allows rapid changes to baking conditions and a high degree of flexibility for different types of product.

Despite the high capital cost and large floor area, these ovens are widely used for large-scale baking. The main advantages are their high capacity, accuracy of control over baking conditions and low labour costs owing to automatic loading and unloading. In both tunnel and tray ovens, heat exchangers are fitted to the exhaust flues to remove heat from the exhaust gases and to heat fresh or recirculated air. Energy savings of 30% are achieved and start-up times can be reduced by 60%.

16.3 Effect on foods

The purpose of baking and roasting is to alter the sensory properties of foods, to improve palatability and to extend the range of tastes, aromas and textures in foods produced from similar raw materials. Baking also destroys enzymes and micro-organisms and lowers the water activity of the food to some extent (Chapter 1, Table 1.4), thereby preserving the food.

16.3.1 Texture

Changes in texture are determined by the nature of the food (moisture content and the composition of fats, proteins and structural carbohydrates (cellulose, starches and pectins)) and by the temperature and duration of heating. A characteristic of many baked foods is the formation of a dry crust which contains the moist bulk of the food (for example meats, bread, potato or yam). Other foods (for example biscuits) are baked to a lower moisture content, and in these the changes that take place in the crust occur throughout the food.

When meat is heated, fats melt and become dispersed as oil through the food or drain out as a component of 'drip losses'. Collagen is solubilised below the surface, to form gelatine. Oils are dispersed through the channels produced in the meat. Proteins become denatured, lose their water-holding capacity and contract. This forces out additional fats and water and toughens and shrinks the food. Further increases in temperature cause destruction of micro-organisms and inactivation of enzymes. The surface dries, and the texture becomes crisper and harder as a porous crust is formed by coagulation, degradation and partial pyrolysis of proteins. In cereal foods, changes to the granular structure of starch, gelatinisation and dehydration produce the characteristic texture of the crust.

Rapid heating produces an impermeable crust which seals in moisture and fat and protects nutrients and flavour components from degradation. A steep moisture vapour gradient is formed between the moist interior (high a_w) and hygroscopic exterior (low a_w) of the food. During storage, moisture migrates through the food. If preservative methods (for example freezing) are not used to immobilise the moisture, this migration softens the crust, lowers the eating quality and thus limits the shelf life of the food. Slower heating permits larger quantities of moisture to escape from the surface of the food before it is sealed by the crust. This results in a shallower moisture vapour gradient and a drier interior in the food. In bread ovens, initial steam heating reduces dehydration of the dough surface, and the crust therefore remains elastic for longer. Ragged breaks in the dough are avoided and the dough expands more fully. The crust is smoother and glossier, and starch hydrolysis promotes Maillard browning reactions to give a better crust colour.

16.3.2 Flavour, aroma and colour

The aromas produced by baking are an important sensory characteristic of baked goods. The severe heating conditions in the surface layers of food cause Maillard browning reactions between sugars and amino acids. Details of the chemistry of the Maillard reaction and Strecker degradation are discussed by a number of workers including Mauron (1982), Danehy (1986) and Fennema (1996). The high temperatures and low moisture contents in the surface layers also cause caramelisation of sugars and oxidation of fatty acids to aldehydes, lactones, ketones, alcohols and esters. The Maillard reaction and Strecker degradation produce different aromas according to the combination of free amino acids and sugars present in a particular food. Each amino acid produces a characteristic aroma when heated with a given sugar, owing to the production of a specific aldehyde. Different aromas are produced, depending on the type of sugar and the heating conditions used (for example the amino acid proline can produce aromas of potato, mushroom or burnt egg, when heated with different sugars and at different temperatures). An abbreviated summary of the aromas produced from the most important amino acids in four foods is shown in Table 16.2.

Further heating degrades some of the volatiles produced by the above mechanisms to produce burnt or smoky aromas. There are therefore a very large number of component aromas produced during baking. The type of aroma depends on the particular combination of fats, amino acids and sugars present in the surface layers of food, the temperature and moisture content of the food throughout the heating period and the time of heating. Details of the aromatic chemicals produced during the baking of bread and roasting of peanuts, coffee, cocoa and meat are given by Adrian (1982).

The characteristic golden brown colour associated with baked foods is due to Maillard reactions, caramelisation of sugars and dextrins (either present in the food or produced by hydrolysis of starches) to furfural and hydroxymethyl furfural, carbonisation of sugars, fats and proteins.

Table 16.2 Aromas produced by baking or roasting

Food	Predominant amino acids	Selected characteristic aromas after heating with a single sugar
Potato	Asparagine	–
	Glutamine	Caramel, butterscotch, burnt sugar
	Valine	Fruity, sweet, yeasty
	Aminobutyric acid	Caramel, maple syrup, nutty
Peanut	Alanine	Caramel, nutty, malt
	Phenylalanine	Sweet and rancid caramel, violets
	Asparagine	–
	Arginine	Bready, buttery, burnt sugar
Beef	Valine	Fruity, sweet, yeasty
	Glycine	Caramel, smoky, burnt
	Leucine	Toasted, cheesy, malt, bready
Cocoa bean	Leucine	Toasted, cheesy, malt, bready
	Alanine	Caramel, nutty, malt
	Phenylalanine	Sweet and rancid caramel, violets
Valine		Fruity, sweet, yeasty

Adapted from Adrian (1982).

16.3.3 Nutritional value

Some baked foods (for example bread and meat) are important components of the diet in many countries and are therefore an important source of proteins, vitamins and minerals. For example, lysine is the limiting amino acid in wheat flour and its destruction by baking is therefore nutritionally important. Other baked foods (for example nuts, biscuits, cocoa, coffee and snackfoods) are less important in the diet, and nutritional losses are therefore less significant.

The main nutritional changes during baking occur at the surface of foods, and the ratio of surface area to volume is therefore an important factor in determining the effect on overall nutritional loss. In pan bread, only the upper surface is affected and the pan

Table 16.3 Vitamin losses in roast meats

Vitamin	Vitamin loss (%)			
	Oven temperature, 150°C		Oven temperature, 205°C	
	Beef; internal temperature, 80°C	Pork; internal temperature, 84°C	Beef; internal temperature, 98°C	Pork; internal temperature, 98°C
Thiamin				
Meat only	39	36	53	46
Drip loss	94	83	–	–
Pantothenic acid				
Meat only	27	35	40	37
Drip loss	80	75	–	–
Niacin				
Meat only	24	31	29	33
Drip loss	84	74	–	–
Riboflavin				
Meat only	25	27	32	31
Drip loss	84	81	–	–

Adapted from Cover *et al.* (1949).

protects the bulk of the bread from substantial nutritional changes. With the exception of vitamin C, which is added to bread dough as an improver and is destroyed during baking, other vitamin losses are relatively small. In chemically leavened doughs the alkaline conditions cause the release of niacin which is bound to polysaccharides and polypeptides and therefore increase its concentration (Appendix B). The vitamin content of bread is also determined by the extent of fermentation which increases the amount of B vitamins (Chapter 7). In meats, nutrient losses are affected by the size of the piece, the type of joint, the proportions of bone and fat, pre- and post-slaughter treatments and the type of animal. Some thiamine is removed in pan drippings but, as these are usually consumed, the overall losses are smaller. Cover *et al.* (1949) studied the effect of baking temperature on vitamin losses in different meats. At 150°C the meats were well cooked and total thiamine losses were moderate. At higher temperatures the pan drippings were charred and inedible, and total losses were therefore substantially increased (Table 16.3).

In biscuits, breakfast cereals and crispbread the bulk of the food is heated to a similar extent. However, these are smaller pieces which require a shorter baking time, and losses are therefore reduced. In prepared foods, which have ingredients that have been processed to stabilise them for storage, there may be additional losses in nutritional quality (for example from milling wheat, drying fruit, frozen storage of meats or fermentation and drying of cocoa and coffee beans).

Thiamine is the most important heat-labile vitamin in both cereal foods and meats, and losses are reported in Table 16.4. In cereal foods the extent of thiamine loss is determined by the temperature of baking and the pH of the food. Loss of thiamine in pan bread is approximately 15% (Bender, 1978) but in cakes or biscuits that are chemically leavened by sodium bicarbonate, the losses increase to 50–95%.

During baking, the physical state of proteins and fats is altered, and starch is gelatinised and hydrolysed to dextrins and then reducing sugars. However, in each case the nutritional value is not substantially affected. The loss of amino acids and reducing sugars in Maillard browning reactions causes a small reduction in nutritive value. In particular, lysine is lost in Maillard reactions, which slightly reduces the protein quality. In bread the *protein efficiency ratio* is reduced by 23% compared with that of the original flour (Bender, 1978). The extent of loss is increased by higher temperatures, longer baking times and larger amounts of reducing sugars. The amylase activity of flour, the addition of sugar to dough, the use of fungal amylases (Chapter 7), and steam injection into ovens to gelatinise the surface starch and to improve crust colour all therefore affect the nutritive value of the proteins to some extent. In biscuits, a reduction in dough thickness from 4.9 mm to 3.8 mm, each baked at 170°C for 8 min, produced higher losses

Table 16.4 Thiamin losses during baking

Food	Thiamin loss (%)
Beef	40–60
Pork	30–40
Ham	50
Lamb	40–50
Poultry	30–45
Bread	15
Cake	23
Cake ^a	30–95
Soya bean	90

^aChemical leavening agent used.

Adapted from Farrer (1955).

of amino acids as follows: tryptophan, from 8% to 44%; methionine, from 15% to 48%; lysine, from 27% to 61% (Mauron *et al.*, 1960). In maize, lysine loss is increased from 5% to 88% during the manufacture of breakfast cereals, which is corrected by fortification.

16.4 Acknowledgements

Grateful acknowledgement is made for information supplied by: Spooner Industries Ltd, Ilkley, West Yorkshire LS29 8JB, UK; Werner and Pfienderer Industrial Baking Technology GmbH, Postfach 136, 71730, Tamm, Germany; Thomas Collins Ltd, Kingswood, Bristol BS15 1QH, UK; Atlas Equipment Ltd, London N17 6AZ, UK; Baker Perkins BCS Ltd, Peterborough PE3 6TA, UK; Mono Equipment Ltd, Swansea SA5 4EB, UK.

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C. Heat processing using hot oils

Frying

Frying is a unit operation which is mainly used to alter the eating quality of a food. A secondary consideration is the preservative effect that results from thermal destruction of micro-organisms and enzymes, and a reduction in water activity at the surface of the food (or throughout the food, if it is fried in thin slices). The shelf life of fried foods is mostly determined by the moisture content after frying: foods that retain a moist interior (for example doughnuts, fish and poultry products which may also be breaded or battered (Chapter 23)), have a relatively short shelf life, owing to moisture and oil migration during storage. These foods are important in catering applications and are produced on a commercial scale for distribution to retail stores, preserved by chilling (Chapter 19) and/or gas packing (Chapter 20). Foods that are more thoroughly dried by frying, for example potato crisps (potato chips in the USA), maize and other potato snackfoods, have a shelf life of up to 12 months at ambient temperature. The quality is maintained by adequate barrier properties of packaging materials (Chapter 24) and correct storage conditions.

17.1 Theory

When food is placed in hot oil, the surface temperature rises rapidly and water is vaporised as steam. The surface then begins to dry out in a similar way to that described during baking and roasting (Chapter 16). The plane of evaporation moves inside the food, and a crust is formed. The surface temperature of the food then rises to that of the hot oil, and the internal temperature rises more slowly towards 100°C. The rate of heat transfer is controlled by the temperature difference between the oil and the food and by the surface heat transfer coefficient. The rate of heat penetration into the food is controlled by the thermal conductivity of the food (Chapter 1, Table 1.5). These mechanisms are described in detail in Chapter 1.

The surface crust has a porous structure, consisting of different-sized capillaries. During frying, both water and water vapour are removed from the larger capillaries first, and replaced by hot oil. Moisture moves from the surface of the food through a boundary

film of oil, the thickness of which controls the rate of heat and mass transfer (Chapter 1). The thickness of the boundary layer is determined by the viscosity and velocity of the oil. The water vapour pressure gradient between the moist interior of the food and the dry oil is the driving force behind moisture loss, in a similar way to hot air dehydration (Chapter 15).

The time taken for food to be completely fried depends on:

- the type of food
- the temperature of the oil
- the method of frying (shallow or deep-fat frying)
- the thickness of the food
- the required change in eating quality.

Foods that retain a moist interior are fried until the thermal centre has received sufficient heat to destroy contaminating micro-organisms and to change the organoleptic properties to the desired extent. This is particularly important for comminuted meat products (for example sausages or burgers) or other foods that are able to support the growth of pathogenic bacteria.

The temperature used for frying is determined mostly by economic considerations and the requirements of the product. At high temperatures (180–200°C), processing times are reduced and production rates are therefore increased. However, high temperatures also cause accelerated deterioration of the oil and formation of free fatty acids, which alter the viscosity, flavour and colour of the oil and promote foaming. This increases the frequency with which oil must be changed and hence increases costs. A second economic loss arises from the vigorous boiling of the food at high temperatures which causes loss of oil by aerosol formation and entrainment in the product. Acrelein is a breakdown product of oil, produced at high temperatures, which forms a blue haze above the oil and is a source of atmospheric pollution.

The temperature of frying is also determined by the product requirements. Foods in which a crust and a moist interior are required, are produced by high-temperature frying. The rapid crust formation is beneficial in that it seals moisture into the food but it also restricts the rate of heat transfer to the interior. The bulk of the food therefore retains a moist texture and the flavour of the ingredients. Foods which are dried by frying are processed at a lower temperature to cause the plane of evaporation to move deeper inside the food before the crust forms. They are dried before excessive changes to the surface colour or flavour occur.

There are two main methods of commercial frying which are distinguished by the method of heat transfer involved: these are shallow frying and deep-fat frying.

17.1.1 Shallow (or contact) frying

This method is most suited to foods which have a large surface-area-to-volume ratio (for example bacon slices, eggs, burgers and other types of pattie). Heat is transferred to the food mostly by conduction from the hot surface of the pan through a thin layer of oil (Fig. 17.1). The thickness of the layer of oil varies as a result of irregularities in the surface of the food. This, together with the action of bubbles of steam which lift the food off the hot surface, causes temperature variations as frying proceeds and produces the characteristic irregular browning of shallow fried foods. Shallow frying has a high surface heat transfer coefficient (200–450 W m⁻² K⁻¹), although as explained above, this is not uniformly found across the entire surface of the food.

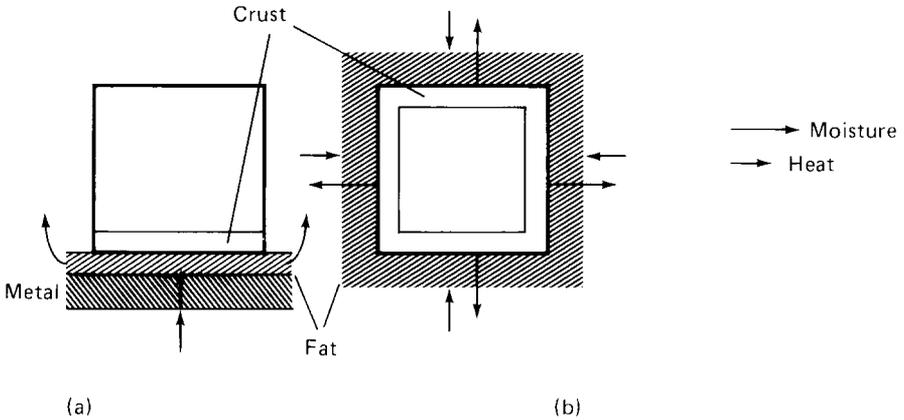


Fig. 17.1 Heat and mass transfer in (a) shallow frying and (b) deep fat frying.

17.1.2 Deep-fat frying

Here heat transfer is a combination of convection within the hot oil and conduction to the interior of the food. All surfaces of the food receive a similar heat treatment (Fig. 17.1), to produce a uniform colour and appearance. Deep-fat frying is suitable for foods of all shapes, but irregularly shaped food or pieces with a greater surface:mass ratio tend to absorb and entrain a greater volume of oil when it is removed from the fryer (Selman, 1989). Heat transfer coefficients are $250\text{--}300\text{ W m}^{-2}\text{ K}^{-1}$ before evaporation of moisture from the surface begins but subsequently increase to $800\text{--}1000\text{ W m}^{-2}\text{ K}^{-1}$ owing to the violent turbulence caused by steam escaping from the food. However, if the rate of evaporation is too high, a thin film of water vapour remains around the food and reduces the heat transfer coefficient (Hallstrom, 1980). Saguy and Pinthus (1995) report a number of studies which show that moisture loss is proportional to the square root of frying time and that oil absorption occurs as moisture is removed from the food.

Sample problem 17.1

A deep-fat fryer tank measuring 2.8 m deep, 1 m high and 1.5 m wide, and constructed from 4 mm stainless steel, is operated for 12 h day^{-1} and $250\text{ days year}^{-1}$ at 200°C . Ignoring the resistance to heat transfer caused by boundary films, calculate the annual financial savings arising from reduced energy consumption if the tank is insulated with 30 mm of fibre insulation. (Additional data: the thermal conductivity of stainless steel is $21\text{ W m}^{-2}\text{ K}^{-1}$, the thermal conductivity of the fibre insulation is $0.035\text{ W m}^{-2}\text{ K}^{-1}$, the average ambient air temperature is 18°C and the energy cost is $\text{£}0.01\text{ kW h}^{-1}$.)

Solution to Sample problem 17.1

First,

$$\begin{aligned}\text{area of uninsulated tank} &= 2(1.5 \times 1 + 2.8 \times 1 + 2.8 \times 1.5) \\ &= 17\text{ m}^2\end{aligned}$$

From equations (1.21) and (1.22),

$$200 - 18 = \frac{Q}{17} \frac{0.004}{21}$$

Therefore,

$$Q = 1.625 \times 10^7 \text{ W}$$

Now

$$\begin{aligned} \text{area of insulated tank} &= 2(1.506 \times 1.06 + 2.806 \times 1.06 + 2.806 \times 1.506) \\ &= 17.88 \text{ m}^2 \end{aligned}$$

and

$$200 - 18 = \frac{Q}{17.88} \left(\frac{0.004}{21} + \frac{0.03}{0.035} \right)$$

Thus,

$$Q = 3797 \text{ W}$$

The number of hours of operation per year is 3000 which equals 10.8×10^6 s. Now 1 kWh = 1000 W for 3600 s = 3.6×10^6 J. Therefore

$$\begin{aligned} \text{cost of energy without insulation} &= \frac{(1.625 \times 10^7)(10.8 \times 10^6)}{3.6 \times 10^6} \times 0.01 \\ &= \text{£}487\,500 \end{aligned}$$

and

$$\begin{aligned} \text{cost of energy with insulation} &= \frac{3797(10.8 \times 10^6)}{3.6 \times 10^6} \times 0.01 \\ &= \text{£}114 \end{aligned}$$

Thus

$$\begin{aligned} \text{saving} &= 487\,500 - 114 \\ &= \text{£}487\,386 \end{aligned}$$

17.2 Equipment

Shallow-frying equipment consists of a heated metal surface, covered in a thin layer of oil. Commercially, continuous deep-fat friers are more important. In batch operation the food is suspended in a bath of hot oil and retained for the required degree of frying, often assessed by changes in surface colour. Continuous deep-fat friers consist of a stainless steel mesh conveyor which is submerged in a thermostatically controlled oil tank (Fig. 17.2). They are heated by electricity, gas, fuel oil or steam. Food is metered into the oil by slow-moving paddles and either sinks to a submerged conveyor or, if the food floats, is held below the surface by a second conveyor (Fig. 17.3). The size of pieces, conveyor speed and oil temperature control the frying time. An inclined conveyor then removes the food and allows excess oil to drain back into the tank. The equipment operates automatically at production rates of up to 15 t of fried product per hour.

Oil is continuously recirculated through external heaters and filters to remove particles of food, and fresh oil is added automatically to maintain the desired level in the tank. These features extend the useful life of the oil by removing food particles that would otherwise burn and affect the flavour and colour of the product. The viscosity of the oil is important for optimum heat transfer and minimum entrainment in the food. The correct

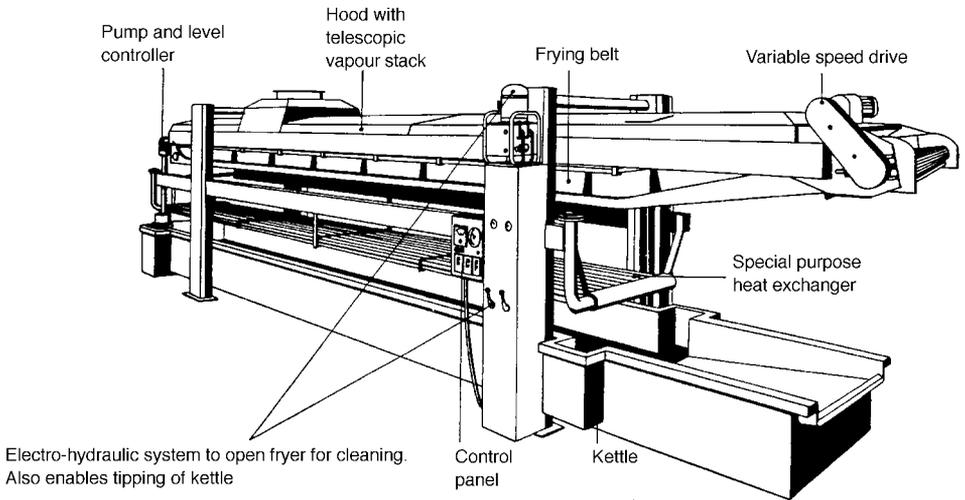


Fig. 17.2 Continuous deep-fat fryer.
(Courtesy of Coat and Fry Ltd.)

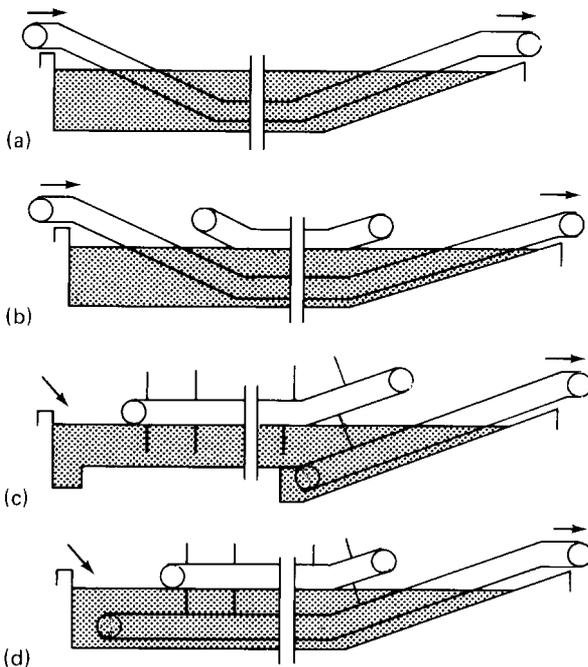


Fig. 17.3 Different conveyor arrangements: (a) delicate non-buoyant products (for example fish sticks); (b) breadcrumb-coated products; (c) dry buoyant bulk products (for example half-product snacks); (d) dual purpose (for example nuts and snacks).

(Courtesy of Coat and Fry Ltd.)

viscosity is achieved when the oil is heated until the free fatty acid content reaches 0.4%. Methyl silicone may be added to prevent foaming.

Heat and oil recovery systems are used to reduce energy and oil costs. Energy saving is achieved by heat exchangers, mounted in the exhaust hood. These recover heat from escaping steam and use it to pre-heat incoming food or oil, or to heat process water. Oil

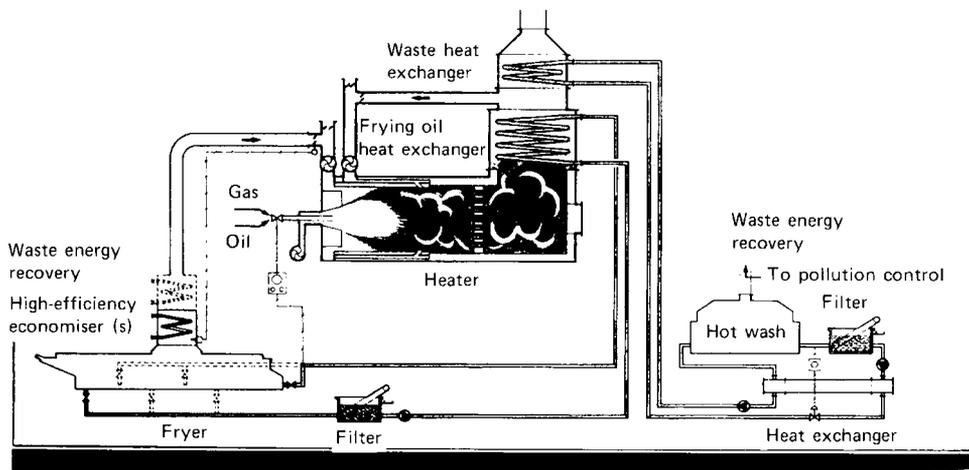


Fig. 17.4 Heat and oil recovery system.
(Courtesy of Flomech Ltd.)

recovery systems remove entrained oil from the steam and return it to the oil tank. In addition, pollution control systems prevent smoke and other products of oil degradation from being discharged into the atmosphere, by feeding the exhaust air into the burner used to heat the oil (Fig. 17.4). Computer control of the air temperature in the heater, exhaust gas temperature, oil temperature, oil level and flow rate reduces the exhaust temperature from 245°C to 110°C to give thermal efficiencies of 80–90%.

17.3 Effect on foods

Frying is an unusual unit operation in that the product of one food process (cooking oil) is used as the heat transfer medium in another. The effect of frying on foods therefore involves both the effect on the oil, which in turn influences the quality of the food, and the direct effect of heat on the fried product.

17.3.1 Effect of heat on oil

Prolonged heating of oils at the high temperatures used in frying, in the presence of moisture and oxygen released from foods, causes oxidation of the oil to form a range of volatile carbonyls, hydroxy acids, keto acids and epoxy acids. These cause unpleasant flavours and darkening of the oil. The various breakdown products are classified as volatile decomposition products (VDP) and non-volatile decomposition products (NVDP). VDPs have a lower molecular weight than the oil and are lost in vapour from the frier. Analysis of the vapour has indicated up to 220 different components (Nielsen, 1993), which form the smoke and odour of frying. However, these components are also present in the oil and contribute to the flavour of the fried product. The potential toxicity of the products of oil decomposition and other nutritional changes are discussed by Witting and Dimick (1982) and Poling *et al.* (1960).

NVDPs are formed by oxidation and polymerisation of the oil and form sediments on the sides and at the base of the frier. Polymerisation in the absence of oxygen produces cyclic compounds and high-molecular-weight polymers, which increase the viscosity of the oil.

This lowers the surface heat transfer coefficient during frying and increases the amount of oil entrained by the food. Many of these compounds are polar and they slow the evaporation of water and generate foam. However, these polar compounds also have beneficial effects in frying: they add flavour to the fried food, contribute towards the characteristic golden brown colour and optimum fat retention. Oil that has been used for a short period gives improved frying compared to fresh oil because these polar compounds promote better contact between the oil and both water on the product surface and vapour leaving the product. This results in improved and more uniform heat transfer and flavour absorption (Blumenthal, 1991). However, quality deteriorates when oil is used for a longer period. In continuous commercial production, oil that is entrained in the product is replaced continuously and NVDPs are filtered out, thus keeping the oil quality at an optimum level. The optimisation of oil quality is discussed in more detail by Nielsen (1993).

Oxidation of fat-soluble vitamins in the oil results in a loss of nutritional value. Retinol, carotenoids and tocopherols are each destroyed and contribute to the changes in flavour and colour of the oil. However, the preferential oxidation of tocopherols has a protective (anti-oxidant) effect on the oil. This is particularly important as most frying oils are of vegetable origin and contain a large proportion of unsaturated fats which are readily oxidised. The essential fatty acid, linoleic acid, is readily lost and therefore changes the balance of saturated and unsaturated fatty acids in the oil (Kilgore and Bailey, 1970).

17.3.2 Effect of heat on fried foods

The main purpose of frying is the development of characteristic colours, flavours and aromas in the crust of fried foods. These eating qualities are developed by a combination of Maillard reactions (described in Chapter 16) and compounds absorbed from the oil. The main factors that control the changes to colour and flavour in a given food are therefore:

- the type of oil used for frying
- the age and thermal history of the oil
- the interfacial tension between the oil and the product
- the temperature and time of frying
- the size, moisture content and surface characteristics of the food
- post-frying treatments.

Each of these factors, together with any pre-treatments, such as blanching or partial drying, also influences the amount of oil entrained within the food. In many fried foods, oil can account for up to 45% of the product (Saguy and Pinthus, 1995). Where fried foods form a large part of the diet, excess fat consumption can be an important source of ill-health, and is a key contributor to obesity, coronary heart disease and perhaps some types of cancer (Browner *et al.*, 1991). These risks and consumer trends towards lower fat products is creating pressure on processors to alter processing conditions to reduce the amount of oil absorbed or entrained in their products.

The texture of fried foods is produced by changes to proteins, fats and polymeric carbohydrates which are similar to those produced by baking (Chapter 16). Changes to protein quality occur as a result of Maillard reactions with amino acids in the crust. Losses of carbohydrates and minerals are largely unreported but are likely to be small. The fat content of the food increases owing to oil absorption and entrainment, but the nutritional significance of this is difficult to determine as it varies according to a number of factors including the type and thermal history of the oil, and the amount entrained in the food. Saguy and Pinthus (1995) give a detailed review of studies of oil uptake during frying.

The effect of frying on the nutritional value of foods depends on the type of process used. High oil temperatures produce rapid crust formation and seal the food surface. This reduces the extent of changes to the bulk of the food, and therefore retains a high proportion of the nutrients. In addition, these foods are usually consumed shortly after frying and there are few losses during storage. For example a 17% loss of available lysine is reported in fried fish, although this increased to 25% when thermally damaged oil was used (Tooley, 1972). Shallow-fried liver lost 15% thiamin (Kotschevar *et al.*, 1955) and no folate (Hurdle *et al.*, 1968). Vitamin C losses in fried potatoes are reported to be lower than in boiling (Domah Aabmud *et al.*, 1974). The vitamin accumulates as dehydroascorbic acid (DAA) owing to the lower moisture content whereas, in boiling, DAA is hydrolysed to 2,3-diketogluconic acid and therefore becomes unavailable.

Frying operations that are intended to dry the food and to extend the shelf life cause substantially higher losses of nutrients, particularly fat-soluble vitamins. For example vitamin E, which is absorbed from oil by crisps during frying, is oxidised during subsequent storage. Bunnell *et al.* (1965) found 77% loss after 8 weeks at ambient temperature. Oxidation proceeds at a similar rate at low temperatures and French-fried potatoes lost 74% of the vitamin E in a similar period under frozen storage. Heat- or oxygen-sensitive water soluble vitamins are also destroyed by frying under these conditions.

17.4 Acknowledgements

Grateful acknowledgement is made for information supplied by: Atlas Equipment Ltd, London N17 6AZ, UK; Flo-Mech Ltd, Peterborough PE2 0YA, UK; Coat and Fry Ltd, Derby DE2 8JD, UK; Heat and Control Inc., San Francisco, California 94080, USA.

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D. Heat processing by direct and radiated energy

Dielectric, ohmic and infrared heating

Dielectric (microwave and radio frequency) energy and infrared (or radiant) energy are two forms of electromagnetic energy (Fig. 18.1). They are both transmitted as waves, which penetrate food and are then absorbed and converted to heat. In contrast, ohmic (or resistance) heating uses the electrical resistance of foods to directly convert electricity to heat.

Foods can be heated by either direct or indirect methods: dielectric and ohmic heating are direct methods in which heat is generated within the product, whereas infrared heating is an indirect method that relies on heat that is generated externally being applied to the surface of the food mostly by radiation, but also by convection and to a lesser extent, conduction.

The main differences between dielectric, ohmic and infrared energy can be summarised as follows:

- Dielectric energy induces molecular friction in water molecules to produce heat, whereas ohmic heating is due to the electrical resistance of a food and infrared energy is simply absorbed and converted to heat.
- Dielectric heating is determined in part by the moisture content of the food, whereas the extent of heating by radiant energy depends on the surface characteristics and colour of the food and ohmic heating depends on the electrical resistance of the food.
- Dielectric and ohmic heating are used to preserve foods, whereas infrared radiation is mostly used to alter the eating qualities by changing the surface colour, flavour and aroma.
- Commercially, microwaves and radio frequency energy are produced at specified frequency bands that are allocated to prevent interference with radio transmissions, whereas radiant heat is less controlled and has a wider range of frequencies. Ohmic heating uses mains frequency electricity.
- The depth of penetration into a food is directly related to frequency; the lower frequency dielectric energy penetrates more deeply than radiant energy. In contrast, ohmic heating penetrates throughout the food instantly.
- The thermal conductivity of the food (Chapter 1) is a limiting factor in infrared heating, whereas it is not so important in dielectric and ohmic heating.

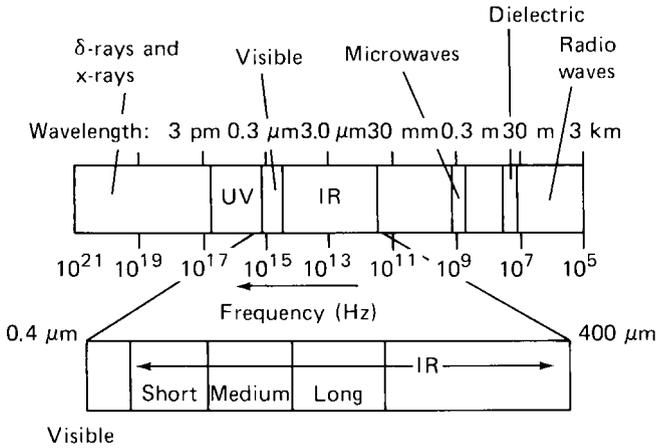


Fig. 18.1 Electromagnetic spectrum.
(Courtesy of the Electricity Council.)

18.1 Dielectric heating

18.1.1 Theory

The majority of foods contain a substantial proportion of water. The molecular structure of water consists of a negatively charged oxygen atom, separated from positively charged hydrogen atoms and this forms an electric dipole. When a microwave or radio frequency electric field is applied to a food, dipoles in the water and in some ionic components such as salt, attempt to orient themselves to the field (in a similar way to a compass in a magnetic field). Since the rapidly oscillating electric field changes from positive to negative and back again several million times per second, the dipoles attempt to follow and these rapid reversals create frictional heat. The increase in temperature of water molecules heats surrounding components of the food by conduction and/or convection. Because of their widespread domestic use, some popular notions have arisen that microwaves 'heat from the inside out'. What in fact occurs is that outer parts receive the same energy as inner parts, but the surface loses its heat faster to the surroundings by evaporative cooling. It is the distribution of water and salt within a food that has the major effect on the amount of heating (although differences also occur in the rate of heating as a result of the shape of the food, at its edges etc.).

The depth of penetration of both microwaves and radio frequency energy is determined by the dielectric constant and the loss factor of the food. These properties have been recorded for some foods (Kent, 1987), (Table 18.1). They vary with the moisture content and temperature of the food and the frequency of the electric field. In general, the lower the loss factor (i.e. greater transparency to microwaves) and the lower the frequency, the greater the penetration depth. It is possible to choose a frequency from the permitted bands that will give a suitable electric field strength for a given loss factor. Because most foods have a high moisture content and therefore a high loss factor, they readily absorb microwave and radio frequency energy and flash-over is not a problem. However, care is needed when selecting equipment for drying low moisture foods (Section 18.1.3) to prevent the electric field strength from exceeding a level at which flash-over would take place. Radio frequency energy is mostly used to heat or evaporate

Table 18.1 Dielectric properties of materials at 20–25°C and 2450 MHz

Material	Dielectric constant (Fm^{-1})	Loss factor	Penetration depth (cm)
Banana (raw)	62	17	0.93
Beef (raw)	51	16	0.87
Bread	4	0.005	1170
Brine (5%)	67	71	0.25
Butter	3	0.1	30.5
Carrot (cooked)	71	18	0.93
Cooking oil	2.6	0.2	19.5
Distilled water	77	9.2	1.7
Fish (cooked)	46.5	12	1.1
Glass	6	0.1	40
Ham	85	67	0.3
Ice	3.2	0.003	1162
Paper	4	0.1	50
Polyester tray	4	0.02	195
Potato (raw)	62	16.7	0.93

Adapted from Mudget (1982), Buffler (1993) and Mohsenin (1984).

moisture from a product, whereas higher frequency microwaves are used for defrosting and low pressure drying (Jones, 1987). Garcia and Bueno (1998) describe improved energy efficiency from combined microwave and hot air drying.

Microwaves

The depth of penetration of microwaves is found from the loss factor and the frequency of the microwaves:

$$x = \frac{\lambda_0}{2\pi\sqrt{(\epsilon' \tan \delta)}} \quad \boxed{18.1}$$

where x (m) = the depth of penetration; λ (m) = the wavelength, ϵ' = dielectric constant and $\tan \delta(\epsilon''/\epsilon')$ = loss tangent (or loss factor or dissipation constant).

The power absorbed by the food is found using:

$$P = 55.61 + 10^{-14}fE^2\epsilon'' \quad \boxed{18.2}$$

where P ($W m^{-3}$) = power per unit volume, f (Hz) = frequency and E ($V m^{-1}$) = electrical field strength.

Microwave penetration increases dramatically when water changes phase to ice (Fig. 18.2), possibly because the molecules are less free to move or absorb energy from the

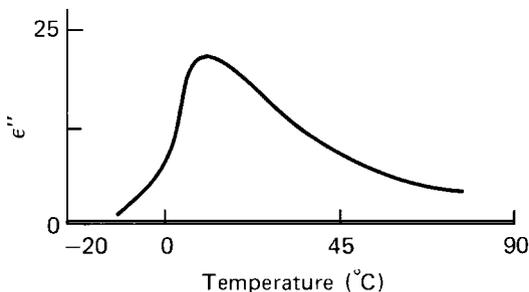


Fig. 18.2 Variation in dielectric loss factor of water and ice.
(After Lewis (1990).)

alternating electric field. Ice therefore has a lower loss factor than water and this has important implications for microwave thawing and tempering applications (Section 18.1.3). Glass, papers and some polymer films have a low loss factor and are not therefore heated. Metals reflect microwaves and are not heated (Chapter 24), therefore making microwave ovens very efficient in energy use as the metal oven is not heated.

Radio frequency heating

This operates using a similar principle to microwave heating, but at lower frequencies (Fig. 18.1). Food is passed between electrodes and a radio frequency voltage is applied across the electrodes. This changes the orientation of water dipoles in a similar way to microwaves and results in very rapid heating. Radio frequency heating allows greater concentration of heat energy, selectivity in the location of heating and accuracy in control of the duration of heating. However, the thickness of the food is restricted by the distance between the capacitor plates, which is an important limitation of the method.

A simple method to calculate the amount of radio frequency energy needed for a particular process is

$$E = \frac{m(\theta_1 - \theta_2)C_p}{863} \quad \boxed{18.3}$$

where E = energy supplied (kW), m = mass flow rate of product (kg h^{-1}), θ_1 = final product temperature ($^{\circ}\text{C}$), θ_2 = initial product temperature ($^{\circ}\text{C}$), C_p = specific heat ($\text{kJ}^{-1} \text{kg}^{-1} \text{K}^{-1}$) (courtesy of Strayfield International).

There are a number of additions to the calculated amount of energy required:

- 1 kW is added for each 1.4 kg of water to be evaporated per hour in a drying application.
- An additional 10–20% of energy required is added to account for surface cooling, depending on the surface area to volume ratio of the product.
- If it is assumed that the equipment is 65% efficient in the use of energy supplied, an additional correction is needed to calculate the actual power requirement.

In drying applications for baked goods, radio frequency ovens heat the product to a point at which rapid evaporation of water can take place and then supply the latent heat of evaporation (Chapter 15). If the product is to be dried to around 4% moisture, this is usually ‘free’ moisture which is easily removed at 100°C . However, for lower final moisture contents, it is necessary to remove moisture that is ‘bound’ into the cellular structure of the food, and higher temperatures are needed (see Section 1.5). Typically a temperature of $102\text{--}105^{\circ}\text{C}$ is needed to achieve 3% moisture, $105\text{--}110^{\circ}\text{C}$ for 2% moisture and 116°C for 1.5% moisture. When products are reduced to these very low moisture levels, there are likely to be changes to the colour of baked goods that are similar to those found in conventional ovens. The advantages of microwave and radio frequency heating can be summarised as:

- heating is rapid
- the surface of the food does not overheat, which produces minimum heat damage and no surface browning
- equipment is small, compact, clean in operation and suited to automatic control
- there is no contamination of foods by products of combustion.

18.1.2 Equipment

Microwave equipment consists of a microwave generator (termed a *magnetron*) (Fig. 18.3), aluminium tubes named *wave guides*, and a metal chamber for batch operation, or a tunnel fitted with a conveyor belt for continuous operation. Because microwaves heat all biological tissues, there is a risk of leaking radiation causing injury to operators, particularly to eyes which have insufficient blood flow to provide sufficient cooling. Chambers and tunnels are therefore sealed to prevent the escape of microwaves. Detailed descriptions of component parts and operation of microwave heaters are given by Copson (1975) and Buffler (1993).

The magnetron is a cylindrical diode ('di' meaning two and 'electrode'), which consists of a sealed copper tube with a vacuum inside. The tube contains copper plates pointing towards the centre like spokes on a wheel. This assembly is termed the 'anode' and has a spiral wire filament (the cathode) at the centre (Fig. 18.3). When a high voltage (e.g. 4000 V) is applied, the cathode produces free electrons, which give up their energy to produce rapidly oscillating microwaves, which are then directed to the waveguide by electromagnets. The waveguide reflects the electric field internally and thus transfers it to the heating chamber. It is important that the electric field is evenly distributed inside the heating chamber to enable uniform heating of the food. In batch equipment a rotating antenna or fan is used to distribute the energy, or the food may be rotated on a turntable. Both methods reduce shadowing (areas of food which are not exposed to the microwaves). In continuous tunnels a different design of antennae is used to direct a beam of energy over the food as it passes on a conveyor. It is important that the power output from the magnetron is matched to the size of the heating chamber to prevent flash-over. Power outputs of continuous industrial equipment range from 30 to 120 kW.

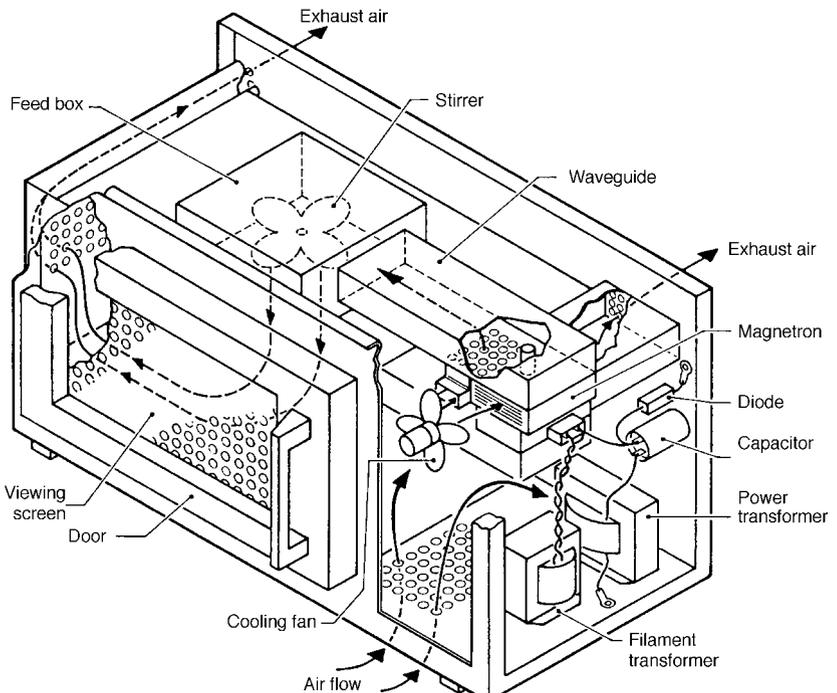


Figure 18.3 A microwave oven showing the magnetron.
(From Buffler (1993).)

Radio frequency heaters consist of banks of capacitor plates, most often located at the end of bakery tunnel ovens (Chapter 16) or conveyor driers (Chapter 15) with the conveyor band passing between the plates. The electrical circuit is arranged so that the food becomes an essential electrical component. Variations in the amount of food passing between the plates, its temperature and moisture content, will therefore cause a variation in the power output of the generator. This is a valuable self controlling feature: for example, the loss factor of a food falls as the moisture content is reduced and the power output correspondingly falls, so reducing the possibility of burning the food.

18.1.3 Applications

The high rates of heating and absence of surface changes to the food have led to studies of dielectric heating of a large number of foods. The most important industrial applications are thawing, tempering, dehydration and baking. These are reviewed by Rosenberg and Bogl (1987a) and Decareau (1985, 1990). Other applications, which involve bulk heating of foods with higher moisture contents (for example blanching and pasteurisation), are less successful. This is due to the low depth of penetration in large pieces of food and to evaporative cooling at the surface, which results in survival of large numbers of micro-organisms. These applications are discussed briefly in this section and are reviewed by Rosenberg and Bogl (1987b). Accelerated freeze drying by microwaves has been extensively investigated (Copson, 1975), but the process remains expensive and is not widely used commercially (Chapter 22).

Thawing and tempering

During conventional thawing of frozen foods (Chapter 21), the lower thermal conductivity of water, compared with ice, reduces the rate of heat transfer and thawing slows as the outer layer of water increases in thickness. Microwaves and radio frequency energy are used to rapidly thaw small portions of food and for melting fats (for example butter, chocolate and fondant cream) (Jones, 1987). However, difficulties arise with larger (e.g. 25 kg) frozen blocks (for example egg, meat, fish and fruit juice) used in industrial processes. Water has a higher loss factor than ice and, as a result, heats rapidly once the ice melts. In the large blocks, thawing does not take place uniformly, and some portions of the food may cook while others remain frozen. This is overcome to some extent by reducing the power and extending the thawing period or by using pulsed microwaves to allow time for temperature equilibration.

A more common application is '*tempering*' frozen foods. Here the temperature is raised from around -20°C to -3°C and the food remains firm but is no longer hard. After frozen food has been tempered, it is more easily sliced, diced or separated into pieces. Tempering is widely used for meat and fish products, which are more easily boned or ground at a temperature just below the freezing point, and for butter and other edible fats. If foods are tempered but not allowed to melt, the lower energy cost gives a good return on investment in dielectric equipment. The energy required to temper frozen beef, for example, is 62.8 J/g from -17.7 to -4.4°C whereas 123.3 J/g is needed to raise the temperature a further 2.2°C as more rapid melting begins to occur (Decareau, 1990). Production rates range from 14 t of meat per hour or 1.5–6 t of butter per hour in equipment which has power outputs of 25–150 kW. The advantages over conventional tempering in cold rooms include:

- faster processing (for example meat blocks are defrosted in 10 min instead of several days in a cold room)

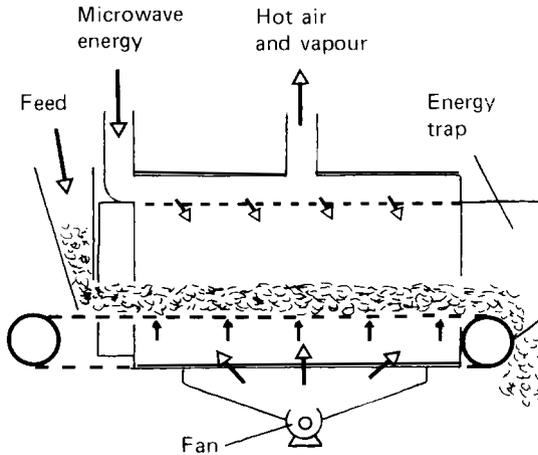


Fig. 18.4 Continuous microwave finish drying equipment.
(After Decareau (1985).)

- there is a minimal amount of food being processed at any one time and little loss or spoilage in the event of a process delay
- greater flexibility in operation
- the cost of operating a refrigerated tempering room is eliminated
- no drip loss or contamination, which improves product yields and reduces nutritional losses
- improved plant productivity and simplified production scheduling
- savings in storage space and labour
- more hygienic defrosting because products are defrosted in the storage boxes
- better control over defrosting conditions and hence improved product quality.

Dehydration

The main disadvantages of hot-air drying are:

- low rates of heat transfer, caused by the low thermal conductivity of dry foods (Chapter 1, Table 1.5)
- damage to sensory characteristics and nutritional properties caused by long drying times and overheating at the surface
- oxidation of pigments and vitamins by hot air
- case hardening (Chapter 15).

Microwaves and radio frequency energy overcome the barrier to heat transfer caused by the low thermal conductivity. This prevents damage to the surface, improves moisture transfer during the later stages of drying and eliminates case hardening. The radiation selectively heats moist areas while leaving dry areas unaffected. It is not necessary to heat large volumes of air, and oxidation by atmospheric oxygen is minimised. However, the higher cost of microwaves and radio frequency units, together with the smaller scale of operation, compared with traditional methods of dehydration, restrict microwave drying to 'finishing' (removing the final moisture) of partly dried or low-moisture foods (Fig. 18.4).

For example, in pasta drying the fresh pasta is pre-dried in hot air to 18% moisture and then in a combined hot air and microwave drier to lower the moisture content to 13%. Drying times are reduced from 8 h to 90 min, bacterial counts are 15 times lower, there is

a reduction in energy consumption of 20–25%, the drying tunnel is reduced from 36–48 m to 8 m, clean-up time is reduced from 24 to 6 person-hours and there is no case hardening (Decareau, 1985, 1990). In grain finish drying, microwaves are cheaper, more energy efficient and quieter than conventional methods and do not cause dust pollution. The lower drying temperature also improves grain germination rates.

In conventional freeze drying, the low rate of heat transfer to the sublimation front limits the rate of drying (Chapter 22). Microwave freeze drying overcomes this problem because heat is supplied directly to the ice front. However, careful control over drying conditions is necessary to prevent localised melting of the ice. Any water produced in the drying food heats rapidly, owing to the higher loss factor, and causes a chain reaction, leading to widespread melting and an end to sublimation.

Baking

The efficiency of baking is improved by radio frequency or microwave finishing, for thin products such as breakfast cereals, babyfoods, biscuits, crackers, crispbread and sponge cake. Conventional ovens operate effectively when products have relatively high moisture contents, but the thermal conductivity falls as baking proceeds, and considerable time is necessary to bake the centre of the product adequately without excessive changes to the surface colour. Radio frequency or microwave heaters are located at the exit to tunnel ovens (Chapter 16) to reduce the moisture content and to complete the baking without further changes in colour. This reduces baking times by up to 30% and hence increases the throughput of the ovens. Meat pies, which require a good crust colour in addition to pasteurisation of the filling, can be baked in about one third of the time required in a conventional oven by the use of radio frequency heating (Jones, 1987). Other advantages include:

- increases in production by up to 50%
- savings in energy, space and labour costs
- close control of final moisture contents (typically $\pm 2\%$) and automatic levelling of moisture contents as only moist areas are heated
- separate control over baking and drying stages allows separate control over internal and external product colour and moisture content
- improved product texture and elimination of ‘centre bone’ (dense dough in the centre of cookies)
- improved taste as flavours are subjected to shorter periods at high temperatures.

Other applications

Compared with conventional cooking, microwave *rendering* of fats improves the colour, reduces fines by 95% and costs by 30% and does not cause unpleasant odours (Decareau, 1985). Microwave *frying* is not successful when deep baths of oil are used, but can be used with shallow trays in which the food is heated rapidly (Chapter 17). There is also less deterioration in oil quality (Copson, 1975). Doughnuts are cooked without oil using microwaves, which reduces processing times by 20% and increases product yield by 25% (Schiffman *et al.*, 1972). Other commercial microwave cooking applications include bacon and meat patties for the fast-food industry and investigation of skinless frankfurters and other sausage products by setting meat emulsions in microwave transparent moulds (Decareau, 1990).

Blanching by microwaves has been extensively investigated, but at present the higher costs, compared with steam blanching (Chapter 10), have prevented its use for relatively

low-value vegetables. Microwave blanching of products that are more difficult to blanch by conventional methods is under development but may be limited by the high capital investment. Studies of combined steam and microwave blanching are reported to reduce blanching time (Huxsoll *et al.*, 1970).

Pasteurisation of packed complete pasta meals, soft bakery goods and peeled potatoes by microwaves is reported by Brody (1992). Most systems developed so far involve packaging the products in flat packages using thermoform/vacuum/gas flush seal equipment (Chapters 20 and 25). Packages are heated in tunnel conveyors, up to 25 m long, using a combination of microwaves and hot air at 70–90°C, followed by an equilibration stage where the slowest heating parts of the packs reach 80–85°C within 10 min. The packs are then cooled to 1–2°C and have a shelf life of approximately 40 days at 8°C. Details of a procedure for the microwave pasteurisation of fruit juices, to inactivate pectinesterase, are reported by Copson (1975) and for fruits in syrup by Brody (1992).

Sterilisation by microwaves is achieved in laminated pouches made from polypropylene/EVOH or PVDC/polypropylene (Chapter 24) in the Multitherm process. The pouches, which are transparent to microwaves, are formed and filled from a continuous reel of film but are not separated. This produces a chain of pouches that passes through a continuous hydrostat system, similar to a small hydrostatic steam steriliser (Chapter 12). In this case the pouches are submerged in a medium that has a higher dielectric constant than the product and heating is by microwaves instead of steam. In a system described by Stenstrom (1972, 1973), the product passes through seven liquid baths, heated at up to 90°C, and the final sterilising temperature reaches more than 130°C, before cooling. Both sterilisation and pasteurisation using microwaves have yet to be widely used in the food industry, but they have the potential to become increasingly important.

18.1.4 Effect on foods

Microwaves and radio frequency energy have no direct effect on micro-organisms, in contrast with ionising radiation (Chapter 8), and all changes are caused by heat alone. In pasteurisation and blanching applications, the high rates of heat transfer for a specified level of microbial or enzyme destruction result in reduced losses of heat-sensitive nutrients (for example there is no loss of carotene in microwave-blanched carrots, compared with 28% loss by steam blanching and 45% loss by water blanching (von Loesecke, 1942)). However, the results for some foods are highly variable and, for these, microwave heating offers no nutritional advantage over steaming. Changes to foods in other types of processing (frying, baking dehydration, etc.) are described in the relevant chapters. The effects of microwave cooking on nutrient retention in domestic and catering applications are described by Klein (1982) and Lachance (1975).

18.2 Ohmic heating

Also termed ‘resistance heating’ or ‘electroheating’, this is a more recent development in which an alternating electric current is passed through a food, and the electrical resistance of the food causes the power to be translated directly into heat. As the food is an electrical component of the heater, it is essential that its electrical properties (its resistance) are matched to the capacity of the heater.

The concept of direct heating in this way is not new, but it has been developed into a commercial process during the last 15 years by the APV Baker company, using a licensed design by EA Technology. The process can be used for UHT sterilisation of foods, and especially those that contain large particles (up to 2.5 cm) that are difficult to sterilise by other means (see Chapter 12). It is now in commercial use in Europe, the USA and Japan for:

- aseptic processing of high added-value ready meals, stored at ambient temperature
- pasteurisation of particulate foods for hot filling
- pre-heating products before canning
- high added-value prepared meals, distributed at chill temperatures (Fryer, 1995).

Ohmic heating is more efficient than microwave heating because nearly all of the energy enters the food as heat. Another important difference is that microwave and radio frequency heating have a finite depth of penetration into a food whereas ohmic heating has no such limitation. However, microwave heating requires no contact with the food, whereas ohmic heating requires electrodes to be in good contact. In practice the food should be liquid or have sufficient liquid with particulate foods to allow good contact and to pump the product through the heater.

The advantages of ohmic heating are as follows:

- the food is heated rapidly (1°C s^{-1}) at the same rate throughout and the absence of temperature gradients results in even heating of solids and liquids if their resistances are the same
- heat transfer coefficients do not limit the rate of heating
- temperatures sufficient for UHT processing can be achieved
- there are no hot surfaces for heat transfer, as in conventional heating, and therefore no risk of surface fouling or burning of the product which results in reduced frequency of cleaning
- heat sensitive foods or food components are not damaged by localised over-heating
- liquids containing particles can be processed and are not subject to shearing forces that are found in, for example, scraped surface heat exchangers (Chapter 12)
- it is suitable for viscous liquids because heating is uniform and does not have the problems associated with poor convection in these materials
- energy conversion efficiencies are very high (>90%)
- lower capital cost than microwave heating
- suitable for continuous processing.

Further details are given by Sastry (1994) and Rahman (1999).

18.2.1 Theory

Foods that contain water and ionic salts are capable of conducting electricity but they also have a resistance which generates heat when an electric current is passed through them. The electrical resistance of a food is the most important factor in determining how quickly it will heat. Conductivity measurements are therefore made in product formulation, process control and quality assurance for all foods that are heated electrically. Electrical resistance of a food is measured using a multimeter connected to a conductivity cell. The measured resistance is converted to conductivity using:

$$\sigma = (1/R)(L/A)$$

Table 18.2 Electrical conductivity of selected foods at 19°C

Food	Electrical conductivity (S m^{-1})
1 Potato	0.037
2 Carrot	0.041
3 Pea	0.17
4 Beef	0.42
5 Starch solution (5.5%)	
(a) with 0.2% salt	0.34
(b) with 0.55% salt	1.3
(c) with 2% salt	4.3

From Kim *et al.* (1996).

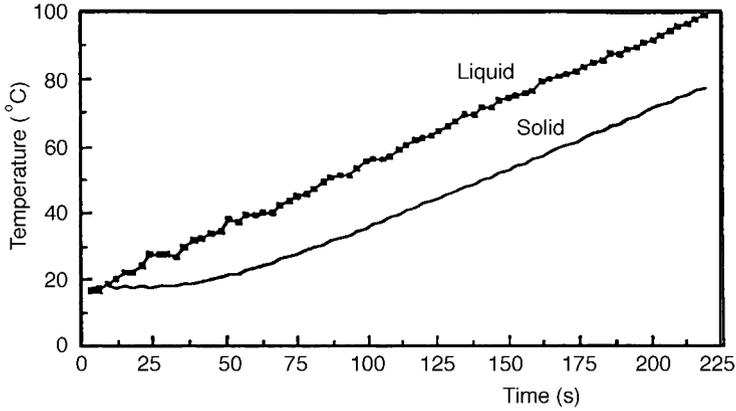
where σ (S m^{-1}) = product conductivity, R (ohms) = measured resistance, L (m) = length of the cell and A (m^2) = area of the cell.

In composite foods, the conductivity of the particle is measured by difference (i.e. the product conductivity minus the carrier medium conductivity). Data on electrical conductivity of foods (Table 18.2) is as yet relatively scarce, but has a much greater range than thermal conductivity (Chapter 1, Table 1.5). It can vary from 10^8 S m^{-1} for copper to 10^{-8} S m^{-1} for an insulating material such as wood. Electrical conductivity is also expressed as the inverse: *specific electrical resistance*. Unlike metals, where resistance increases with temperature, the electrical resistance of a food falls by a factor of 2 to 3 over a temperature rise of 120°C (Reznick, 1996). It can also vary in different directions (e.g. parallel to, or across, a cellular structure), and can change if the structure changes (e.g. gelatinisation of starch, cell rupture or air removal after blanching).

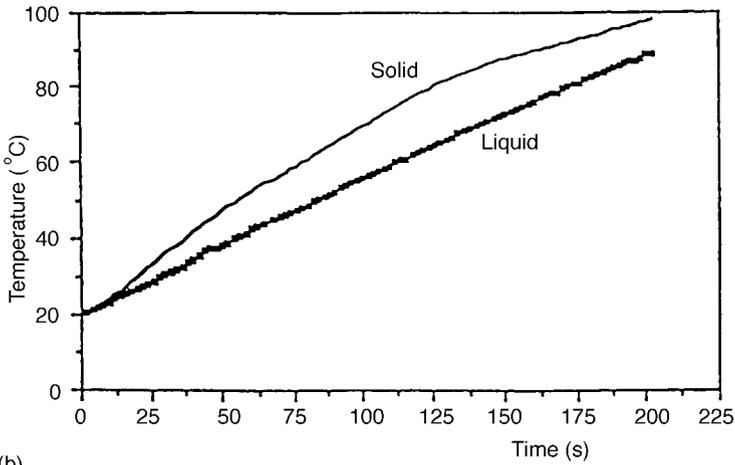
It can be seen in Table 18.2 that the conductivity of vegetables is lower than for muscle tissue, and this in turn is considerably lower than for a sauce or gravy. The salt content of a gravy is typically 0.6–1% and from the data (5b) in Table 18.2 the conductivity of the beef is about a third of that of the gravy. This has important implications for UHT processing of particles (Section 18.2.2): if in a two-component food, consisting of a liquid and particles, the particles have a lower electrical resistance, they are heated at a higher rate. This is not possible in conventional heating due to the lower thermal conductivity of solid foods, which slows heat penetration to the centre of the pieces (Chapter 1), (Fig. 18.5). Ohmic heating can therefore be used to heat sterilise particulate foods under UHT conditions without causing heat damage to the liquid carrier or over-cooking of the outside of particles. Furthermore, the lack of agitation in the heater maintains the integrity of particles and it is possible to process large particles (up to 2.5 cm) that would be damaged in conventional equipment.

The most important feature of ohmic heating is the rate of heat generation, which in addition to the electrical resistance of the product, depends on the specific heat capacities of each component, the way that food flows through the equipment and its residence time in the heater. If the two components have similar resistances, the lower moisture (solid portion) heats faster than the carrier liquid. However, the calculation of heat transfer is extremely complex, involving the simultaneous solution of equations for electrical, thermal and fluid flow fields and is beyond the scope of this book. Details are given in Fryer (1995) and Sastry and Li (1996). A simplified theory of heating is given below.

The resistance in an ohmic heater depends on the specific resistance of the product, and the geometry of the heater:



(a)



(b)

Fig. 18.5 Heat penetration into solid pieces of food by (a) conventional heating and (b) ohmic heating.
(Adapted from Fryer (1995).)

$$R = (R_s x)/A \tag{18.5}$$

where R (ohms) = total resistance of the heater, R_s (ohms m^{-1}) = specific resistance of the product, x (m) = distance between the electrodes and A (m^2) = area of the electrodes.

The resistance determines the current that is generated in the product:

$$R = \frac{V}{I} \tag{18.6}$$

where V (volts) = voltage applied and I (amps) = current.

The available 3-phase power sources in most countries have 220–240 volts per phase at a frequency of 50 Hz and to make the best use of the power, the geometry of the heater and the resistance of the product have to be carefully matched. If the resistance is too high, the current will be too low at maximum voltage. Conversely, if the resistance is too low, the maximum limiting current will be reached at a low voltage and again the heating power will be too low.

Every product has a critical current density and if this is exceeded, there is likely to be arcing (or flash-over) in the heater. The current density is found by:

$$I_d = I/A \quad \boxed{18.7}$$

where I_d (amps cm^{-2}) = current density.

The minimum area for the electrodes can therefore be calculated once the limiting current density and maximum available current are known. As resistance is determined in part by the area of the electrodes (equation 18.5), the distance between the electrodes can be calculated. It is important to recognise that the design of the heater is tailored to products that have similar specific electrical resistances and it cannot be used for other products without modification.

The rate of heating is found using equation (18.8):

$$Q = m.C_p.\Delta\theta \quad \boxed{18.8}$$

and the power by

$$P = V I \quad \boxed{18.9}$$

and

$$P = R I^2 \quad \boxed{18.10}$$

Assuming that heat losses are negligible, the temperature rise in a heater is calculated using

$$\Delta\theta = \frac{V^2\sigma_a A}{xmc_p} \quad \boxed{18.11}$$

where $\Delta\theta$ ($^{\circ}\text{C}$) = temperature rise, σ_a (S m^{-1}) = average product conductivity throughout temperature rise, A (m^2) = tube cross-sectional area, x (m) = distance between electrodes, M (kg s^{-1}) = mass flowrate and c_p ($\text{J kg}^{-1}\text{ }^{\circ}\text{C}^{-1}$) = specific heat capacity of the product.

18.2.2 Equipment and applications

As described in Section 18.2.1, the design of ohmic heaters must include the electrical properties of the specific product to be heated, because the product itself is an electrical component. This concept is only found elsewhere in radio frequency heating and requires more specific design considerations than those needed when choosing other types of heat exchangers. Ohmic heaters should therefore be tailored to a specific application and the following factors taken into account:

- the type of product (electrical resistance and change in resistance over the expected temperature rise)
- flowrate
- temperature rise (determines the power requirement)
- heating rate required
- holding time required.

To be commercially successful, ohmic heaters must:

- have effective control of heating and flow rates
- be cost effective

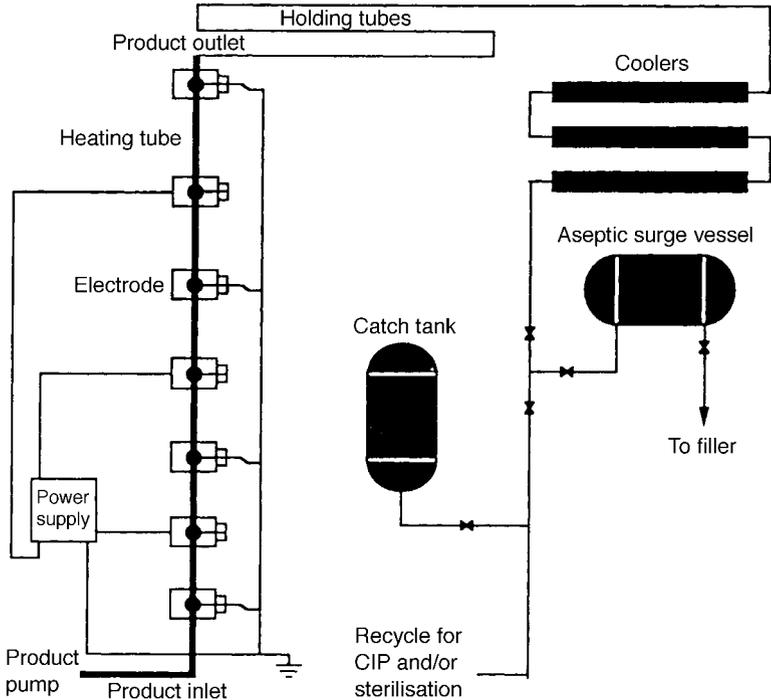


Fig. 18.6 Flowsheet for ohmic heating system.
(After Parrott (1992).)

- allow aseptic processing and packaging
- have an electrical design that avoids electrolysis or product scorching.

Early designs used DC power, which caused electrolysis (corrosion of electrodes and product contamination) and also had expensive electrodes. The use of mains power supply at 50 Hz reduces the risk of electrolysis and minimises the complexity and cost. Alternatively, higher frequencies (>100 kHz) or carbon electrodes may be used to reduce electrolysis. The layout of the APV Baker ohmic heating system is shown in Fig. 18.6.

Pre-treatments of solid components include:

- pre-heating in the carrier liquid to equilibrate resistances
- blanching pasta for moisture absorption
- heating the carrier liquid to pre-gelatinise starch
- heating to melt and expel fats
- stabilisation of sauces by homogenisation, especially dairy sauces or others that contain fats and heat sensitive proteins
- blanching vegetables to expel air and/or to denature enzymes
- enzymic marinades to soften texture and enhance flavour of meats
- soaking in acids or salts to alter the electrical resistance of particles
- sautéing to improve appearance of meat particles (Zoltai and Swearingen, 1996).

Ohmic heating has been used to process various combinations of meats, vegetables, pasta and fruits when accompanied by a suitable carrier liquid. A variety of shapes, including cubes, discs, spheres, rods and twists have been processed (Zoltai and

Swearingen, 1996). In operation, the bulk of the carrier liquid is sterilised by conventional plate or tubular heat exchangers (Chapter 12) and then injected into the particle stream as it leaves the holding tube. This has the advantage of reducing the capital and operating costs for a given throughput and allows a small amount of carrier liquid to be used to suspend the particles, thus improving process efficiency (Dinnage, 1990). Ohmic heating costs were found by Allen *et al.* (1996) to be comparable to those for freezing and retort processing of low acid products.

Food is pumped up through a vertical tube containing a series of electrodes where it is heated to process temperature. The stainless steel cantilever electrodes (supported from one side) are contained in a PTFE housing and fit across the tube. An alternating current from a 3-phase supply flows between the electrodes and through the food as it moves along the tube. The tube sections are made from stainless steel, lined with an insulating plastic such as polyvinylidene fluoride (PVDF), polyether ether ketone (PEEK) or glass. The system is designed to maintain the same impedance in each section between the electrodes, and the tubes therefore increase in length between inlet and outlet because the electrical conductivity of the food increases as it is heated. Typically, an overall tube dimension of 0.3 cm internal diameter and 30 cm length could heat several hundred litres per hour, whereas a tube of 2.5 cm diameter and 2 m length could heat several thousand litres per hour (Reznick, 1996). Commercial equipment is available with power outputs of 75 and 300 kW, which correspond to throughputs of approximately 750 and 3000 kg h⁻¹ respectively (Fryer, 1995). The process is automatically controlled via a feed-forward system (Chapter 2), which monitors inlet temperature, product flow rate and specific heat capacity and continuously adjusts the power required to heat the product (Dinnage, 1990).

The almost complete absence of fouling in ohmic heaters means that after one product has been processed, the plant is flushed through with a base sauce and the next product is introduced. At the end of processing, the plant is flushed with a cleaning solution.

In conventional heaters, turbulence is needed to create mixing of the product and maintain maximum temperature gradients and heat transfer coefficients (Chapter 1, Section 1.3). In ohmic heating, the electric current flows through the product at the speed of light and there are no temperature gradients since the temperature is uniform across the cross-section of flow. The flowrate of product is negligible compared to the velocity of the electric current, but if the flowrate is not uniform across the cross-sectional area, the very high rates of heating mean that slower moving food will become considerably hotter. It is therefore important to ensure that uniform (or 'plug') flow conditions are maintained in the heater. Kim *et al.* (1996) give details of experimental studies which confirm that this takes place. Similarly, the type of pump that is used should provide a continuous flow of material without pulses, as these would lead to increased holding times in the tube and uneven heating. A high pressure is maintained in the heater (up to 4 bar for UHT processing at 140°C) to prevent the product from boiling. Food then passes from the heater to a holding tube where it is held for sufficient time to ensure sterility and is then cooled and aseptically packaged (also Chapter 12).

The process is suitable for particulate foods that contain up to about 60% solids. In contrast to conventional UHT processing of particulate foods, where the liquid component is an important medium for heat transfer into the particles, in ohmic heating a high solids content is desirable for two reasons: faster heating of low-conductivity particles than the carrier liquid and plug flow in the heater tubes. High solids concentrations can be processed if the particles are pliable and small, or their geometry is varied to reduce the void spaces between particles. Lower concentrations require a higher

viscosity carrier liquid to keep the particles in suspension. The density of the particles should also be matched to the carrier liquid: if particles are too dense or the liquid is not sufficiently viscous, the particles will sink in the system and be over-processed. Conversely, if the particles are too light they will float and this leads to variable product composition and the risk of under-processing. It is almost impossible to determine the residence time or heating profiles of particles that float or sink. The viscosity of the fluid (sauce or gravy) should therefore be carefully controlled and for example, pre-gelatinised starches should be used to prevent viscosity changes during processing.

In order for ohmic UHT processing of particulate foods to be accepted by the regulatory authorities, it is necessary to ensure that the coldest part of the slowest heating particle in the food has received sufficient heat to ensure sterility (Chapter 1, Section 1.4.5 and Chapter 12). It is not easy to measure heat penetration into particles, whereas it is relatively easy to measure the temperature of the carrier liquid. The process must therefore demonstrate that solid particles are heated to an equal or greater extent than the liquid when they enter the holding tube. By adjustment of the electrical properties of each component (e.g. by control of salt content in the formulation) it is possible to ensure that this takes place for homogenous particles (Fig. 18.5), but data is not yet available for non-homogenous particles (e.g. fatty meat pieces) which have variable electrical resistance. The situation is made more complex when a batch of food is held before processing and, for example, salt leaches out of the particles into the surrounding sauce. This results in changes to the electrical resistance of both components and hence their rate of heating. Furthermore, the presence of fats and other poorly conductive materials means that particles will heat mostly by conduction and a cold spot will be created within the particle (Larkin and Spinak, 1996). It is important that there is no accidental inclusion of either highly conducting materials, or more likely insulating materials such as pieces of bone, fat, nuts or ice in a food, because neither will be heated. If this happens, the surrounding food may also be under-processed.

Other factors that need to be defined include:

- size and shape of particle pieces
- moisture content of solids
- solids/liquid ratio
- viscosity of liquid component
- amount and type of electrolytes
- pH
- specific heat
- thermal conductivity.

Additionally, the effect of processing on the above factors needs to be determined to detect whether they change and hence alter the heating characteristics of the product. Any changes to ingredients that are made to take account of changing consumer tastes or cost/availability should be tested to determine the effects on heating characteristics (Larkin and Spinak, 1996).

18.3 Infrared heating

18.3.1 Theory

Infrared energy is electromagnetic radiation (Fig. 18.1) which is emitted by hot objects. When it is absorbed, the radiation gives up its energy to heat materials. The rate of heat transfer depends on:

- the surface temperatures of the heating and receiving materials
- the surface properties of the two materials
- the shapes of the emitting and receiving bodies.

The amount of heat emitted from a *perfect radiator* (termed a *black body*) is calculated using the Stefan–Boltzmann equation:

$$Q = \sigma AT^4 \quad \boxed{18.12}$$

where Q (J s^{-1}) = rate of heat emission, $s = 5.7 \times 10^{-8}$ ($\text{J s}^{-1} \text{m}^{-2} \text{K}^{-4}$) the Stefan–Boltzmann constant, A (m^2) = surface area and T ($\text{K} = ^\circ\text{C} + 273$) = absolute temperature. This equation is also used for a *perfect absorber* of radiation, again known as a *black body*. However, radiant heaters are not perfect radiators and foods are not perfect absorbers, although they do emit and absorb a constant fraction of the theoretical maximum. To take account of this, the concept of *grey bodies* is used, and the Stefan–Boltzmann equation is modified to:

$$Q = \epsilon \sigma AT^4 \quad \boxed{18.13}$$

where ϵ = emissivity of the grey body (a number from 0 to 1) (Table 18.3). Emissivity varies with the temperature of the grey body and the wavelength of the radiation emitted.

The amount of absorbed energy, and hence the degree of heating, varies from zero to complete absorption. This is determined by the components of the food, which absorb radiation to different extents, and the wavelength of the radiated energy. Some of this radiation is absorbed and some is reflected back out of the food. The amount of radiation absorbed by a grey body is termed the *absorptivity* (α) and is numerically equal to the emissivity (Table 18.3). Radiation which is not absorbed is reflected and this is expressed as the *reflectivity* ($1 - \alpha$). There are two types of reflection: that which takes place at the surface of the food and that which takes place after radiation enters the food structure and becomes diffuse due to scattering. Surface reflection produces the gloss observed on polished materials whereas body reflection produces the colours and patterns of a material.

The wavelength of infrared radiation is determined by the temperature of the source. Higher temperatures produce shorter wavelengths which have a greater depth of penetration. The net rate of heat transfer to a food therefore equals the rate of absorption minus the rate of emission:

$$Q = \epsilon \sigma A(T_1^4 - T_2^4) \quad \boxed{18.14}$$

where T_1 (K) = temperature of emitter and T_2 (K) = temperature of absorber.

Table 18.3 Approximate emissivities of materials in food processing

Material	Emissivity
Burnt toast	1.00
Dough	0.85
Water	0.955
Ice	0.97
Lean beef	0.74
Beef fat	0.78
White paper	0.9
Painted metal or wood	0.9
Unpolished metal	0.7–0.25
Polished metal	< 0.05

From Earle (1983) and Lewis (1990).

Sample problem 18.1

An 8 kW oven has a hearth area of 4 m^2 and operates at 210°C . It is loaded with two batches of bread dough in baking tins; 150 loaves on the first batch and 120 loaves on the second batch. The surface of each loaf measures $12 \text{ cm} \times 20 \text{ cm}$. Assuming that the emissivity of dough is 0.85, that the dough bakes at 100°C , and that 90% of the heat is transmitted in the form of radiant energy, calculate the efficiency of energy use (as the percentage of the supplied radiant energy which is absorbed by the food) for each batch.

Solution to Sample problem 18.1

In the first batch,

$$\begin{aligned}\text{area of dough} &= 150(0.2 \times 0.12) \\ &= 3.6 \text{ m}^2\end{aligned}$$

From equation (18.14)

$$\begin{aligned}Q &= 3.6 \times 0.85 (5.73 \times 10^{-8}) (483^4 - 373^4) \\ &= 6145.6 \text{ W}\end{aligned}$$

In the second batch,

$$\begin{aligned}\text{area of dough} &= 120(0.2 \times 0.12) \\ &= 2.88 \text{ m}^2\end{aligned}$$

and

$$\begin{aligned}Q &= 2.88 \times 0.85 (5.73 \times 10^{-8}) (483^4 - 373^4) \\ &= 4916 \text{ W}\end{aligned}$$

Thus, for the first batch,

$$\begin{aligned}\text{efficiency} &= \frac{6145.6}{8 \times 0.9} \\ &= 85\%\end{aligned}$$

and, for the second batch,

$$\begin{aligned}\text{efficiency} &= \frac{4916}{8 \times 0.9} \\ &= 68\%\end{aligned}$$

18.3.2 Equipment

Types of radiant heaters include flat or tubular metal heaters, ceramic heaters, and quartz or halogen tubes fitted with electric filaments (Table 18.4).

The main commercial application of radiant energy is in drying low-moisture foods (for example breadcrumbs, cocoa, flours, grains, malt, pasta products and tea) and in baking or roasting ovens (Chapter 16). Products pass through a tunnel, beneath banks of radiant heaters, on a conveyor (Ginzberg, 1969). It is not, however, widely used as a single source of energy for drying larger pieces of food because of the limited depth of penetration. Radiant energy is also used in vacuum band driers and cabinet driers (Chapter 15), in accelerated freeze driers (Chapter 22), in some

Table 18.4 Infrared emitter characteristics

Type of emitter	Maximum running temperature (°C)	Maximum intensity (kW m ⁻²)	Maximum process temperature (°C)	Radiant heat (%)	Convection heat (%)	Heating-cooling time (s)	Expected life
<i>Short wavelength</i>							
Heat lamp	2200	10	300	75	25	1	5000 h
IR gun	2300	2	1600	98	2	1	–
Quartz tube	2200	80	600	80	20	1	5000 h
<i>Medium wavelength</i>							
Quartz tube	950	60	500	55	45	30	Years
<i>Long wavelength</i>							
Element	800	40	500	50	50	< 120	Years
Ceramic	700	40	400	50	50	< 120	Years

From Anon. (1981).

domestic microwave ovens to brown the surface of foods; and to heat-shrink packaging film (Chapter 25).

18.3.3 Effect on foods

The rapid surface heating of foods seals in moisture and flavour or aroma compounds. Changes to surface components of foods are similar to those that occur during baking and are described in Chapter 16.

18.4 Acknowledgements

Grateful acknowledgement is made for information supplied by: APV Baker Ltd, Peterborough PE4 7AP, UK; The National Committee for Electroheat, London SW1P 4RD, UK; Strayfield International Ltd, Reading RG4 7DW, UK; Raytheon Corporation, Waltham, MA 02154, USA.

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Part IV

Processing by the removal of heat

In the unit operations described in this section, a reduction in the temperature of foods slows the biochemical and microbiological changes that would otherwise take place during storage. Preservation by lowering the temperature of foods has important benefits in maintaining their sensory characteristics and nutritional value to produce high quality products. As a result these products have substantially increased in importance during the 1980s and 1990s. Many of the developments in minimal processing methods (Chapter 9) as well as storage of fresh foods rely on chilling (Chapter 19) as a main preservation component. Rapid expansion of ready-to-eat chilled foods, which may also be packed in modified atmospheres (Chapter 20) has been an important development over the last ten years.

In general, the lower the storage temperature, the longer foods can be stored, and freezing (Chapter 21) continues to be an important method of processing to produce foods that have a long shelf life. Freeze drying and freeze concentration (Chapter 22) remain important processes for some high-value products, but the high operating costs of these technologies remain important deterrents to their more widespread adoption.

Micro-organisms and enzymes are inhibited at low temperatures, but unlike heat processing they are not destroyed. Any increase in temperature can therefore permit the growth of pathogenic bacteria or increase the rate of spoilage of foods. Careful control is needed to maintain a low storage temperature and prepare foods quickly under strict hygienic conditions to prevent spoilage or food poisoning. The need to maintain chill- or frozen temperatures throughout the distribution chain is a major cost to producers and retailers, and this area has seen significant developments to improve efficiency, reduce costs and reduce the risk of spoilage and food poisoning.

19

Chilling

Chilling is the unit operation in which the temperature of a food is reduced to between -1°C and 8°C . It is used to reduce the rate of biochemical and microbiological changes, and hence to extend the shelf life of fresh and processed foods. It causes minimal changes to sensory characteristics and nutritional properties of foods and, as a result, chilled foods are perceived by consumers as being convenient, easy to prepare, high quality and 'healthy', 'natural' and 'fresh'. Since the 1980s there has been substantial product development and strong growth in the chilled food market, particularly for sandwiches, desserts, ready meals, prepared salads, pizza and fresh pasta (Jennings, 1997). Bond (1992), for example, describes the introduction of 1000 new chilled products *per annum* in the late 1980s, with product development still continuing at a rate of some 750 new products per year.

Chilling is often used in combination with other unit operations (for example fermentation (Chapter 7) or pasteurisation (Chapter 11)) to extend the shelf life of mildly processed foods. There is a greater preservative effect when chilling is combined with control of the composition of the storage atmosphere (Chapter 20) than that found using either unit operation alone. However, not all foods can be chilled and tropical, subtropical and some temperate fruits, for example, suffer from chilling injury at $3\text{--}10^{\circ}\text{C}$ above their freezing point.

Chilled foods are grouped into three categories according to their storage temperature range as follows (Hendley, 1985):

1. -1°C to $+1^{\circ}\text{C}$ (fresh fish, meats, sausages and ground meats, smoked meats and breaded fish).
2. 0°C to $+5^{\circ}\text{C}$ (pasteurised canned meat, milk, cream, yoghurt, prepared salads, sandwiches, baked goods, fresh pasta, fresh soups and sauces, pizzas, pastries and unbaked dough).
3. 0°C to $+8^{\circ}\text{C}$ (fully cooked meats and fish pies, cooked or uncooked cured meats, butter, margarine, hard cheese, cooked rice, fruit juices and soft fruits).

Details of the range of available chilled foods and future trends are given by Bond (1992) and Dade (1992).

The successful supply of chilled foods to the consumer is heavily dependent on sophisticated and relatively expensive distribution systems which involve chill stores, refrigerated transport and retail chill display cabinets, together with widespread ownership of domestic refrigerators. Precise temperature control is essential at all stages to avoid the risk of food spoilage or food poisoning. In particular, low-acid chilled foods, which are susceptible to contamination by pathogenic bacteria (for example fresh and pre-cooked meats, pizzas and unbaked dough) must be prepared, packaged and stored under strict conditions of hygiene and temperature control. Details of legislation that affects temperature control of chilled foods in Europe and North America are given by Turner (1992) and Woolfe (2000).

19.1 Theory

19.1.1 Fresh foods

The rate of biochemical changes caused by either micro-organisms or naturally occurring enzymes increases logarithmically with temperature (Chapter 1). Chilling therefore reduces the rate of enzymic and microbiological change and retards respiration of fresh foods. The factors that control the shelf life of fresh crops in chill storage include:

- the type of food and variety or cultivar
- the part of the crop selected (the fastest growing parts have the highest metabolic rates and the shortest storage lives (Table 19.1))
- the condition of the food at harvest (for example the presence of mechanical damage or microbial contamination, and the degree of maturity)
- the temperature of harvest, storage, distribution and retail display
- the relative humidity of the storage atmosphere, which influences dehydration losses.

Further details are given in Section 19.3.

The rate of respiration of fresh fruits is not necessarily constant at a constant storage temperature. Fruits which undergo 'climacteric' ripening show a short but abrupt increase in the rate of respiration which occurs near to the point of optimum ripeness.

Table 19.1 Botanical function related to respiration rate and storage life for selected products

Product	Relative respiration rate	Botanical function	Typical storage life (weeks at 2°C)
Asparagus	40	Actively growing	0.2–0.5
Mushrooms	21	shoots	
Artichokes	17		
Spinach	13	Aerial parts of plants	1–2
Lettuce	11		
Cabbage	6		
Carrots	5	Storage roots	5–20
Turnips	4		
Beetroots	3		
Potatoes	2	Specialised storage organs	25–50
Garlic	2		
Onions	1		

From Alvarez and Thorne (1981).

Table 19.2 Heat produced by respiration in selected foods

Food	Heat (W t^{-1}) of respiration for the following storage temperatures		
	0°C	10°C	15.5°C
Apples	10–12	41–61	58–87
Bananas	–	65–116	–
Beans	73–82	–	440–580
Carrots	46	93	–
Celery	21	58–81	–
Oranges	9–12	35–40	68
Lettuce	150	–	620
Pears	8–20	23–63	–
Potatoes	–	20–30	–
Strawberries	36–52	145–280	510
Tomatoes	57–75	–	78

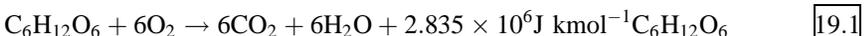
Adapted from Leniger and Beverloo (1975) and Lewis (1990).

Climacteric fruits include apple, apricot, avocado, banana, mango, peach, pear, plum and tomato. Non-climacteric fruits include cherry, cucumber, fig, grape, grapefruit, lemon, pineapple and strawberry. Vegetables respire in a similar way to non-climacteric fruits. Differences in respiratory activity of selected fruits and vegetables are shown in Tables 19.1 and 19.2.

Undesirable changes to some fruits and vegetables occur when the temperature is reduced below a specific optimum for the individual fruit. This is termed *chilling injury* and results in various physiological changes (for example internal or external browning, failure to ripen and skin blemishes). The reasons for this are not fully understood but may include an imbalance in metabolic activity which results in the over-production of metabolites that then become toxic to the tissues (Haard and Chism, 1996). It is found for example in apples (less than 2–3°C), avocados (less than 13°C), bananas (less than 12–13°C), lemons (less than 14°C), mangoes (less than 10–13°C) and melons, pineapples and tomatoes (each less than 7–10°C). The optimum storage temperature and relative humidity, and expected storage times are shown in Table 19.3 for a variety of fresh fruits and vegetables. Undesirable changes due to incorrect relative humidity are described by van den Berg and Lentz (1974).

In animal tissues, aerobic respiration rapidly declines when the supply of oxygenated blood is stopped at slaughter. Anaerobic respiration of glycogen to lactic acid then causes the pH of the meat to fall, and the onset of *rigor mortis*, in which the muscle tissue becomes firm and inextensible. Cooling during anaerobic respiration is necessary to produce the required texture and colour of meat and to reduce bacterial contamination. Undesirable changes, caused by cooling meat before rigor mortis has occurred, are termed *cold shortening*. Details of these and other post-mortem changes to meat are described by Laurie (1998).

To chill fresh foods it is necessary to remove both sensible heat (also known as *field heat*) and heat generated by respiratory activity. The production of respiratory heat at 20°C and atmospheric pressure is given by equation (19.1).



The size of refrigeration plant and the processing time required to chill a crop are calculated using unsteady-state heat transfer methods (Chapter 1). The calculations are

Table 19.3 Optimum storage conditions for some fruits and vegetables

Food	Temperature (°C)	Relative humidity (%)	Storage life (days)
Apricot	-0.5-0	90	7-14
Banana	11-15.5	85-95	7-10
Bean (snap)	7	90-95	7-10
Broccoli	0	95	10-14
Carrot	0	98-100	28-42
Celery	0	95	30-60
Cherry	-1	90-95	14-20
Cucumber	10-15	90-95	10-14
Eggplant	7-10	90-95	7-10
Lemon	10-14	85-90	30-180
Lime	9-10	85-90	40-140
Lettuce	0-1	95-100	14-20
Mushroom	0	90	3-4
Peach	-0.5-0	90	14-30
Plum	-1-0	90-95	14-30
Potato	3-10	90-95	150-240
Spinach	0	95	10-14
Strawberry	-0.5-0	90-95	5-7
Tomato	4-10	85-90	4-7
Watermelon	4-10	80-90	14-20

Adapted from Farrall (1976), Frazier and Westhoff (1988), Duckworth (1966), Kader *et al.* (1998) and Yang (1998).

simpler when processed foods are chilled as respiratory activity does not occur. A number of assumptions are made to simplify calculations further; for example the initial temperature of a food is constant and uniform throughout the food, and the temperature of the cooling medium, respiratory activity and all thermal properties of the food are constant during cooling. Detailed derivations of theoretical considerations and examples of calculations of heat load and chilling rate are described by van Beek and Meffert (1981).

Sample problem 19.1

Freshly harvested berries measuring 2 cm in diameter are chilled from 18°C to 7°C in a chiller at -2°C, with a surface heat transfer coefficient of 16 W m⁻² K⁻¹. They are then loaded in 250 kg batches into containers and held for 12 h in a cold store operating at -2°C, prior to further processing. The cold store holds an average of 2.5 t of food and measures 3 m high by 10 m × 10 m. The walls and roof are insulated with 300 mm of polyurethane foam, and the floor is constructed from 450 mm of concrete. The ambient air temperature averages 12°C and the soil temperature 9°C. An operator spends an average of 45 min day⁻¹ moving the containers in the store and switches on four 100 W lights when in the store. Each container weighs 50 kg. Calculate the time required to cool the berries in the chiller and determine whether a 5 kW refrigeration plant would be suitable for the cold store. (Additional data: the thermal conductivity of the berries is 0.127 W m⁻¹ K⁻¹, the thermal conductivity of the insulation is 0.026 W m⁻¹ K⁻¹, the thermal conductivity of the concrete is 0.87 W m⁻¹ K⁻¹ (Table 1.5), the specific heat of the berries is 3778 J kg⁻¹ K⁻¹, the specific heat of the container is 480 J kg⁻¹ K⁻¹, the density of berries is 1050 kg m⁻³, the heat produced by the operator is 240 W, and the average heat of respiration of berries is 0.275 J kg⁻¹ s⁻¹.)

Solution to Sample problem 19.1

To calculate the time required to cool the berries, from equation (1.25) for unsteady-state heat transfer ($Bi = h\delta/k$) for berries,

$$Bi = \frac{16 \times 0.01}{0.127} \\ = 1.26$$

$$\frac{1}{Bi} = 0.79$$

From equation (1.26) for cooling,

$$\frac{\theta_h - \theta_f}{\theta_h - \theta_i} = \frac{7 - (-2)}{18 - (-2)} \\ = 0.45$$

From Fig. 1.10 for a sphere, $Fo = 0.38$. From equation (1.27),

$$0.38 = \frac{k}{c\rho} \frac{t}{\delta^2}$$

Therefore,

$$t = \frac{0.38 \times 3778 \times 1050(0.01)^2}{0.127}$$

$$\text{time of cooling} = 1187 \text{ s} \\ = 19.8 \text{ min}$$

To determine whether the refrigeration plant is suitable as a cold store, assume that the berries enter the store at chill temperature.

Total heat = heat of respiration + sensible heat of containers + heat evolved by operators and lights + heat loss through roof and walls + heat loss through floor

Now

$$\text{heat of respiration} = 2500 \times 0.275 \\ = 687.5 \text{ W}$$

Assuming that the containers have the same temperature change as the berries and the number of containers is $2500/250 = 10$,

$$\text{heat removed from containers} = \frac{10 \times 50 \times 480(18 - 7)}{12 \times 3600} \\ = 61 \text{ W}$$

Next

$$\begin{aligned} \text{heat evolved by operators and lights} &= \frac{(240 + 4 \times 100)(45 \times 60)}{24 \times 3600} \\ &= 20 \text{ W} \end{aligned}$$

From equation (1.12), for an area of $60 + 60 + 100 = 220 \text{ m}^2$

$$\text{heat loss through roof and walls} = \frac{0.026 \times 220[12 - (-2)]}{0.3} = 267 \text{ W}$$

Finally,

$$\text{heat loss through floor (of area } 100 \text{ m}^2) = \frac{0.87 \times 100[9 - (-2)]}{0.45} = 2127 \text{ W}$$

Therefore the total heat loss is the sum of the heat loads $687.5 \text{ W} + 61 \text{ W} + 20 \text{ W} + 2394 \text{ W} = 3162.5 \text{ W} = 3.2 \text{ kW}$.

Thus a 5 kW refrigeration plant is suitable.

19.1.2 Processed foods

A reduction in temperature below the minimum necessary for microbial growth extends the generation time of micro-organisms and in effect prevents or retards reproduction. This mechanism is described in detail in most microbiological texts (for example Frazier and Westhoff, 1978). There are four broad categories of micro-organism, based on the temperature range for growth (Walker and Betts, 2000):

1. thermophilic (minimum: 30–40°C, optimum: 55–65°C)
2. mesophilic (minimum: 5–10°C, optimum: 30–40°C)
3. psychrotrophic (minimum: <0–5°C, optimum: 20–30°C)
4. psychrophilic (minimum: <0–5°C, optimum: 12–18°C).

Chilling prevents the growth of thermophilic and many mesophilic micro-organisms. The main microbiological concerns with chilled foods are a number of pathogens that can grow during extended refrigerated storage below 5°C, or as a result of any increase in temperature (temperature abuse) and thus cause food poisoning (Kraft, 1992). Previously it was considered that refrigeration temperatures would prevent the growth of pathogenic bacteria, but it is now known that some species can either grow to large numbers at these temperatures, or are sufficiently virulent to cause poisoning after ingestion of only a few cells. Examples of these pathogens are *Aeromonas hydrophilia*, *Listeria* spp, *Yersinia enterocolitica*, some strains of *Bacillus cereus*, *Vibrio parahaemolyticus* and enteropathogenic *Escherichia coli* (Marth, 1998). An example of the last (*E.coli* 0157:H7) may cause hemorrhagic colitis after ingestion of as little as ten cells (Buchanan and Doyle, 1997). A summary of the sources of these bacteria, types of infection or spoilage and typical high-risk foods is given in Table 19.4. Details of the taxonomy, pathogenicity, detection and distribution of important pathogens are given by Anon. (1996), Marth (1998) and Walker and Betts (2000).

It is therefore essential that good manufacturing practice (GMP) is enforced during the production of chilled foods. Details of the hygienic design of chilling plants, cleaning schedules and total quality management (TQM) procedures are discussed in detail by Holah and Brown (2000), Holah (2000) and Rose (2000), respectively.

Table 19.4 Pathogenic or spoilage bacteria in high-risk chilled foods

Micro-organism	Source	Minimum growth temperature (°C)	Type of infection/spoilage and incubation period	Typical high-risk foods
Pathogens				
<i>Aeromonas hydrophilia</i>	Fresh or brackish water	1–5	Diarrhoea, vomiting, fever (12–36 h)	Most commonly from water but also raw milk, poultry, lamb, cheese, shellfish
Enteropathogenic <i>Escherichia coli</i>	Intestinal tract of humans and warm blooded animals	4–7	Six types of illness including intestinal haemorrhage and toxic reaction (6–36 h)	Meat, poultry, fish, vegetables, Brie and Camembert cheeses, water, radish, alfalfa sprouts
<i>Vibrio parahaemolyticus</i>	Inshore marine waters	5–10	Gastro-enteritis, abdominal cramps, nausea, fever, wound infection (12–36 h)	Raw, improperly cooked or re-contaminated fish and shellfish, water
<i>Bacillus cereus</i>	Soil, cereal, vegetable and meat surfaces	4–10	Two types: diarrhoeal illness or emetic nausea and vomiting (12–36 h)	Cereal or spice containing products
<i>Yersinia enterocolitica</i>	Pigs	–1–7	Fever, diarrhoea, severe abdominal pain, vomiting, joint pain (24–36 h)	Lamb, pork, seafoods, milk, tofu, chitterlings (raw pork intestine)
<i>Campylobacter jejuni</i>	Water, milk, poultry	20	Diarrhoea, muscular pain, headache, vomiting (48–120 h)	Milk, milk products, seafood, water
<i>Salmonella enteritidis</i>	Poultry, cattle, other animals	5.2–6	Nausea, vomiting, high fever, abdominal pain (6–48 h)	Eggs, poultry, milk, meats, gravies
<i>Clostridium botulinum</i>	Ubiquitous, especially soil, water		7 types of toxin: blurred vision, vomiting, diarrhoea, progressive difficulty in swallowing, respiratory failure. Up to 70% fatal (12–36 h).	Canned vegetables and other low acid foods, smoked fish
Group I		10		
Group II		3.3		
<i>Staphylococcus aureus</i>	Cattle, other animals, processing equipment	6 (10 for toxin)	Vomiting, nausea, diarrhoea, headache, collapse, wound infection (2–4 h)	Milk, dairy products, cooked meats, seafoods

Table 19.4 Continued

Micro-organism	Source	Minimum growth temperature (°C)	Type of infection/spoilage and incubation period	Typical high-risk foods
<i>Clostridium perfringens</i>	Soil, dust, vegetation, raw, dried and cooked foods	12	Acute diarrhoea, nausea but little fever or vomiting (8–24 h)	Raw meats, poultry, fish, dairy products, dried foods, soups, spices, pasta
<i>Listeria monocytogenes</i>	Ubiquitous (soil, healthy humans or animals, food processing surfaces)	–0.4–3	Gastro-enteritis. Individuals having compromised immune systems are especially vulnerable (24–96 h)	Milk, seafoods, ready-to-eat sandwiches and salads, especially those containing meat, coleslaw, soft cheeses
Spoilage micro-organisms <i>Brochothrix thermosphacta</i>	–		Sliminess, off-odours or flavours	Vacuum packed beef, pork, lamb, sliced cured meats, corned beef
Lactic acid bacteria	Ubiquitous	0–5	Production of either lactic acid, acetic acid, formic acid, ethanol, carbon dioxide	Milk, milk products, meats, fruit juices, vegetables, alcoholic beverages, sugar products
<i>Pseudomonas</i> spp	–	–3–0	Development of bitterness and rancidity, green colouration	Most chilled foods
Yeasts (e.g. <i>Candida</i> spp), and moulds (e.g. <i>Mucor</i> spp, <i>Rhizopus</i> spp)	Ubiquitous	<0	Fermentation by yeasts causing yeasty, fruity or alcoholic off-flavours and odours Visible mould growth, softening, flavour and aroma changes and mycotoxin production	Fruit juices, meat products, vegetables, dairy products

Adapted from Marth (1998), Frazier and Westhoff (1988), Anon. (1996) and Walker and Betts (2000).

The shelf life of chilled processed foods is determined by:

- the type of food
- the degree of microbial destruction or enzyme inactivation achieved by the process
- control of hygiene during processing and packaging
- the barrier properties of the package
- temperatures during processing, distribution and storage.

Each of the factors that contribute to the shelf life of chilled foods can be thought of as 'hurdles' to microbial growth and further details of this concept are given in Chapter 1. Packaging of chilled foods is described in Chapter 24. Details of correct storage conditions for specific chilled products are listed by Anon. (1979), and procedures for the correct handling of chilled foods are described by Anon. (1982).

19.1.3 Cook–chill systems

Individual foods (for example sliced roast meats) or complete meals are produced by *cook–chill* or *cook–pasteurise–chill* processes (Byrne, 1986). An example is *sous-vide* products, which is the term commonly used to refer to foods that are vacuum packed prior to pasteurisation (although it strictly refers only to vacuum packing). These products, which include complete meals or components such as sauces, were developed for institutional catering to replace warm-holding,¹ which reduces losses in nutritional and eating quality and is less expensive. Their production is described in detail in Ghazala and Trenholm (1998) and Creed and Reeve (1998). In retail stores, sales of an increasingly wide range of cooked–chilled ready meals have rapidly expanded owing to their convenience, high quality and healthy image.

The range of chilled foods can be characterised by the class of microbial risk that they pose to consumers as follows:

- Class 1 foods containing raw or uncooked ingredients, such as salad or cheese as ready-to-eat (RTE) foods (also includes chill-stable raw foods, such as meat, fish, etc.)
- Class 2 products made from a mixture of cooked and low risk raw ingredients
- Class 3 cooked products that are then packaged
- Class 4 products that are cooked after packaging, including ready-to-eat-products-for-extended-durability (REPFEDs) having a shelf life of 40+ days (the acronym is also used to mean refrigerated-pasteurised-foods-for-extended-durability).

In the above classification, 'cooking' refers to a heat process that results in a minimum 6D reduction in target pathogens (see Chapters 1 and 12 for an explanation of *D*-values). Some Class 1 products require cooking by the consumer, whereas other cooked–chilled products may be ready to eat or eaten after a short period of re-heating. Gorris (1994) and Betts (1998) describe other methods of mild processing to improve the safety of ready-to-eat foods.

The manufacturer is only able to control the safety of these products by minimising the levels of pathogens on the incoming ingredients and by ensuring that processing and storage procedures do not introduce pathogens or allow their numbers to increase. Therefore, in addition to normal hygienic manufacturing areas, the products in Classes 1, 2 and 4 require a special 'hygienic area', designed to be easily cleaned to prevent

1. Where food is kept hot for long periods before consumption.

bacteria, such as *Listeria* spp. becoming established in it. Products in Classes 2 and 3 also require an additional 'high-care area', which is physically separated from other areas and is carefully designed to isolate cooked foods during preparation, assembly of meals, chilling and packaging. Such areas have specified hygiene requirements including:

- positive pressure ventilation with micro-filtered air supplied at the correct temperature and humidity
- entry and exit of staff only through changing rooms
- 'no-touch' washing facilities
- construction standards and materials for easy cleaning
- only fully processed foods and packaging materials admitted through hatches or air-locks
- special hygiene training for operators and fully protective clothing (including boots, hairnets, coats, etc.)
- operational procedures to limit the risk of contamination
- production stopped for cleaning and disinfection every 2 hours.

Detailed descriptions of the design and operation of facilities for cooked–chilled foods are given by Brown and Gould (1992), Rose (2000) and Anon. (1998), and Nicolai *et al.* (1994) describe computer aided design of cook–chill foods. Microbiological considerations when producing REPFEDs are described by Gorris and Peck (1998).

After preparation, cooked–chilled foods are portioned and chilled within 30 min of cooking. Chilling to 3°C should be completed within 90 min and the food should be stored at 0–3°C. In the cook–pasteurise–chill system, hot food is filled into a flexible container, a partial vacuum is formed to remove oxygen and the pack is heat sealed. It is then pasteurised to a minimum temperature of 80°C for 10 min at the thermal centre, followed by immediate cooling to 3°C. These foods have a shelf life of 2–3 weeks (Hill, 1987).

19.2 Equipment

Chilling equipment is classified by the method used to remove heat, into:

- mechanical refrigerators
- cryogenic systems.

Batch or continuous operation is possible with both types of equipment, but all should lower the temperature of the product as quickly as possible through the critical warm zone (50–10°C) where maximum growth of micro-organisms occurs.

19.2.1 Mechanical refrigerators

Mechanical refrigerators have four basic elements: an evaporator, a compressor, a condenser and an expansion valve (Fig. 19.1). Components of refrigerators are frequently constructed from copper as the low thermal conductivity (Chapter 1, Table 1.5) allows high rates of heat transfer and high thermal efficiencies.

A refrigerant (Table 19.5) circulates between the four elements of the refrigerator, changing state from liquid to gas, and back to liquid as follows:

- In the evaporator the liquid refrigerant evaporates under reduced pressure, and in doing so absorbs latent heat of vaporisation and cools the freezing medium. This is the

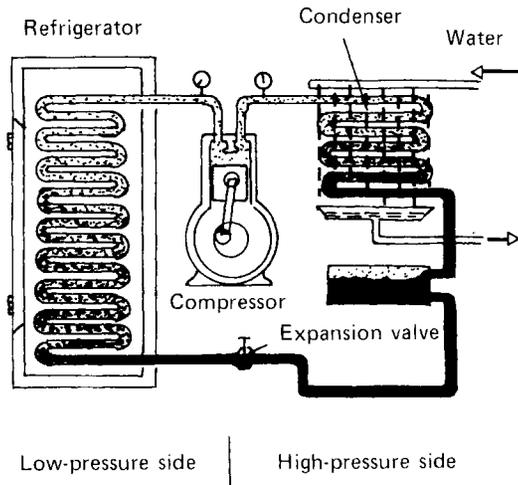


Fig. 19.1 Mechanical (compression–expansion) refrigerator.
(After Patchen (1971).)

most important part of the refrigerator; the remaining equipment is used to recycle the refrigerant.

- Refrigerant vapour passes from the evaporator to the compressor where the pressure is increased.
- The vapour then passes to the condenser where the high pressure is maintained and the vapour is condensed.
- The liquid passes through the expansion valve where the pressure is reduced to restart the refrigeration cycle.

The important properties of refrigerants are as follows:

- a low boiling point and high latent heat of vaporisation
- a dense vapour to reduce the size of the compressor
- low toxicity and non-flammable
- low miscibility with oil in the compressor
- low cost.

Ammonia has excellent heat transfer properties and is not miscible with oil, but it is toxic and flammable, and causes corrosion of copper pipes. Carbon dioxide is non-flammable and non-toxic,² making it safer for use for example on refrigerated ships, but it requires considerably higher operating pressures compared to ammonia. Halogen refrigerants (chlorofluoro-carbons or CFCs) are all non-toxic and non-flammable and have good heat transfer properties and lower costs than other refrigerants. However, their interaction with ozone in the earth's atmosphere, and consequent contribution to global warming as 'greenhouse gases', has resulted in an international ban on their use as refrigerants under the Montreal Protocol. Partially halogenated CFCs (or HCFCs) are less environmentally harmful and existing HCFCs are being temporarily substituted for CFCs, but these too are to be phased out before the first decades of the new century. Newer, ozone-friendly HCFCs are being developed and are likely to become important refrigerants. These developments are described in more detail by Heap (1997). The

2. Note: CO₂ causes asphyxia in concentrations above 0.5% by volume (Section 19.2.2).

Table 19.5 Properties of refrigerants

Refrigerant		Boiling point (°C) at 100 kPa	Latent heat (kJ kg ⁻¹)	Toxicity	Flammability	Vapour density (kg m ⁻³)	Oil solubility
Number	Formula						
11	CCl ₃ F	23.8	194.2	Low	Low	1.31	Complete
12	CCl ₂ F ₂	-29.8	163.54	Low	Low	10.97	Complete
21	CHCl ₂ F	-44.5	254.2	Low	Low	1.76	Complete
22	CHClF ₂	-40.8	220.94	Low	Low	12.81	Partial
717	NH ₃	-33.3	1328.48	High	High	1.965	<1%
744	CO ₂	-78.5	352	Low	Low	60.23	<1%

main refrigerants that are now used are Freon-22 and ammonia, with the possibility of future use of propane. However, the latter two in particular are more expensive and could cause localised hazards, thus requiring additional safety precautions and training for equipment users (Heap, 2000).

The chilling medium in mechanically cooled chillers may be air, water or metal surfaces. Air chillers (for example *blast chillers*) use forced convection to circulate air at around -4°C at high speed (4 m s⁻¹), and thus reduce the thickness of boundary films (Chapter 1) to increase the rate of heat transfer. Air-blast chillers are also used in refrigerated vehicles, but food should be adequately chilled when loaded onto the vehicle, as the refrigeration plant is only designed to hold food at the required temperature and cannot provide additional cooling of incompletely chilled food. *Eutectic plate systems* are another type of cooling that is used in refrigerated vehicles, especially for local distribution. Salt solutions (e.g. potassium chloride, sodium chloride or ammonium chloride) are frozen to their eutectic temperature³ (from -3 to -21°C) and air is circulated across the plates, to absorb heat from the vehicle trailer. The plates are regenerated by re-freezing in an external freezer.

Retail chill cabinets use chilled air which circulates by natural convection. The cost of chill storage is high and to reduce costs, large stores may have a centralised plant to circulate refrigerant to all cabinets. The heat generated by the condenser (Fig. 19.1) can also be used for in-store heating. Computer control of multiple cabinets detects excessive rises in temperature and warns of any requirement for emergency repairs or planned maintenance (Cambell-Platt, 1987). Other energy-saving devices include night blinds or glass doors on the front of cabinets to trap cold air. Details of the design and operation of refrigerated retail display cabinets, chilled distribution vehicles and cold stores are given by Heap (2000) (also Section 19.3).

Other methods of cooling

Foods with a large surface area (for example lettuce) are washed and *vacuum cooled*. The food is placed in a large vacuum chamber and the pressure is reduced to approximately 0.5 kPa. Cooling takes place as moisture evaporates from the surface (a reduction of approximately 5°C for each reduction of 1% in moisture content). Direct immersion in chilled water (*hydrocooling*) is used to remove field heat from fruit and vegetables, and cheese is often cooled by direct immersion in refrigerated brine. Recirculated chilled water is also used in *plate heat exchangers* (Chapter 11, Fig. 11.4) to cool liquid foods

3. Where the water and salt form a single phase.

after pasteurisation. Liquid and semi-solid foods (for example butter and margarine (Chapter 4)) are cooled by contact with refrigerated, or water-chilled metal surfaces in *scraped-surface heat exchangers* (also Chapters 11, 12 and 21).

19.2.2 Cryogenic chilling

A cryogen is a refrigerant that changes phase by absorbing latent heat to cool the food. Cryogenic chillers use solid carbon dioxide, liquid carbon dioxide or liquid nitrogen. Solid carbon dioxide removes latent heat of sublimation (352 kJ kg^{-1} at -78°C), and liquid cryogenics remove latent heat of vaporisation (358 kJ kg^{-1} at -196°C for liquid nitrogen; liquid carbon dioxide has a similar latent heat to the solid). The gas also absorbs sensible heat as it warms from -78°C (CO_2) or from -196°C (liquid nitrogen) to give a total refrigerant effect of 565 kJ kg^{-1} and 690 kJ kg^{-1} respectively.

The advantages of carbon dioxide include:

- a higher boiling and sublimation point than nitrogen, and therefore a less severe effect on the food
- most of enthalpy (heat capacity) arises from the conversion of solid or liquid to gas.

Only 13% of the enthalpy from liquid carbon dioxide and 15% from the solid is contained in the gas itself. This compares with 52% in nitrogen gas (that is, approximately half of the refrigerant effect of liquid nitrogen arises from sensible heat absorbed by the gas). Carbon dioxide does not therefore require gas handling equipment to extract most of the heat capacity, whereas liquid nitrogen does. The main limitation of carbon dioxide, and to a lesser extent nitrogen, is its ability to cause asphyxia. There is therefore a maximum safe limit for operators of 0.5% CO_2 by volume and excess carbon dioxide is removed from the processing area by an exhaust system to ensure operator safety, which incurs additional setup costs. Other hazards associated with liquefied gases include cold burns, frostbite and hypothermia after exposure to intense cold.

Solid carbon dioxide can be used in the form of 'dry-ice' pellets, or liquid carbon dioxide can be injected into air to produce fine particles of solid carbon dioxide 'snow', which rapidly sublime to gas. Both types are deposited onto, or mixed with, food in combo bins, trays, cartons or on conveyors. A small excess of snow or pellets continues the cooling during transportation or storage prior to further processing. If products are despatched immediately in insulated containers or vehicles, this type of chilling is able to replace on-site cold stores and thus saves space and labour costs. Snow is replacing dry-ice pellets because it is cheaper and does not have the problems of handling, storage and operator safety associated with dry ice. For example, in older meat processing operations, dry-ice pellets were layered with minced meat as it was filled into containers. However, lack of uniformity in distribution of pellets resulted in some meat becoming frozen and some remaining above 5°C , which permitted bacterial growth and resulted in variable product temperatures for subsequent processing. More recently the use of snow horns to distribute a fine layer of snow over minced meat as it is loaded into combo bins has eliminated these problems and resulted in rapid uniform cooling to $3\text{--}4^\circ\text{C}$. A recent advance in the use of carbon dioxide snow for chilled and frozen distribution of foods is described in Chapter 21.

Liquid nitrogen is used in both freezing (Chapter 21) and chilling operations. For batch chilling, typically 90–200 kg of food is loaded into an insulated stainless steel cabinet, containing centrifugal fans and a liquid nitrogen injector. The liquid nitrogen vaporises immediately and the fans distribute the cold gas around the cabinet to achieve a uniform reduction in product temperature. The chiller has a number of pre-programmed

time/temperature cycles which are microprocessor controlled. A food probe monitors the temperature of the product and the control system changes the temperature inside the cabinet as the food cools, thus allowing the same pre-programmed cycle to be used irrespective of the temperature of the incoming food. As with other types of batch equipment, it is highly flexible in operation and it is therefore suitable for low production volumes or where a large number of speciality products are produced.

For continuous chilling, food is passed on a variable speed conveyor to an inclined, insulated, cylindrical barrel having a diameter of 80–120 cm and length 4–10 m depending on the capacity. The barrel rotates slowly and internal flights lift the food and tumble it through the cold nitrogen gas. The temperature and gas flow rate are controlled by a microprocessor and the tumbling action prevents food pieces sticking together, to produce a free-flowing product. It is used to chill diced meat or vegetables at up to 3 t h^{-1} . Controlled temperature liquid nitrogen tumblers are used to improve the texture and binding capacity of mechanically formed meat products. The gentle tumbling action in a partial vacuum, cooled by nitrogen gas to -2°C , solubilises proteins in poultry meat, which increases their binding capacity and water holding capacity, thus improving later forming and coating operations.

An alternative design is a screw conveyor inside a 2.5 m long stainless steel housing, fitted with liquid carbon dioxide injection nozzles. Foods such as minced beef, sauce mixes, mashed potato and diced vegetables are chilled rapidly as they are conveyed through the chiller at up to 1 t h^{-1} . It is used to firm foods before portioning or forming operations or to remove heat from previous processing stages.

Other applications of cryogenic cooling include sausage manufacture, where carbon dioxide snow removes the heat generated during size reduction and mixing (Chapter 4) and *cryogenic grinding* where the cryogen reduces dust levels, prevents dust explosions and improves the throughput of mills. In spice milling, cryogens also prevent the loss of aromatic compounds. In the production of multi-layer chilled foods (for example trifles and other desserts) the first layer of product is filled and the surface is hardened with carbon dioxide. The next layer can then be added immediately, without waiting for the first layer to set, and thus permit continuous and more rapid processing. Other applications include cooling and case-hardening of hot bakery products and chilling flour to obtain accurate and consistent flour temperatures for dough preparation.

19.3 Chill storage

Once a product has been chilled, the temperature must be maintained by refrigerated storage. Chill stores are normally cooled by circulation of cold air produced by mechanical refrigeration units, and foods may be stored on pallets, racks, or in the case of carcass meats, hung from hooks. Transport of foods into and out of stores may be done manually using pallet trucks, by forklift truck or by computer-controlled robotic trucks (Chapters 2 and 26). Materials that are used for the construction of refrigerated storerooms are described by Brennan *et al.* (1990).

19.3.1 Control of storage conditions

The importance of maintaining temperatures below 5°C to meet safety, quality and legal requirements for high-risk products is described in Section 19.1. Fresh products may also require control of the relative humidity in a storeroom, and in some cases control over the

composition of the storage atmosphere (Chapter 20). In all stores it is important to maintain an adequate circulation of air using fans, to control the temperature, relative humidity or atmospheric composition. Foods are therefore stacked in ways that enable air to circulate freely around all sides. This is particularly important for respiring foods, to remove heat generated by respiration (Section 19.1.1) or for foods, such as cheese, in which flavour development takes place during storage. Adequate air circulation is also important when high storage humidities are used for fresh fruits and vegetables (Table 19.2) as there is an increased risk of spoilage by mould growth if 'deadspots' permit localised increases in humidity. In some situations, a lower relative humidity may be used, with some product wilting accepted as a compromise for reduced microbial spoilage.

Temperature monitoring

Temperature monitoring is an integral part of quality management and product safety management throughout the production and distribution chain. Improvements to micro-electronics over the last ten years has enabled the development of monitoring devices that can both store large amounts of data and integrate this into computerised management systems (Chapter 2). Woolfe (2000) lists the specifications of commonly used data loggers. These are connected to temperature sensors which measure either air temperatures or product temperatures to give a representative picture of the way in which the refrigeration system is functioning.

There are three main types of sensor that are used commercially: thermocouples, platinum resistance thermometers and semiconductor (thermistors). Thermocouples are a pair of dissimilar metals joined together at one end. The most widely used are Type K (nickel-chromium and nickel-aluminium), or Type T (copper and copper-nickel). The advantages over other sensors are lower cost, rapid response time and very wide range of temperature measurement (-184°C – 1600°C). Thermistors change resistance with temperature and have a higher accuracy than thermocouples, but they have a much narrower range (-40°C – 140°C). Platinum resistance thermometers are accurate and have a temperature range from -270°C – 850°C , but their response time is slower and they are more expensive than other sensors. Sensors are usually connected to either a chart recorder or an electronic digital display, which may also be able to store data and sound an alarm if the temperature exceeds a pre-set limit. Further details of sensors are given in Chapter 2.

Monitoring air temperatures is more straightforward than product temperature monitoring and does not involve damage to the product or package. It is widely used to monitor chill stores, refrigerated vehicles and display cabinets, and Woolfe (2000) describes in detail the positioning of temperature sensors in these types of equipment. However, it is necessary to establish the relationship between air temperature and product temperature in a particular installation. Air is continuously recirculated through the refrigeration unit and storeroom. Cold air is warmed by the product, by lights in a store, by vehicles or by doors opening or operators entering. The temperature of the returning air is therefore likely to be the same as the product temperature or slightly higher. By comparing this to the temperature of the air leaving the evaporator in the refrigeration unit to find the temperature differential, it is possible to measure the performance of the refrigeration system and its effectiveness in keeping the food cold. To relate air temperature to product temperature it is necessary to conduct a 'load test', which involves examining the differential in air temperatures over a length of time and comparing it with the product temperature under normal working conditions.

Where a store, cabinet or vehicle is not opened for long periods, the only changes in temperature come from defrost cycles and intermittent door opening, and the relationship between product and air temperature is relatively simple. However, the operation of open retail display cabinets is more sensitive to variations in room temperature or humidity, the actions of customers and staff in handling foods, and lighting to display products. The temperature distribution in the cabinet can therefore change and load testing becomes more difficult. In such situations there is likely to be substantial variations in air temperature, but the mass of the food remains at a more constant temperature, and air temperature measurement has little meaning. To overcome this problem the food temperature can be measured or the air temperature sensor can be electronically ‘damped’ to respond more slowly and eliminate short-term fluctuations.

In addition to temperature sensors, the temperature of chilled foods can be monitored by temperature- or time-temperature indicators, which use physico-chemical changes to display

- the current temperature
- crossing of a threshold temperature
- integration of the temperature and the time that a food has been exposed to a particular temperature.

These devices are based on either melting point temperature, enzyme reaction, polymerisation, electrochemical corrosion or liquid crystals (Woolfe, 2000). They are described in more detail in their application to frozen foods (Chapter 21), and are now also finding greater use in the chill chain (Van Loey *et al.*, 1998).

19.4 Effect on foods

The process of chilling foods to their correct storage temperature causes little or no reduction in the eating quality or nutritional properties of food. The most significant effect of chilling on the sensory characteristics of processed foods is hardening due to solidification of fats and oils. Chemical, biochemical and physical changes during refrigerated storage may lead to loss of quality, and in many instances it is these changes rather than micro-biological growth that limit the shelf life of chilled foods. These changes include enzymic browning, lipolysis, colour and flavour deterioration in some products and retrogradation of starch to cause staling of baked products (which occurs more rapidly at refrigeration temperatures than at room temperature). Lipid oxidation is one of the main causes of quality loss in cook-chilled products, and cooked meats in particular rapidly develop an oxidised flavour termed ‘warmed-over flavour’ (WOF), described in detail by Brown (2000). Physico-chemical changes including migration of oils from mayonnaise to cabbage in chilled coleslaw, syneresis in sauces and gravies due to changes in starch thickeners, evaporation of moisture from unpackaged chilled meats and cheeses, more rapid staling of sandwich bread at reduced temperatures and moisture migration from sandwich fillings may each result in quality deterioration (Brown, 2000). Vitamin losses during chill storage of selected fresh and processed foods are shown in Table 19.6 and details are given by Bognar (1990).

In cook-chill systems, nutritional losses are reported by Bognar (1980) as insignificant for thiamine, riboflavin and retinol, but vitamin C losses are 3.3–16% day⁻¹ at 2°C. The large variation is due to differences in the chilling time, storage temperature, oxidation (the amount of food surface exposed to air) and reheating conditions. Vitamin C losses in cook-pasteurise-chill procedures are lower than cooked-chilled foods (for example

Table 19.6 Loss of vitamins during chilled storage of selected foods

Food	Losses (% per day)				
	Ascorbic acid ¹	Thiamin ²	Riboflavin ²	Pyridoxine ²	Carotene ³
<i>Fruit and vegetables</i>					
Apples	0.1–0.5				
Brussels sprouts (cooked)	4.6	0.3			
Cabbage (white)	0.1–0.2				
Carrots	0–0.6	0	0	1.6	0.2–0.8
Cauliflower	0.1–0.2				
French beans	1.9–10.0*	0	0	1.8	1.8–2.2
Lettuce	4.8–9.7*	4.7	5.4	2.9	
Oranges	26.0				
Parsley	2.2–4.5*	+8.2	3.9	1.8	1.0–3.0
Peas	1.0–2.0				
Pineapples	18.0				
Potatoes (boiled)	10.7	1.3			
Strawberries	0				
Spinach (cooked)	6.4				
Tomatoes					41
<i>Meats</i>					
Pork liver (fried)	10.3	0.7	0.7	0	
Roast pork		0.1			

¹ Storage at 0–2°C and relative humidity 76–98%, storage time: 2–21 days

² Storage at 1°C and relative humidity 50±10%, storage time 3–14 days

³ Storage at 7°C and relative humidity 60–80%, storage time 2–21 days

* Rapid wilting at low storage humidity

Adapted from Ezell and Wilcox (1959 and 1962), Adisa (1986) and Bognar (1980).

spinach lost 66% within 3 days at 2–3°C after cook–chilling compared with 26% loss within 7 days at 24°C after cook–pasteurising–chilling.

19.5 Acknowledgements

Grateful acknowledgement is made for information supplied by: Air Products plc, Basingstoke, Hampshire RG24 8YP, UK; BOC Gases, London SW19 3UF, UK; Frigoscandia Equipment AB, S-251 09 Helsingborg, Sweden.

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Controlled- or modified-atmosphere storage and packaging

A reduction in the concentration of oxygen and/or an increase in carbon dioxide concentration of the storage atmosphere surrounding a food reduces the rate of respiration of fresh fruits and vegetables and also inhibits microbial and insect growth. When combined with chilling (Chapter 19), modified or controlled atmospheres are an increasingly important method of maintaining high quality in processed foods during an extended shelf life. Modified atmospheres are often included with other minimal processing methods (Chapters 1 and 9) as an important area of future development of mild processed, convenient and ready-to-eat foods that have good nutritional properties and a 'natural' image.

There remain differences in, and some confusion over, the terminology used. *Modified-atmosphere* storage (MAS) and packaging (MAP) are the use of gases to replace air around non-respiring foods without further controls after storage or packing. In *controlled-atmosphere* storage (CAS) and packaging (CAP), the composition of gas around respiring foods is monitored and constantly controlled, but with advances in 'active' packaging systems (Section 20.2.4) the distinction between MAP and CAP is no longer clear. In this book, MAP is used to refer to all methods to change atmospheres in packed food regardless of whether or not the atmosphere changes over time. It also includes vacuum packing (VP), equilibrium-modified-atmosphere (EMA) packaging, passive atmosphere modification (PAM), vacuum-skin packaging (VSP) and gas-exchange preservation (GEP). For definitions of these terms, see Section 20.2 or Church (1994).

In commercial operation, controlled-atmosphere storage (CAS) and modified-atmosphere storage (MAS) are mostly used with apples and smaller quantities of pears and cabbage. Modified-atmosphere packaging (MAP) is used for fresh foods and an increasing number of mildly processed foods, and is gaining in popularity as new applications are developed. Examples of MAP products include raw or cooked meats, poultry, fish, seafood, vegetables, fresh pasta, cheese, bakery products, sandwiches, sous vide foods, potato crisps, coffee and tea (Davies, 1995), and with new products including prepared salads, part-baked bread, croissants, pizzas, peeled fruits and prepared vegetables with dressing (Church, 1994).

The normal composition of air is 78% nitrogen and 21% oxygen, with the balance made up of carbon dioxide (0.035%), other gases and water vapour. An increase in the proportion of carbon dioxide and/or a reduction in the proportion of oxygen within specified limits (Section 20.2) maintains the original product quality and extends the product shelf life. This is achieved by:

- inhibiting bacterial and mould growth
- protecting against insect infestation
- reducing moisture loss
- reducing oxidative changes
- controlling biochemical and enzymic activity to slow down senescence and ripening.

CO₂ inhibits microbial activity in two ways: it dissolves in water in the food to form mild carbonic acid and thus lowers the pH of the product; and it has negative effects on enzymic and biochemical activities in cells of both foods and micro-organisms. However, close control over the degree of atmospheric modification is necessary to prevent physiological disorders in the living tissues and secondary spoilage by anaerobic micro-organisms in non-respiring foods. The effects of CO₂ on microbial growth are discussed by Dixon and Kell (1989) and reviewed by Farber (1991).

20.1 Modified- and controlled-atmosphere storage (MAS and CAS)

In MAS, the store is made airtight, and respiratory activity of fresh foods is allowed to change the atmosphere as oxygen is used up and CO₂ is produced (Chapter 19). In CAS, the concentrations of oxygen, carbon dioxide and sometimes ethylene (ethene) are monitored and regulated. Oxygen concentrations as low as 0%, and carbon dioxide concentrations of 20% or higher can be produced in for example grain storage, where these conditions destroy insects and inhibit mould growth. When storing fruits, a higher oxygen concentration is needed to prevent anaerobic respiration which would risk producing alcoholic off-flavours. Different types of fruit, and even different cultivars of the same species, require different atmospheres for successful storage and each therefore needs to be independently assessed. Examples of atmospheres for apple storage are 8% CO₂, 13% O₂ and 79% N₂ for Bramley's Seedling; and 5% CO₂, 3% O₂ and 92% N₂ for Cox's Orange Pippin at 3.5°C to produce an increase from 3 months storage in air to 5 months under CAS. This can be further increased to 8 months using a CAS atmosphere of 1% CO₂, 1% O₂ and 98% N₂ although such low oxygen levels risk anaerobic respiration in other fruits. Refrigerated storage of winter white cabbage in 5% CO₂, 3% O₂ and 92% N₂ enables the crop to be stored until the following summer (Brennan *et al.*, 1990). Details of the atmospheric composition required for other products, building construction, equipment and operating conditions are described by Ryall and Lipton (1979). Safety measures for operators when using increased concentrations of CO₂ are described in Chapter 19 and by Anon. (undated).

Storage is achieved using gas-tight stores, sealed using metal cladding and carefully sealed doorways. When CO₂ and oxygen levels change due to respiration in MAS, or when adjustment to atmospheric composition is needed in CAS, solid or liquid CO₂ can be used to increase gas concentration; controlled ventilation is used to admit oxygen or 'scrubbers' may be used to remove CO₂ and thus maintain a constant gas composition in the atmosphere. CO₂ scrubbers operate either by passing the atmosphere from the store over bags of hydrated calcium hydroxide (lime), under sprays of sodium hydroxide or

over activated carbon, to absorb the CO₂. Individual gases may be added from pressurised cylinders in MAS stores that are not completely gas-tight, to speed up the creation of the required atmosphere rather than relying on the action of the fruit alone.

The CO₂ content in the atmosphere can be monitored using sensors to measure differences in the thermal conductivity between CO₂ (0.015 W m⁻¹ K⁻¹) and N₂ (0.024 W m⁻¹ K⁻¹) and O₂ (0.025 W m⁻¹ K⁻¹) or by differences in infrared absorption. Gas composition is automatically controlled by microprocessors using information from the sensors (Chapter 2) to control air vents and gas scrubbers, to maintain a pre-determined atmosphere.

MAS and CAS are useful for crops that ripen after harvest, or deteriorate quickly; even at optimum storage temperatures CA stores have a higher relative humidity (90–95%) than normal cold stores and therefore retain the crispness of fresh foods and reduce weight losses.

The main disadvantages of MAS and CAS are economic: crops other than apples (and to a lesser extent cabbage and pears) have insufficient sales to justify the investment. Short season crops, which increase in price out of season, justify the additional costs of MAS or CAS, but the plant cannot be used throughout the year. Also plant utilisation cannot be increased by storing crops together, because of the different requirements for gas composition, and the risk of odour transfer. Other limitations of MAS and CAS are as follows:

- the low levels of oxygen, or high levels of carbon dioxide, which are needed to inhibit bacteria or fungi, are harmful to many foods
- CAS conditions may lead to an increase in the concentration of ethylene in the atmosphere and accelerate ripening and the formation of physiological defects
- an incorrect gas composition may change the biochemical activity of tissues, leading to development of off-odours, off-flavours, a reduction in characteristic flavours, or anaerobic respiration

Table 20.1 Maximum levels of carbon dioxide and minimum levels of oxygen for storage of selected fruits and vegetables

Food	CO ₂ (%)	O ₂ (%)
Apple ^a (Golden Delicious)	2	2
Asparagus (5°C)	10	10
Avocado	5	3
Banana	5	–
Broccoli	15	1
Cabbage	5	2
Carrot	4	3
Cauliflower	5	2
Citrus fruits	–	5
Cucumber	10	3
Lettuce	1	2
Onion	10	1
Pea	7	5
Pear (Bartlett)	5	2
Potato	10	10
Spinach	20	–
Strawberry	20	2
Sweetcorn	20	–
Tomato	2	3

^a Dewey (1983) describes gas compositions for other varieties of UK apples. From Anon. (1979) and Ryall and Pentzner (1982).

- tolerance to low oxygen and high carbon dioxide concentrations (Table 20.1), varies according to type of crop, conditions under which a crop is grown and maturity at harvest
- different cultivars of the same species respond differently to a given gas composition, and growers who regularly change cultivars are unwilling to risk losses due to incorrect CAS conditions
- economic viability may be unfavourable owing to competition from other producing areas which have different harvest seasons, and higher costs of CAS over a longer storage period (twice that of cold storage).

An alternative approach is storage in a partial vacuum which reduces the oxygen concentration by the same proportion as the reduction in air pressure (that is, if the pressure is reduced by a factor of 10, then the oxygen concentration is reduced by the same factor). The main advantages are the continuous removal of ethylene and other volatiles from the atmosphere and precise control of air pressure ($\pm 0.1\%$). However, the method is not commonly used owing to the higher costs.

20.2 Modified-atmosphere packaging

20.2.1 MAP for fresh foods

MAP (or gas flushing) is the introduction of an atmosphere, other than air, into a food package without further modification or control (Wilbrandt, 1992). Although the term 'MAP' is used throughout this book to describe packaging in modified atmospheres, other terminology is in use to more specifically designate different operations, including *controlled-atmosphere packaging* (CAP) (continuous monitoring and control of gas composition in bulk containers), *equilibrium-modified atmosphere* (EMA) or *passive atmosphere modification* (PAM) (gas flushing of packs of fresh fruits or vegetables or sealing without gas modification to allow a gas equilibrium to be established as a result of respiration), *vacuum packing* (VP) (the removal of the majority of air from a pack that has low oxygen permeability, with subsequent changes in gas composition due to metabolic activities of the product or micro-organisms), *vacuum-skin packaging* (VSP) (placing a softened film over the product and applying a vacuum to form a skin) and *gas-exchange preservation* (GEP) (replacing air with a series of gases in quick succession to inhibit enzymes or kill micro-organisms, before packing in nitrogen) (Church, 1994; Davies, 1995).

MAP is used to extend a product shelf life to give processors additional time to sell the food without sacrificing quality or freshness (Table 20.2). The potential advantages and limitations of MAP are shown in Table 20.3 and differences in the market potential for MAP foods in Europe and USA are reviewed by Davies (1995). The atmosphere is not, however, constant in all MAP products and will change according to:

- the permeability of the packaging material
- microbiological activity
- respiration by the food.

Successful MAP requires raw materials with a low microbiological count and strict temperature control throughout the process (Chapter 19). The three main gases used in MAP are nitrogen, oxygen and CO₂, although others, including carbon monoxide, nitrous oxide, argon, helium and chlorine have also been investigated, but largely eliminated due

Table 20.2 Extension of shelf life using MAP

Product	Shelf life (days)	
	Air	MAP
Beef ^a	4	12
Bread ^b	7	21
Cake ^b	14	180
Chicken ^a	6	18
Coffee ^b	3	548
Cooked meats ^a	7	28
Fish ^a	2	10
Fresh pasta ^a	2	28
Fresh pizza ^a	6	21
Pork ^a	4	9
Sandwiches ^a	2	21

^a Refrigerated storage.

^b Ambient storage.

Adapted from Brody (1990) and Blackstone (1998b).

to safety, cost or effects on food quality. Nitrogen is inert and tasteless, with low solubility in both water and fats. It is used to replace oxygen and thus inhibit oxidation or the growth of aerobic micro-organisms.

Oxygen is used in MAP to maintain the red colour of oxymyoglobin in unprocessed meats, or to permit respiration of fresh produce, but in other applications its level is reduced to prevent growth of spoilage micro-organisms and oxidative rancidity. Typically, the shelf life of fresh red meat is extended from 3 days to 7 days at 0–2°C by packaging in an 80% O₂ / 20% CO₂ atmosphere, but this may cause problems of oxidative rancidity in fatty fish or development of off-colours in cured meats. Bacon, for example, is therefore packed in 35% O₂ / 65% CO₂ or 69% O₂ / 20% CO₂ / 11% N₂. In both atmospheres the oxygen concentration is sufficient to inhibit anaerobic bacteria. Pork, poultry and cooked meats have no oxygen requirement to maintain the colour, and a higher carbon dioxide concentration (90%) is possible to extend the shelf life to 11 days. Further details are given by Blackstone (1998a).

In fresh fruits and vegetables, a concentration of 10–15% carbon dioxide is required to control decay. Some crops can tolerate this level (for example strawberries and spinach) but most cannot (Table 20.1) and MAP is unsuitable. A high carbon dioxide

Table 20.3 Advantages and limitations of MAP

Advantages	Limitations
Increased shelf life of 50–400%	Added cost
Extended storage results in reduced economic losses and wider distribution radius	Temperature control required
Fewer distribution deliveries leads to lower costs	Different gas compositions for each type of product
Little or no need for chemical preservatives	Requirement for special equipment and operator training
Easier separation of sliced foods (except vacuum packing)	Increased pack volume has impact on transport and retail display costs
Good presentation of products	Benefits are lost once the pack is opened or leaks
	Product safety to be established for some foods

Adapted from Davies (1995), Farber (1991) and Blackstone (1998b).

concentration prevents mould growth in cakes and increases the shelf life to 3–6 months. Other bakery products (for example hamburger buns) have the shelf life increased from 2 days to 3–4 weeks (Guise, 1983).

CO₂ dissolves in both water and fats in a food and is more soluble in cold water than it is in warm water. It is absorbed into fish tissue, which lowers the pH and increases drip losses. In MAP, the absorption of CO₂ should be carefully controlled to prevent too great a reduction in gas pressure which causes collapse of the pack. Nitrogen is often added as a filler gas to prevent pack collapse, although in some products collapse may be advantageous (for example hard cheeses), where a tight pack is formed around the product. Additionally, the relative volume of gas and product is important to ensure the effectiveness of MAP (a sufficiently high gas:product ratio for the gas to have a preservative effect). There should therefore be adequate space between the product and the package to contain the correct amount of gas.

For fresh produce, the aim of MAP is to minimise respiration and senescence without causing damage to metabolic activity that would result in loss of quality (Section 20.1). However, the effects of low oxygen and raised CO₂ concentrations on respiration are cumulative, and respiration also continually alters the atmosphere in a MA pack. The rate at which oxygen is used up and CO₂ is produced also depends on the storage temperature. The optimum gas composition in a pack is therefore difficult to predict or achieve. In practice, the CO₂ concentration is increased by gas flushing before sealing and a film that is permeable to oxygen and CO₂ is selected to enable respiration to continue (see also Section 20.2.4). Changes in gas composition during storage depend on.

- the respiration rate of fresh foods, and hence the temperature of storage
- the permeability of the packaging material to water vapour and gases
- the external relative humidity, which affects the permeability of some films
- the surface area of the pack in relation to the amount of food it contains.

MAP permits an extension to the shelf life of cut red meat of up to 18 days, and for ground beef up to 10 days. Cut lettuce has a two-week shelf life at 0–1.1°C (Brody, 1990) (Table 20.2). Details of MAP for fresh produce are given by Garrett (1998).

20.2.2 MAP for processed foods

For processed (that is non-respiring) foods, atmospheres should be as low as possible in oxygen and as high as possible in CO₂ without causing the pack to collapse or produce changes to the flavour or appearance of the product. Ground coffee, for example, is protected against oxidation by MAP using a CO₂/N₂ mixture or by vacuum packing.

Reducing the concentration of oxygen inhibits the development of 'normal' spoilage micro-organisms, especially *Pseudomonas* sp. (Walker, 1992). Other spoilage bacteria that can grow in low oxygen concentrations grow more slowly and so extend the time taken for spoilage to occur, for example lactic acid bacteria or *Brochothrix thermosphacta*, which cause spoilage by souring (Nychas and Arkoudelos, 1990). Concern has been expressed over potential risks to consumer safety from modified atmospheres or vacuum packaging because they inhibit 'normal' spoilage micro-organisms and thus allow food to appear fresh, while permitting the growth of anaerobic pathogens. Details of pathogens found on chilled foods are given in Chapter 19. Several pathogens including *Clostridium botulinum*, *Listeria monocytogenes*, *Yersinia enterocolitica*, *Salmonella* sp., and *Aeromonas hydrophila* are anaerobes or facultative anaerobes (Blakistone, 1998b). A large number of studies of the effect of MAP on the

microbiology of foods are reported; for example meat poultry and fish (Church, 1998; Finne, 1982; Christopher *et al.*, 1980), baked goods (Knorr and Tomlins, 1985; Ooraikul, 1982). These are reviewed for example by Davies (1995), Church (1994), Ooraikul and Stiles (1991) and Farber (1991). The studies have indicated that growth of pathogens in MAP products is no greater, and frequently lower than in aerobically stored foods. However, for products in which there is a potential safety hazard, it is recommended that one or more of the following criteria are met:

- water activity (Chapter 1) is below 0.92
- pH is below 4.5
- use of sodium nitrite or other preservative
- the temperature is maintained below +3°C.

The application of HACCP techniques (Chapter 1) also plays a major role in ensuring the safety of all MAP foods. Different foods respond in different and sometimes unpredictable ways to modified atmospheres, and each product should therefore be individually assessed using MAP trials, to monitor microbial activity, moisture content, pH, texture, flavour and colour changes in order to determine the optimum gas composition. Care is also needed to prevent temperature abuse during processing and distribution, and high standards of hygiene should be used throughout the production process (also Chapter 19).

Examples of gas mixtures that are used for fresh and processed foods are shown in Table 20.4. In MAP of bread, CO₂ inhibits mould growth and the retention of moisture maintains softness. This is not inhibition of staling (a process that involves partially reversible crystallisation of starch), but the effects are similar. Spraying bread with 1% ethanol doubles the ambient shelf life, by retarding mould growth and an apparent inhibition of staling (also Section 20.2.4). A novel MAP approach to packing baguettes is to pack them straight from the oven while the CO₂ produced by the fermentation is still being emitted. As they are placed into thermoformed packs the CO₂ expels air and

Table 20.4 Gas mixtures used for selected MAP foods

Commodity	% CO ₂	% O ₂	% N ₂
Baked products	60	0	40
Cheese (hard)	60	0	40
Cheese (mould ripened)	0	0	100
Cream	0	0	100
Crustaceans	40–60	20–30	0–30
Dry snackfoods	20–30	0	70–80
Fish (oily)	30–60	0	40–70
Fish (white)	40–60	20–30	0–30
Fruit/vegetables	3–10	2–10	80–95
Kebabs	40–60	0–10	40–60
Meat (cooked)	25–30	–	70–75
Meat (cured)	20–35	–	65–80
Meat (red)	15–40	60–85	0–10
Meat pies	20–50	–	50–80
Pasta (fresh)	50–80	–	20–50
Pizza	40–60	0–10	40–60
Poultry	20–50	–	50–80
Quiche	40–60	–	40–60
Sausage	60	40	0

Adapted from Day (1992) and Smith *et al.* (1990).

saturates the atmosphere to give 3 month shelf life at ambient temperature. The consumer briefly heats the bread in an oven to create a crust and produce a product that is similar to freshly baked bread (Brody, 1990).

20.2.3 Packaging materials for MAP

The two most important technical parameters of packs for MAP are gas permeability and moisture vapour permeability. Packaging materials are classified according to their barrier properties to oxygen into:

- low barrier ($>300 \text{ cc m}^{-2}$) for over-wraps on fresh meat or other applications where oxygen transmission is desirable
- medium barrier ($50\text{--}300 \text{ cc m}^{-2}$)
- high barrier ($10\text{--}50 \text{ cc m}^{-2}$)
- ultra high barrier ($<10 \text{ cc m}^{-2}$), which protect the product from oxygen to the end of its expected shelf life.

Typical film materials are single or coextruded films or laminates of ethylene vinyl alcohol (EVOH), polyvinyl dichloride (PVDC), polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polyester, amorphous nylon (polyamide resin) and nylons, although the last provides only moderate barrier. Details of types of film and their permeability to moisture and gases are given in Chapter 24 and described by Greengrass (1998). Films are usually coated on the inside of the pack with an antifogging agent, typically a silicone or stearate material, to disperse droplets of condensed moisture and permit the food to be visible. New developments include films that change permeability to moisture and gases under specified temperature conditions that are designed to match the respiration rate of a fresh product (Vermeiren *et al.*, 1999 and Chapter 24).

In MAP operation, air is removed from the pack and replaced with a controlled mixture of gases, and the package is heat sealed. In batch equipment, pre-formed bags are filled, evacuated, gas flushed and heat sealed in a microprocessor-controlled programmed sequence. In continuous operation, food is packaged in three basic ways: in semi-rigid, thermoformed trays covered with film that has the required permeability (for example, for meats); or second, in pillow pouches (for example, for fresh salads). The design of MAP packs for fresh produce is described by Yam and Lee (1995). Third, foods such as baked products are packed in horizontal form-fill-seal equipment or 'flowpacks'. All types allow space around food for the gas. The different types of packaging systems are described in detail by Hastings (1998) and in Chapter 25.

20.2.4 Active packaging systems

The development of active packaging systems (also termed 'intelligent' packaging or 'smart films'), is a significant new area of MAP technology (Table 20.5). They have the following capabilities:

- edible moisture barriers for fresh fruits and vegetables or edible oxygen barriers to prevent enzymic browning
- ethylene scavengers – these are sachets of silica gel containing potassium permanganate, which oxidises ethylene to slow the ripening of fruits
- oxygen scavengers to create low-oxygen atmospheres or slow the oxidation of lipids

Table 20.5 Examples of active packaging systems

Method	Variations	Examples of products
Oxygen scavenger	Powdered iron oxide Ferrous carbonate Iron/sulphur Platinum catalyst Glucose-oxidase enzyme Alcohol oxidase enzyme	Cookies, cured meats, pizza crusts, bread, rice cakes
Carbon dioxide scavenger/emitter	Powdered iron oxide/calcium hydroxide Ferrous carbonate/metal halide	Coffee, fresh meats/fish
Preservative	BHA/BHT (Appendix C) Sorbates Mercurial compounds Zeolite system	Meats, fish, bread, cereals, cheese
Ethanol emitter	Ethanol spray Encapsulated ethanol	Cakes, bread, buns, tarts, fish
Moisture absorber	PVA blanket	Fish, meats, poultry
Temperature or humidity control	Non-woven plastics PET containers Foams	Prepared entrées, meats, poultry, fish

From Day (1992).

and films that scavenge off-odours or carbon dioxide. Oxygen scavenging sachets contain iron which is oxidised in the presence of water vapour to produce ferric hydroxide. If the oxidation rate of the food and the oxygen permeability of the film are known, the amount of iron needed in the sachet for the required shelf life can be calculated. Other approaches include a film that contains a reactive dye and ascorbic acid; a film incorporating platinum to reduce oxygen to water vapour; and attachment of immobilised enzymes, including glucose oxidase and alcohol oxidase to the inner surface of a film. The products of these enzymic reactions also lower the surface pH of the food and release hydrogen peroxide which extend the shelf life of fresh fish. Others include a film that contains an organic chelation agent that binds oxygen, and a film that incorporates a free-radical scavenger to react with oxygen. A sachet containing iron powder and calcium hydroxide scavenges both oxygen and CO₂ and has been used to produce a threefold extension to the shelf life of packaged ground coffee. Conversely in some CAP/MAP applications, high levels of CO₂ are required, but many films are 3–5 times more permeable to CO₂ than to oxygen. In these situations, a carbon dioxide generator is used. In other situations, low oxygen levels can create favourable conditions for the growth of pathogenic anaerobic bacteria and a ‘smart’ film which permits a substantial increase in gas permeability with higher temperatures, is used to re-oxygenate packs of food to prevent anaerobic conditions from forming.

- zeolite films to inactivate micro-organisms on food surfaces and sachets and films that release microbial inhibitors
- ethanol that is trapped in silica gel, contained in a sachet made from a film that is highly permeable to ethanol vapour, has been used to extend the shelf life of bakery products, cheese and semi-dried fish products. Similarly a sulphur dioxide generating film or a film that releases trapped sorbate have been used to extend the shelf life of grapes by preventing mould growth. A sachet system which rapidly increases absorption of moisture as the temperature approaches the dew point is used to prevent

droplets of water forming on the product which could promote microbial growth. A similar effect is produced by trapping propylene glycol or diatomaceous earth in a film placed in contact with the surface of fresh meat or fish to absorb water and injure spoilage bacteria.

These developments are described by Labuza and Breene (1989), Church (1994) and Smith *et al.* (1990). Other developments, including films that have selective gas transmission (by tailoring the film materials or by microperforation), selective water vapour transmission, the use of noble gases and films that change permeability to compensate for temperature fluctuations are described by Gorris and Peppelenbos (1999).

Oxygen scavengers are the most widely developed application to date and operate in two ways to remove oxygen from a pack: either small amounts of chemicals are placed in a sachet contained within the food pack; or foods are packed in oxygen-scavenging films, which absorb oxygen from the headspace above the food. In the first method, sachets of ferrous powders or similar chemicals that can absorb large amounts of oxygen are used (Table 20.5). The use of oxygen-scavenging chemicals is widespread in Japan, but has not been widely accepted in Europe or USA to date, possibly because of fears over accidental consumption of the chemicals or litigation if they are consumed. The use of oxygen-absorbing labels (Anon., 1994) or sachets contained in sealed compartments in a pack may overcome this resistance. Immobilisation of oxidising enzymes (glucose oxidase, alcohol oxidase) on the inner surface of films has also been shown to be feasible, but is too expensive at present. Applications of oxygen scavengers so far include bakery products, pre-cooked pasta, cured and smoked meats, cheese, spices, nuts, coffee (Davies, 1995), jelly confectionery, soybean cakes, rice cakes, soft cakes and seaweed-based foods in oriental countries (Table 20.5).

Systems for CO₂ production involve placing sachets of chemicals in the base of a tray, covered by a plastic mesh. When activated by moisture or water vapour, the sachets either release CO₂ or in other applications, they absorb ethylene and/or CO₂, depending on the chemicals used. Ethylene absorption delays ripening (Chapter 19) and systems based on activated carbon or potassium permanganate have been developed. Other systems include combined oxygen and CO₂ scavenging in packed, freshly roasted coffee beans, one-way valves which release CO₂ from the pack without allowing other gases to enter (for mould-ripened cheese), and high CO₂ permeable films for coffee (Church, 1994). Japanese companies have also developed an oxygen-sensitive ink and an indicator that changes from pink to blue when oxygen levels rise from <0.1% to >0.5% (Church, 1994), which are used to ensure that gas composition is maintained and may have applications to check non-destructively pack integrity.

Ethanol has anti-microbial properties, especially against moulds, and ethanol generators have been used to increase the shelf life of baked products, cheeses and semi-dried fish.

The growing awareness of environmental problems caused by packaging materials has renewed interest in edible protective superficial layers (EPSL). These are applied directly to the surface of a food and act as an additional hurdle to loss of quality and protection against microbial spoilage. Active EPSLs, with antimicrobial properties (for example using sorbic acid) or antioxidant properties have been developed to fix the additives at the product surface where they are required, and therefore reduce the amounts that are used. Flexible, hydrophilic EPSLs, having good resistance to breakage and abrasion have been developed from gluten and pectin (Gontard *et al.*, 1992, 1993). Developments in active packaging are reviewed by Vermeiren *et al.* (1999).

20.3 Acknowledgement

Grateful acknowledgement is made for information supplied by: BOC Gases, London SW19 3UF, UK.

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21

Freezing

Freezing is the unit operation in which the temperature of a food is reduced below its freezing point and a proportion of the water undergoes a change in state to form ice crystals. The immobilisation of water to ice and the resulting concentration of dissolved solutes in unfrozen water lower the water activity (a_w) of the food (a_w is described in Chapter 1). Preservation is achieved by a combination of low temperatures, reduced water activity and, in some foods, pre-treatment by blanching. There are only small changes to nutritional or sensory qualities of foods when correct freezing and storage procedures are followed.

The major groups of commercially frozen foods are as follows:

- fruits (strawberries, oranges, raspberries, blackcurrants) either whole or puréed, or as juice concentrates
- vegetables (peas, green beans, sweetcorn, spinach, sprouts and potatoes)
- fish fillets and seafoods (cod, plaice, shrimps and crab meat) including fish fingers, fish cakes or prepared dishes with an accompanying sauce
- meats (beef, lamb, poultry) as carcasses, boxed joints or cubes, and meat products (sausages, beefburgers, reformed steaks)
- baked goods (bread, cakes, fruit and meat pies)
- prepared foods (pizzas, desserts, ice cream, complete meals and cook–freeze dishes).

Rapid increases in sales of frozen foods in recent years are closely associated with increased ownership of domestic freezers and microwave ovens. Frozen foods and chilled foods (Chapter 19) have an image of high quality and ‘freshness’ and, particularly in meat, fruit and vegetable sectors, outsell canned or dried products.

Distribution of frozen foods has a relatively high cost, due to the need to maintain a constant low temperature. Distribution logistics are discussed further in Chapter 19 in relation to chilled foods and in Chapter 26. A recent advance in distribution of chilled and frozen foods is described by Jennings (1999), in which carbon dioxide ‘snow’ (Section 21.2.4) is added to sealed containers of food, which are then loaded into normal distribution vehicles. The time that a product can be held at the required chilled or frozen storage temperature can be varied from four to 24 hours by adjusting the

amount of added snow. Other advantages of the system include greater flexibility in being able to carry mixed loads at different temperatures in the same vehicle, greater control over storage temperature and greater flexibility in use, compared to standard refrigerated vehicles.

21.1 Theory

During freezing, sensible heat is first removed to lower the temperature of a food to the freezing point. In fresh foods, heat produced by respiration is also removed (Chapter 19). This is termed the *heat load*, and is important in determining the correct size of freezing equipment for a particular production rate. Most foods contain a large proportion of water (Table 21.1), which has a high specific heat ($4200 \text{ J kg}^{-1} \text{ K}^{-1}$) and a high latent heat of crystallisation (335 kJ kg^{-1}). A substantial amount of energy is therefore needed to remove latent heat, form ice crystals and hence to freeze foods. The latent heat of other components of the food (for example fats) must also be removed before they can solidify but in most foods these other components are present in smaller amounts and removal of a relatively small amount of heat is needed for crystallisation to take place. Energy for freezing is supplied as electrical energy, which is used to compress gases (refrigerants) in mechanical freezing equipment (Sections 21.2.1–3) or to compress and cool cryogenes (Section 21.2.4).

If the temperature is monitored at the thermal centre of a food (the point that cools most slowly) as heat is removed, a characteristic curve is obtained (Fig. 21.1).

The six components of the curve are as follows.

- AS The food is cooled to below its freezing point θ_f which, with the exception of pure water, is always below 0°C (Table 21.1). At point S the water remains liquid, although the temperature is below the freezing point. This phenomenon is known as *supercooling* and may be as much as 10°C below the freezing point.
- SB The temperature rises rapidly to the freezing point as ice crystals begin to form and latent heat of crystallisation is released.
- BC Heat is removed from the food at the same rate as before, but it is latent heat being removed as ice forms and the temperature therefore remains almost constant. The freezing point is gradually depressed by the increase in solute concentration in the unfrozen liquor, and the temperature therefore falls slightly. It is during this stage that the major part of the ice is formed (Fig. 21.2).
- CD One of the solutes becomes supersaturated and crystallises out. The latent heat of crystallisation is released and the temperature rises to the eutectic temperature for that solute (Section 21.1.2).

Table 21.1 Water contents and freezing points of selected foods

Food	Water content (%)	Freezing point ($^\circ\text{C}$)
Vegetables	78–92	–0.8 to –2.8
Fruits	87–95	–0.9 to –2.7
Meat	55–70	–1.7 to –2.2
Fish	65–81	–0.6 to –2.0
Milk	87	–0.5
Egg	74	–0.5

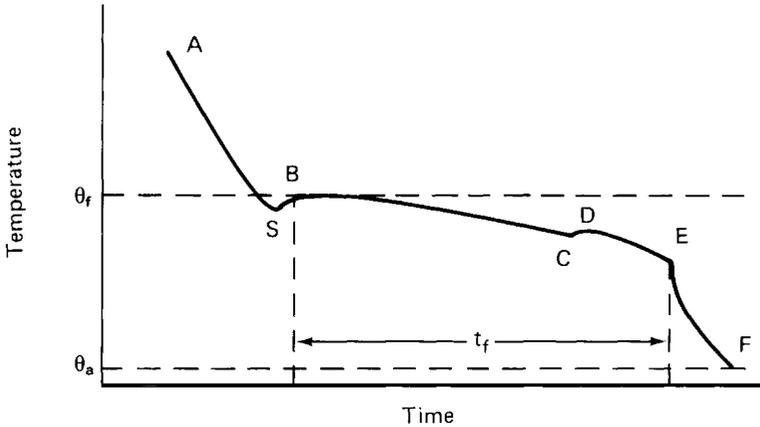


Fig. 21.1 Time-temperature data during freezing.

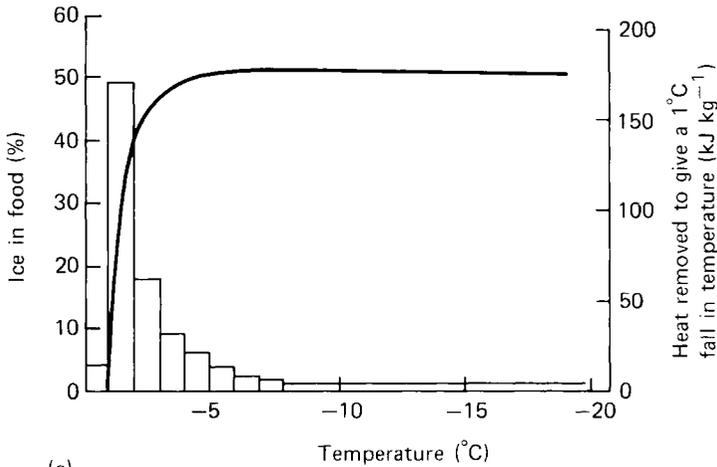
- DE Crystallisation of water and solutes continues. The total time t_f taken (the *freezing plateau*) is determined by the rate at which heat is removed.
- EF The temperature of the ice-water mixture falls to the temperature of the freezer. A proportion of the water remains unfrozen at the temperatures used in commercial freezing; the amount depends on the type and composition of the food and the temperature of storage. For example at a storage temperature of -20°C the percentage of water frozen is 88% in lamb, 91% in fish and 93% in egg albumin.

21.1.1 Ice crystal formation

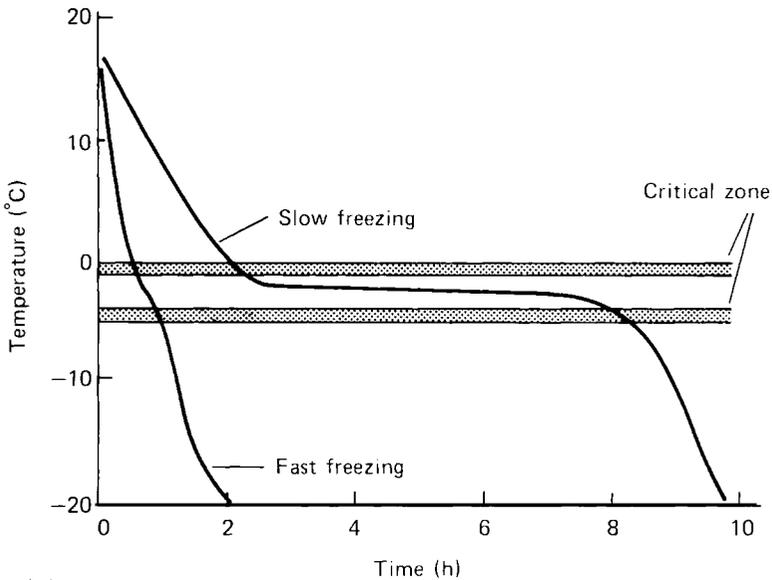
The freezing point of a food may be described as 'the temperature at which a minute crystal of ice exists in equilibrium with the surrounding water'. However, before an ice crystal can form, a nucleus of water molecules must be present. *Nucleation* therefore precedes ice crystal formation. There are two types of nucleation: homogeneous nucleation (the chance orientation and combination of water molecules), and heterogeneous nucleation (the formation of a nucleus around suspended particles or at a cell wall). Heterogeneous nucleation is more likely to occur in foods and takes place during supercooling (Fig. 21.1). The length of the supercooling period depends on the type of food and the rate at which heat is removed.

High rates of heat transfer produce large numbers of nuclei and, as water molecules migrate to existing nuclei in preference to forming new nuclei, fast freezing therefore produces a large number of small ice crystals. However, large differences in crystal size are found with similar freezing rates due to different types of food and even in similar foods which have received different pre-freezing treatments.

The rate of ice crystal growth is controlled by the rate of heat transfer for the majority of the freezing plateau. The time taken for the temperature of a food to pass through the *critical zone* (Fig. 21.2) therefore determines both the number and the size of ice crystals. The rate of mass transfer (of water molecules moving to the growing crystal and of solutes moving away from the crystal) does not control the rate of crystal growth except towards the end of the freezing period when solutes become more concentrated. Further details of the freezing process are given by Sahagian and Goff (1996).



(a)



(b)

Fig. 21.2 Freezing: (a) ice formation at different freezing temperatures; (b) temperature changes of food through the critical zone.
(After Leniger and Beverloo (1975).)

21.1.2 Solute concentration

An increase in solute concentration during freezing causes changes in the pH, viscosity, surface tension and redox potential of the unfrozen liquor. As the temperature falls, individual solutes reach saturation point and crystallise out. The temperature at which a crystal of an individual solute exists in equilibrium with the unfrozen liquor and ice is its *eutectic temperature* (for example for glucose this is -5°C , for sucrose -14°C , for sodium chloride -21.13°C and for calcium chloride -55°C). However, it is difficult to identify individual eutectic temperatures in the complex mixture of solutes in foods, and the term *final eutectic temperature* is therefore used. This is the lowest eutectic

Table 21.2 Examples of glass transition values of foods

Food	Glass transition temperature (°C)
Fruits and fruit products	
Apple	-41 to -42
Banana	-35
Peach	-36
Strawberry	-33 to -41
Tomato	-41
Grape juice	-42
Pineapple juice	-37
Vegetables	
Sweetcorn, fresh	-15
Potato, fresh	-12
Pea, frozen	-25
Broccoli head, frozen	-12
Spinach, frozen	-17
Desserts	
Ice cream	-31 to -33
Cheese	
Cheddar	-24
Cream cheese	-33
Fish and meat	
Cod muscle	-11.7 ± 0.6
Mackerel muscle	-12.4 ± 0.2
Beef muscle	-12 ± 0.3

Adapted from Fennema (1996).

temperature of the solutes in a food (for example for ice-cream this is -55°C , for meat -50 to -60°C and for bread -70°C (Fennema, 1975a). Maximum ice crystal formation is not possible until this temperature is reached. Commercial foods are not frozen to such low temperatures and unfrozen water is therefore always present.

As food is frozen below point E in Fig. 21.1, the unfrozen material becomes more concentrated and forms a 'glass' which encompasses the ice crystals. The temperature range at which this occurs depends on the solute composition and the initial water content of the food. Where the temperature of storage is below this temperature range, the formation of a glass protects the texture of the food and gives good storage stability (for example meats and vegetables in Table 21.2). Many fruits however, have very low glass transition temperatures and as a result suffer losses in texture during frozen storage, in addition to damage caused by ice crystals (Section 21.3). Further details of glass transition values are given by Fennema (1996) and are described in Chapter 1.

21.1.3 Volume changes

The volume of ice is 9% greater than that of pure water, and an expansion of foods after freezing would therefore be expected. However, the degree of expansion varies considerably owing to the following factors:

- moisture content (higher moisture contents produce greater changes in volume)
- cell arrangement (plant materials have intercellular air spaces which absorb internal increases in volume without large changes in their overall size (for example whole strawberries increase in volume by 3.0% whereas coarsely ground strawberries increase by 8.2% when both are frozen to -20°C (Leniger and Beverloo, 1975)))

- the concentrations of solutes (high concentrations reduce the freezing point and do not freeze – or expand – at commercial freezing temperatures)
- the freezer temperature (this determines the amount of unfrozen water and hence the degree of expansion)
- crystallised components, including ice, fats and solutes, contract when they are cooled and this reduces the volume of the food.

Rapid freezing causes the food surface to form a crust and prevents further expansion. This causes internal stresses to build up in the food and makes pieces more susceptible to cracking or shattering, especially when they suffer impacts during passage through continuous freezers. Details of the effect of freezing rate on the cracking resistance of different fruits are described by Sebok *et al.* (1994).

21.1.4 Calculation of freezing time

During freezing, heat is conducted from the interior of a food to the surface and is removed by the freezing medium. The factors which influence the rate of heat transfer are:

- the thermal conductivity of the food
- the area of food available for heat transfer
- the distance that the heat must travel through the food (size of the pieces)
- the temperature difference between the food and the freezing medium
- the insulating effect of the boundary film of air surrounding the food (Chapter 1)
- packaging, if present, is an additional barrier to heat flow.

It is difficult to define the freezing time precisely but two approaches are taken. The *effective freezing time*¹ measures the time that food spends in a freezer and is used to calculate the throughput of a manufacturing process whereas the *nominal freezing time*² can be used as an indicator of product damage as it takes no account of the initial conditions or the different rates of cooling at different points on the surface of the food.

The calculation of freezing time is complicated for the following reasons:

- differences in the initial temperature, size and shape of individual pieces of food
- differences in the freezing point and the rate of ice crystal formation within different regions of a piece of food
- changes in density, thermal conductivity, specific heat and thermal diffusivity with a reduction in temperature of the food.

Removal of latent heat further complicates the unsteady-state heat transfer calculations (Chapter 1), and a complete mathematical solution of freezing rate is not possible. For most practical purposes an approximate solution based on formulae developed by Plank (equation (21.1)) is adequate. This involves the following assumptions:

- freezing starts with all water in the food unfrozen but at its freezing point, and loss of sensible heat is ignored
1. The time required to lower the temperature of a food from an initial value to a pre-determined final temperature at the thermal centre.
 2. The time between the surface of the food reaching 0°C and the thermal centre reaching 10°C below the temperature of the first ice formation.

- heat transfer takes place sufficiently slowly for steady-state conditions to operate
- the freezing front maintains a similar shape to that of the food (for example in a rectangular block the freezing front remains rectangular)
- there is a single freezing point
- the density of the food does not change
- the thermal conductivity and specific heat of the food are constant when unfrozen and then change to a different constant value when the food is frozen.

The freezing time for cubes of food is calculated using:

$$t_f = \frac{\lambda \rho}{\theta_f - \theta_a} \left[\frac{L}{6} \left(\frac{1}{h} + \frac{x}{k_1} \right) + \frac{L^2}{24k_2} \right] \quad (21.1)$$

where t_f (s) = freezing time, L (m) = length of the cube, h ($\text{W m}^{-2} \text{K}^{-1}$) = surface heat transfer coefficient, θ_f ($^{\circ}\text{C}$) = freezing point of the food, θ_a ($^{\circ}\text{C}$) = temperature of the freezing medium, λ (J kg^{-1}) = latent heat of crystallisation, ρ (kg m^{-3}) = density of the food, x (m) = thickness of the packaging, k_1 ($\text{W m}^{-1} \text{K}^{-1}$) = thermal conductivity of the packaging, k_2 ($\text{W m}^{-1} \text{K}^{-1}$) = thermal conductivity of the frozen zone, 6 and 24 are factors which represent the shortest distance between the centre and the surface of the food. Other shapes require different factors; these are 2 and 8 for a slab, 4 and 16 for a cylinder and 6 and 24 for a sphere. Derivation of the equation is described by Earle (1983).

Equation (21.1) may be rearranged to find the heat transfer coefficient as follows:

$$h = \frac{L}{6} \left[\frac{t_f(\theta_f - \theta_a)}{\lambda \rho} - \frac{Lx}{6k_1} - \frac{L^2}{24k_2} \right] \quad (21.2)$$

Other equations produced by different research workers are described by Jackson and Lamb (1981). The many assumptions made using these equations lead to a small under-estimation of freezing time when compared with experimental data. More complex formulae which give closer approximations have been described by a number of workers including Cleland and Earle (1982).

Sample problem 21.1

Five-centimetre potato cubes are individually quick frozen (IQF) in a blast freezer operating at -40°C and with a surface heat transfer coefficient of $30 \text{ W m}^{-2} \text{K}^{-1}$ (Table 21.3). If the freezing point of the potato is measured as -1.0°C and the density is 1180 kg m^{-3} , calculate the expected freezing time for each cube. If the cubes are then packed into a cardboard carton measuring $20 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$, calculate the freezing time. Also calculate the freezing time for IQF freezing of 2.5 cm cubes. (Additional data: the thickness of the card is 1.5 mm , the thermal conductivity of the card is $0.07 \text{ W m}^{-1} \text{K}^{-1}$, the thermal conductivity of potato is $2.5 \text{ W m}^{-1} \text{K}^{-1}$ (Table 1.5) and the latent heat of crystallisation $2.74 \times 10^5 \text{ J kg}^{-1}$.)

Solution to Sample problem 21.1

To calculate the expected freezing time of each cube, from equation (21.1), for an unwrapped cube,

$$t_f = \frac{(2.74 \times 10^5)1180}{-1 - (-40)} \left[\frac{0.05}{6} \left(\frac{1}{30} + 0 \right) + \frac{0.05^2}{24 \times 2.5} \right] = 2648 \text{ s} = 44 \text{ min}$$

To calculate the freezing time for cubes packed together to form a slab 10 cm thick,

$$t_f = \frac{(2.74 \times 10^5)1180}{-1 - (-40)} \left[\frac{0.1}{2} \left(\frac{1}{30} + \frac{0.0015}{0.07} \right) + \frac{0.1^2}{8 \times 2.5} \right] = 26\,700 \text{ s}$$

$$\approx 7.4 \text{ h}$$

To calculate the freezing time for IQF freezing of 2.5 cm cubes,

$$t_f = \frac{(2.74 \times 10^5)1180}{-1 - (-40)} \left[\frac{0.025}{6} \left(\frac{1}{30} + 0 \right) + \frac{0.025^2}{24 \times 25} \right] = 1226 \text{ s}$$

$$\approx 20 \text{ min}$$

21.2 Equipment

The selection of freezing equipment should take the following factors into consideration: the rate of freezing required; the size, shape and packaging requirements of the food; batch or continuous operation, the scale of production, range of products to be processed and not least the capital and operating costs.

Freezers are broadly categorised into:

- mechanical refrigerators, which evaporate and compress a refrigerant in a continuous cycle (details are given in Chapter 19) and use cooled air, cooled liquid or cooled surfaces to remove heat from foods
- cryogenic freezers, which use solid or liquid carbon dioxide, liquid nitrogen (or until recently, liquid Freon) directly in contact with the food.

An alternative classification, based on the rate of movement of the ice front is:

- *slow freezers* and *sharp freezers* (0.2 cm h^{-1}) including still-air freezers and cold stores
- *quick freezers* ($0.5\text{--}3 \text{ cm h}^{-1}$) including air-blast and plate freezers
- *rapid freezers* ($5\text{--}10 \text{ cm h}^{-1}$) including fluidised-bed freezers
- *ultrarapid freezers* ($10\text{--}100 \text{ cm h}^{-1}$), that is cryogenic freezers.

All freezers are insulated with expanded polystyrene, polyurethane or other materials which have low thermal conductivity (Chapter 1, Table 1.5). Recent developments in computer control, described in Chapter 2, are incorporated in most freezing equipment to monitor process parameters and equipment status, display trends, identify faults and automatically control processing conditions for different products.

21.2.1 Cooled-air freezers

In *chest freezers* food is frozen in stationary (natural-circulation) air at between -20°C and -30°C . Chest freezers are not used for commercial freezing owing to low freezing rates (3–72 h), which result in poor process economics and loss of product quality (Section 21.3). *Cold stores* are used to freeze carcass meat, to store foods that are frozen by other methods, and as hardening rooms for ice cream. Air is usually circulated by fans

Table 21.3 A comparison of freezing methods

Method of freezing	Typical film heat transfer coefficients ($\text{W m}^{-2} \text{K}^{-1}$)	Typical freezing times for specified foods to -18°C (min)	Food
Still air	6–9	180–4320	Meat carcass
Blast (5 m s^{-1})	25–30	15–20	Unpackaged peas
Blast (3 m s^{-1})	18	–	
Spiral belt	25	12–19	Hamburgers, fish fingers
Fluidised bed	90–140	3–4	Unpackaged peas
		15	Fish fingers
Plate	100	75	25 kg blocks of fish
		25	1 kg carton vegetables
Scraped surface	–	0.3–0.5	Ice cream (layer approximately 1 mm thick)
Immersion (Freon)	500	10–15	170 g card cans of orange juice
		0.5	Peas
		4–5	Beefburgers, fish fingers
Cryogenic (liquid nitrogen)	1500	1.5	454 g of bread
		0.9	454 g of cake
		2–5	Hamburgers, seafood
		0.5–6	Fruits and vegetables

Adapted from Earle (1983), Olsson and Bengtsson (1972), Desrosier and Desrosier (1978), Leeson (1987) and Holdsworth (1987).

to improve the uniformity of temperature distribution, but heat transfer coefficients are low (Table 21.3).

A major problem with cold stores is ice formation on floors, walls and evaporator coils, caused by moisture from the air or from unpackaged products in the store. For example, air at 10°C and 80% relative humidity contains 6 g water per kg of air (see Section 15.1). If air enters the cold store through loading doors at a rate of $1000 \text{ m}^3 \text{ h}^{-1}$, 173 kg of water vapour enters the store per day (Weller and Mills, 1999). This condenses to water and freezes on the cold surfaces, which reduces the efficiency of the refrigeration plant, uses up energy that would otherwise be used to cool the store, creates potential hazards from slippery working conditions and falling blocks of ice, and requires frequent defrosting of evaporator coils. A desiccant dehumidifier, described by Weller and Mills (1999), overcomes these problems by removing moisture from the air as it enters the store and thus reduces ice formation, reduces the size of compressors and fans, and energy needed to maintain the store temperature.

In *blast freezers*, air is recirculated over food at between -30°C and -40°C at a velocity of $1.5\text{--}6.0 \text{ m s}^{-1}$. The high air velocity reduces the thickness of boundary films surrounding the food (Chapter 1, Fig. 1.3) and thus increases the surface heat transfer coefficient (Table 21.3). In batch equipment, food is stacked on trays in rooms or cabinets. Continuous equipment consists of trolleys stacked with trays of food or on conveyor belts which carry the food through an insulated tunnel. The trolleys should be fully loaded to prevent air from bypassing the food through spaces between the trays. Multipass tunnels contain a number of belts, and products fall from one to another. This breaks up any clumps of food and allows control over the product depth (for example a 25–50 mm bed is initially frozen for 5–10 min and then repiled to 100–125 mm on a second belt).

Air flow is either parallel or perpendicular to the food and is ducted to pass evenly over all food pieces. Blast freezing is relatively economical and highly flexible in that

foods of different shapes and sizes can be frozen. The equipment is compact and has a relatively low capital cost and a high throughput (200–1500 kg h⁻¹). However, moisture from the food is transferred to the air and builds up as ice on the refrigeration coils, and this necessitates frequent defrosting. The large volumes of recycled air can also cause dehydration losses of up to 5%, freezer burn and oxidative changes to unpackaged or individually quick frozen (IQF) foods. IQF foods freeze more rapidly, enable packaged foods to be partly used and then refrozen, and permit better portion control. However, the low bulk density and high void space causes a higher risk of dehydration and freezer burn (Section 21.3).

Belt freezers (spiral freezers) have a continuous flexible mesh belt which is formed into spiral tiers and carries food up through a refrigerated chamber. In some designs each tier rests on the vertical sides of the tier beneath (Fig. 21.3) and the belt is therefore ‘self-stacking’. This eliminates the need for support rails and improves the capacity by up to 50% for a given stack height. Cold air or sprays of liquid nitrogen (Section 21.2.4) are directed down through the belt stack in a countercurrent flow, which reduces weight losses due to evaporation of moisture. Spiral freezers require relatively small floor-space and have high capacity (for example a 50–75 cm wide belt in a 32-tier spiral processes up to 3000 kg h⁻¹). Other advantages include automatic loading and unloading, low maintenance costs and flexibility to freeze a wide range of foods including pizzas, cakes, pies, ice cream, whole fish and chicken portions.

Fluidised-bed freezers are modified blast freezers in which air at between –25°C and –35°C is passed at a high velocity (2–6 m s⁻¹) through a 2–13 cm bed of food, contained on a perforated tray or conveyor belt. In some designs there are two stages; after initial rapid freezing in a shallow bed to produce an ice glaze on the surface of the food, freezing is completed on a second belt in beds 10–15 cm deep. The formation of a glaze is useful for fruit pieces and other products that have a tendency to clump together. The shape and size of the pieces of food determine the thickness of the fluidised bed and the air velocity needed for fluidisation (a sample calculation of air velocity is given in Chapter 1). Food comes into greater contact with the air than in blast freezers, and all surfaces are frozen simultaneously and uniformly. This produces higher heat transfer coefficients, shorter freezing times (Table 21.3), higher production rates (10 000 kg h⁻¹) and less dehydration of unpackaged food than blast freezing does. The equipment therefore needs less frequent defrosting. However, the method is restricted to particulate foods (for example peas, sweetcorn kernels, shrimps, strawberries or French fried potatoes). Similar equipment, named *through-flow freezers*, in which air passes through a bed of food but fluidisation is not achieved, is suitable for larger pieces of food (for example fish fillets). Both types of equipment are compact, have a high capacity and are highly suited to the production of IQF foods.

21.2.2 Cooled-liquid freezers

In *immersion freezers*, packaged food is passed through a bath of refrigerated propylene glycol, brine, glycerol or calcium chloride solution on a submerged mesh conveyor. In contrast with cryogenic freezing (Section 21.2.4), the liquid remains fluid throughout the freezing operation and a change of state does not occur. The method has high rates of heat transfer (Table 21.3) and capital costs are relatively low. It is used commercially for concentrated orange juice in laminated card–polyethylene cans, and to pre-freeze film-wrapped poultry before blast freezing.

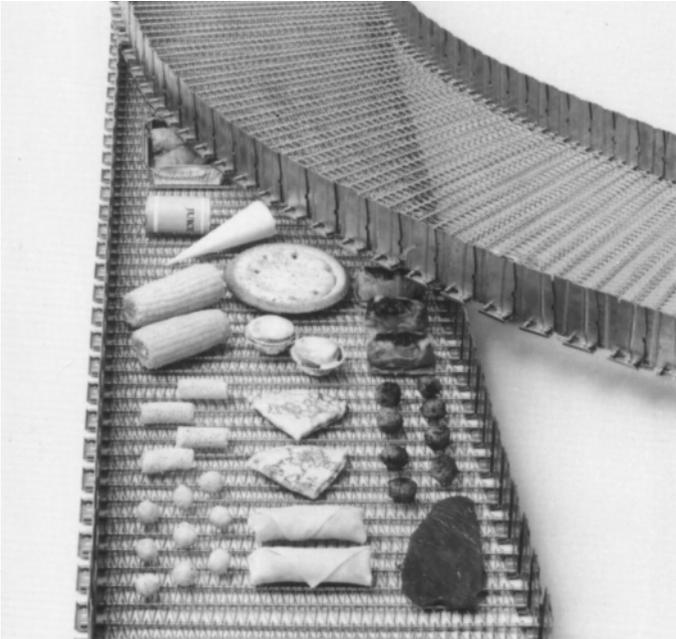
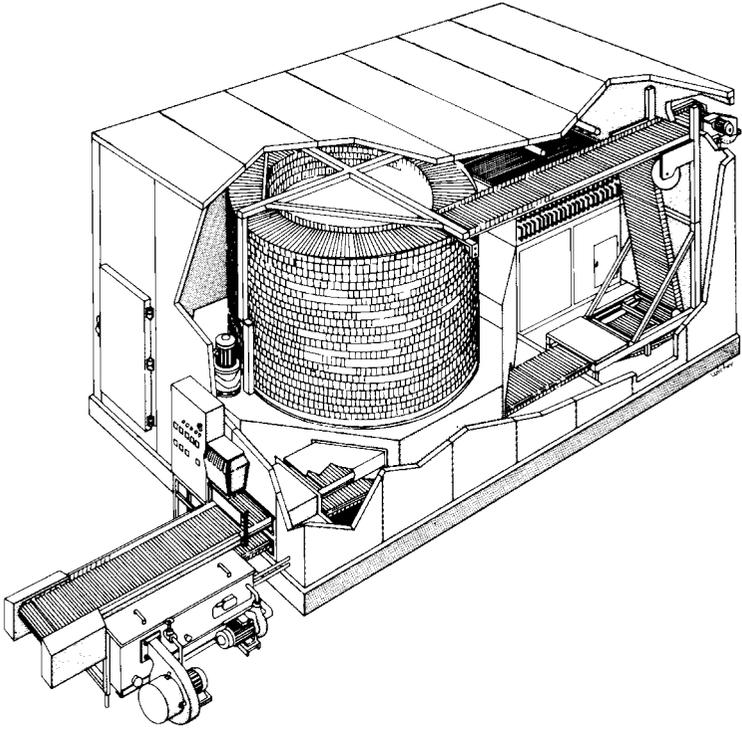


Fig. 21.3 Spiral freezer, self-stacking belt.
(Courtesy of Frigoscandia Ltd.)

21.2.3 Cooled-surface freezers

Plate freezers consist of a vertical or horizontal stack of hollow plates, through which refrigerant is pumped at -40°C (Fig. 21.4). They may be batch, semi-continuous or continuous in operation. Flat, relatively thin foods (for example filleted fish, fish fingers or beefburgers) are placed in single layers between the plates and a slight pressure is applied by moving the plates together. This improves the contact between surfaces of the food and the plates and thereby increases the rate of heat transfer. If packaged food is frozen in this way, the pressure prevents the larger surfaces of the packs from bulging. Production rates range from 90–2700 kg h^{-1} in batch freezers. Advantages of this type of equipment include good economy and space utilisation, relatively low operating costs compared with other methods, little dehydration of the product and therefore minimum defrosting of condensers, and high rates of heat transfer (Table 21.3). The main disadvantages are the relatively high capital costs, and restrictions on the shape of foods to those that are flat and relatively thin.

Scraped-surface freezers are used for liquid or semi-solid foods (for example ice cream). They are similar in design to equipment used for evaporation (Chapter 13, Fig. 13.5) and heat sterilisation (Chapter 12) but are refrigerated with ammonia, brine, or other refrigerants. In ice cream manufacture, the rotor scrapes frozen food from the wall of the freezer barrel and simultaneously incorporates air. Alternatively, air can be injected into the product. The increase in volume of the product due to the air is expressed as *overrun* (see Chapter 1, Section 1.1.1).

Freezing is very fast and up to 50% of the water is frozen within a few seconds (Jaspersen, 1989). This results in very small ice crystals, which are not detectable in the mouth and thus gives a smooth creamy consistency to the product. The temperature is reduced to between -4°C and -7°C and the frozen aerated mixture is then pumped into

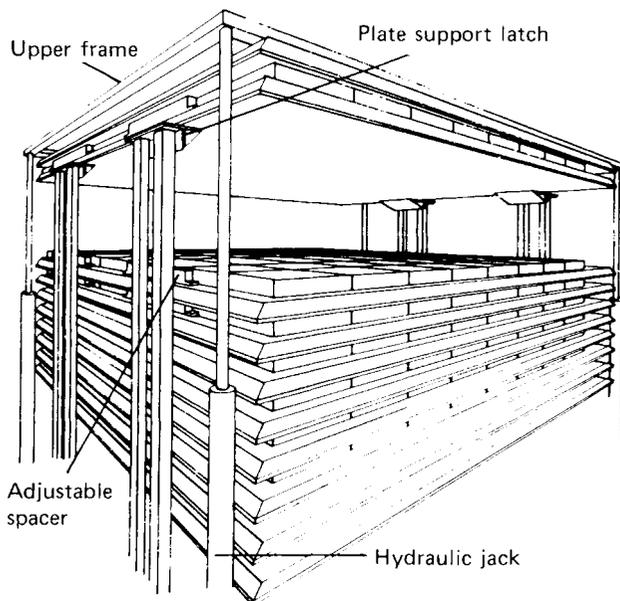


Fig. 21.4 Plate freezer.

(Courtesy of Frigoscandia Ltd. and Garthwaite, A. (1995).)

containers and freezing is completed in a 'hardening room' (see 'chest freezers' above). Further details of ice cream production are given in Chapter 4.

21.2.4 Cryogenic freezers

Freezers of this type are characterised by a change of state in the refrigerant (or cryogen) as heat is absorbed from the freezing food. The heat from the food therefore provides the latent heat of vaporisation or sublimation of the cryogen. The cryogen is in intimate contact with the food and rapidly removes heat from all surfaces of the food to produce high heat transfer coefficients and rapid freezing. The two most common refrigerants are liquid nitrogen and solid or liquid carbon dioxide. Dichlorodifluoromethane (refrigerant 12 or Freon 12) was also previously used for sticky or fragile foods that stuck together in clumps (for example meat paste, shrimps, tomato slices), but its use has now been phased out under the Montreal Protocol, due to its effects on the earth's ozone layer (further details are given in Chapter 19).

The choice of refrigerant is determined by its technical performance for a particular product, its cost and availability, environmental impact and safety (Heap, 1997). The market for frozen foods is increasingly characterised by shorter product life cycles and hence more rapid changes to the number and type of new products. There is a significant commercial risk if the payback period on capital investment exceeds the product life cycle, unless the equipment is sufficiently flexible to accommodate new products (Summers, 1998). Two advantages of cryogenic freezers, compared to mechanical systems, are the lower capital cost and flexibility to process a number of different products without major changes to the system (Miller, 1998).

Both liquid-nitrogen and carbon dioxide refrigerants are colourless, odourless and inert. When liquid nitrogen is sprayed onto food, 48% of the total freezing capacity (enthalpy) is taken up by the latent heat of vaporisation needed to form the gas (Table 21.4). The remaining 52% of the enthalpy is available in the cold gas, and gas is therefore recirculated to achieve optimum use of the freezing capacity. Carbon dioxide has a lower enthalpy than liquid nitrogen (Table 21.4) but most of the freezing capacity (85%) is available from the subliming solid and the lower boiling point produces a less severe thermal shock. In addition, solid carbon dioxide in the form of a fine snow sublimates on contact with the food, and gas is not recirculated. Carbon dioxide is a bacteriostat but is also toxic, and gas should be vented from the factory to avoid injury to operators. Carbon dioxide consumption is higher than liquid-nitrogen consumption, but storage losses are lower.

Table 21.4 Properties of food cryogens

Property	Liquid nitrogen	Carbon dioxide
Density (kg m^{-3})	784	464
Specific heat ($\text{kJ kg}^{-1} \text{K}^{-1}$)	1.04	2.26
Latent heat (kJ kg^{-1})	358	352
Total usable refrigeration effect (kJ kg^{-1})	690	565
Boiling point ($^{\circ}\text{C}$)	-196	-78.5 (sublimation)
Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	0.29	0.19
Consumption per 100 kg of product frozen (kg)	100-300	120-375

From Graham (1984).

In liquid-nitrogen freezers, packaged or unpackaged food travels on a perforated belt through a tunnel (Fig. 21.5), where it is frozen by liquid-nitrogen sprays and by gaseous nitrogen. Production rates are 45–1550 kg h⁻¹. The temperature is either allowed to equilibrate at the required storage temperature (between -18°C and -30°C) before the food is removed from the freezer, or alternatively food is passed to a mechanical freezer to complete the freezing process. The use of gaseous nitrogen reduces the thermal shock to the food, and recirculation fans increase the rates of heat transfer. A newer design of tunnel, with fans located beneath the conveyor to produce gas vortices is described by Summers (1998). This design is said to double the output of conventional freezers of the same length, reduce nitrogen consumption by 20% and reduce already low levels of dehydration by 60%. The temperature and belt speed are controlled by microprocessors to maintain the product at a pre-set exit temperature, regardless of the heat load of incoming food. The equipment therefore has the same efficiency at or below its rated capacity. This results in greater flexibility and economy than mechanical systems, which have a fixed rate of heat extraction (Tomlins, 1995).

Other advantages include:

- simple continuous operation with relatively low capital costs (approximately 30% of the capital cost of mechanical systems)
- smaller weight losses from dehydration of the product (0.5% compared with 1.0–8.0% in mechanical air-blast systems)
- rapid freezing (Table 21.3) which results in smaller changes to the sensory and nutritional characteristics of the product
- the exclusion of oxygen during freezing
- rapid startup and no defrost time
- low power consumption (Leeson, 1987).

The main disadvantage is the relatively high cost of refrigerant (nitrogen and carbon dioxide consumption are shown in Table 21.4).

Liquid nitrogen is also used in spiral freezers (Section 21.2.1) instead of vapour recompression refrigerators. The advantages include higher rates of freezing, and smaller

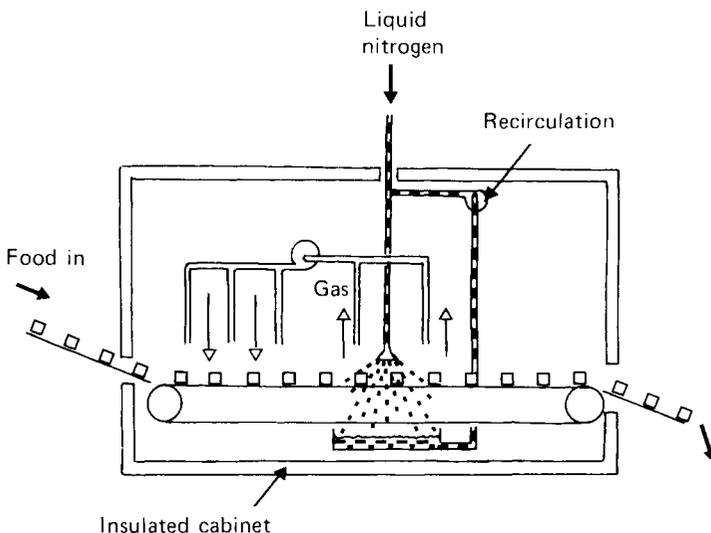


Fig. 21.5 Liquid-nitrogen freezer.

units for the same production rates because heat exchanger coils are not used. Other applications include rigidification of meat for high-speed slicing (Chapter 4), surface hardening of ice cream prior to chocolate coating (Chapter 23) and crust formation on fragile products such as seafood and sliced mushrooms (Londahl and Karlsson (1991), before finishing freezing in mechanical or cryogenic freezers. Other applications are described by Tomlins (1995).

Immersion of foods in liquid nitrogen produces no loss in product weight but causes a high thermal shock. This is acceptable in some products (for example raspberries, shrimps and diced meat), but in many foods the internal stresses created by the extremely high rate of freezing cause the food to crack or split. The rapid freezing permits high production rates of IQF foods using small equipment (for example a 1.5 m long bath of liquid nitrogen freezes 1 t of small-particulate food per hour).

21.3 Changes in foods

21.3.1 Effect of freezing

The main effect of freezing on food quality is damage caused to cells by ice crystal growth. Freezing causes negligible changes to pigments, flavours or nutritionally important components, although these may be lost in preparation procedures (Chapters 3 and 10) or deteriorate later during frozen storage. Food emulsions (Chapter 4) can be destabilised by freezing, and proteins are sometimes precipitated from solution, which prevents the widespread use of frozen milk. In baked goods a high proportion of amylopectin is needed in the starch to prevent retrogradation and staling during slow freezing and frozen storage.

There are important differences in resistance to freezing damage between animal and plant tissues. Meats have a more flexible fibrous structure which separates during freezing instead of breaking, and the texture is not seriously damaged. In fruits and vegetables, the more rigid cell structure may be damaged by ice crystals. The extent of damage depends on the size of the crystals and hence on the rate of heat transfer (Section 21.1.1). However, differences in the variety and quality of raw materials and the degree of control over pre-freezing treatments both have a substantially greater effect on food quality than changes caused by correctly operated freezing, frozen storage and thawing procedures. Details of the changes to meats are described by Devine *et al.* (1996) and changes to vegetables are described by Cano (1996).

The influence of freezing rate on plant tissues is shown in Fig. 21.6. During slow freezing, ice crystals grow in intercellular spaces and deform and rupture adjacent cell walls. Ice crystals have a lower water vapour pressure than regions within the cells, and water therefore moves from the cells to the growing crystals. Cells become dehydrated and permanently damaged by the increased solute concentration and a collapsed and deformed cell structure. On thawing, cells do not regain their original shape and turgidity. The food is softened and cellular material leaks out from ruptured cells (termed 'drip loss'). In fast freezing, smaller ice crystals form within both cells and intercellular spaces. There is little physical damage to cells, and water vapour pressure gradients are not formed; hence there is minimal dehydration of the cells. The texture of the food is thus retained to a greater extent (Fig. 21.6(b)). However, very high freezing rates may cause stresses within some foods that result in splitting or cracking of the tissues. These changes are discussed in detail by Spiess (1980).

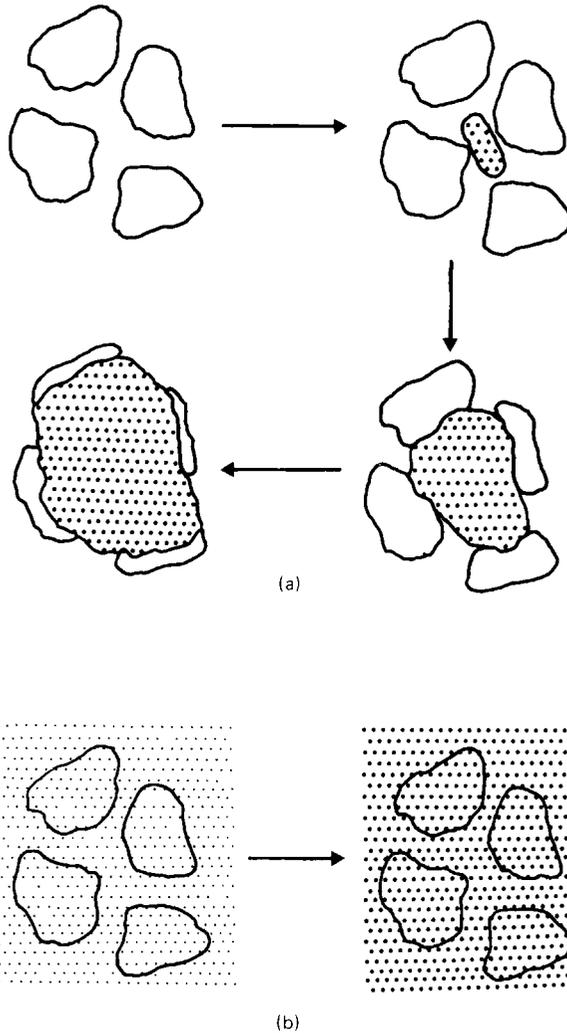


Fig. 21.6 Effect of freezing on plant tissues: (a) slow freezing; (b) fast freezing. (After Meryman (1963).)

21.3.2 Effects of frozen storage

In general, the lower the temperature of frozen storage, the lower is the rate of microbiological and biochemical changes. However, freezing and frozen storage do not inactivate enzymes and have a variable effect on micro-organisms. Relatively high storage temperatures (between -4°C and -10°C) have a greater lethal effect on micro-organisms than do lower temperatures (between -15°C and -30°C). Different types of micro-organism also vary in their resistance to low temperatures; vegetative cells of yeasts, moulds and gram-negative bacteria (for example coliforms and *Salmonella* species) are most easily destroyed; Gram-positive bacteria (for example *Staphylococcus aureus* and *Enterococci*) and mould spores are more resistant, and bacterial spores (especially *Bacillus* species and *Clostridium* species such as *Clostridium botulinum*) are virtually unaffected by low temperatures. The majority of vegetables are therefore blanched to inactivate enzymes and to reduce the

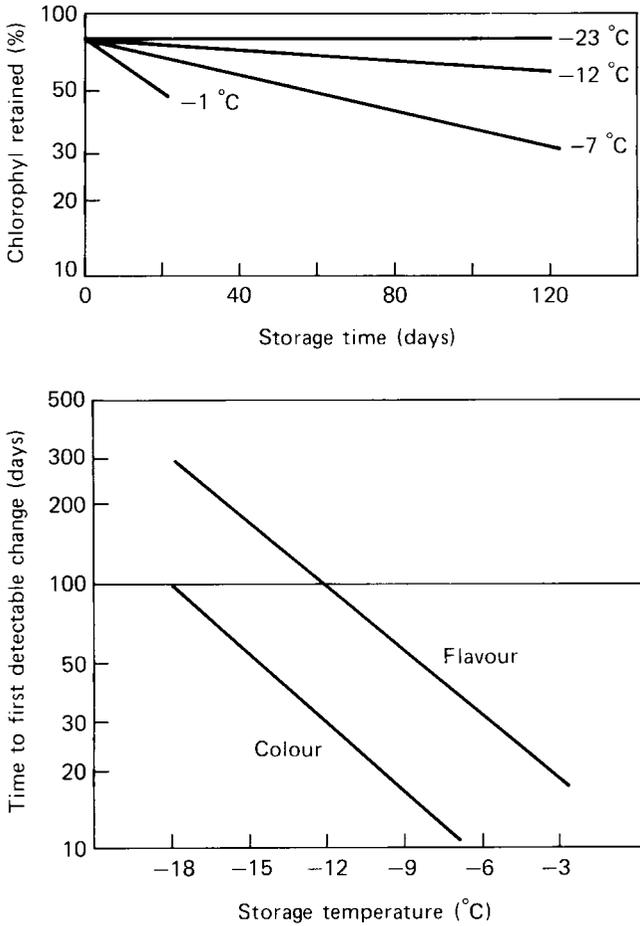


Fig. 21.7 Effect of storage temperature on sensory characteristics. (After Jul (1984).)

numbers of contaminating micro-organisms (Chapter 10). In fruits, enzyme activity is controlled by the exclusion of oxygen, acidification or treatment with sulphur dioxide.

At normal frozen storage temperatures (-18°C), there is a slow loss of quality owing to both chemical changes and, in some foods, enzymic activity. These changes are accelerated by the high concentration of solutes surrounding the ice crystals, the reduction in water activity (to 0.82 at -20°C in aqueous foods) and by changes in pH and redox potential. The effects of storage temperature on food quality are shown in Fig. 21.7. If enzymes are not inactivated, the disruption of cell membranes by ice crystals allows them to react to a greater extent with concentrated solutes.

The main changes to frozen foods during storage are as follows:

- *Degradation of pigments.* Chloroplasts and chromoplasts are broken down and chlorophyll is slowly degraded to brown pheophytin even in blanched vegetables. In fruits, changes in pH due to precipitation of salts in concentrated solutions change the colour of anthocyanins.
- *Loss of vitamins.* Water-soluble vitamins (for example vitamin C and pantothenic acid) are lost at sub-freezing temperatures (Table 21.5). Vitamin C losses are highly

Table 21.5 Vitamin losses during frozen storage

Product	Loss (%) at -18°C during storage for 12 months						
	Vitamin C	Vitamin B ₁	Vitamin B ₂	Niacin	Vitamin B ₆	Pantothenic acid	Carotene
Beans (green)	52	0–32	0	0	0–21	53	0–23
Peas	11	0–16	0–8	0–8	7	29	0–4
Beef steaks ^a		8	9	0	24	22	–
Pork chops ^a		+–18	0–37	+–5	0–8	18	–
Fruit ^b							
Mean	18	29	17	16	–	–	37
Range	0–50	0–66	0–67	0–33	–	–	0–78

+, apparent increase.

^a Storage for 6 months.

^b Mean results from apples, apricots, blueberries, cherries, orange juice concentrate (rediluted), peaches, raspberries and strawberries; storage time not given.

Adapted from Burger (1982) and Fennema (1975b).

temperature dependent; a 10°C increase in temperature causes a sixfold to twentyfold increase in the rate of vitamin C degradation in vegetables and a thirtyfold to seventyfold increase in fruits (Fennema, 1975b). Losses of other vitamins are mainly due to drip losses, particularly in meat and fish (if the drip loss is not consumed).

- *Residual enzyme activity.* In vegetables which are inadequately blanched or in fruits, the most important loss of quality is due to polyphenoloxidase activity which causes browning, and lipoxygenases activity which produces off-flavours and off-odours from lipids and causes degradation of carotene. Proteolytic and lipolytic activity in meats may alter the texture and flavour over long storage periods.
- *Oxidation of lipids.* This reaction takes place slowly at -18°C and causes off-odours and off-flavours.

These changes are discussed in detail by Fennema (1975a, 1982, 1996) and Rahman (1999).

Recrystallisation

Physical changes to ice crystals (for example changes in their shape, size or orientation) are collectively known as *recrystallisation* and are an important cause of quality loss in some foods. There are three types of recrystallisation in foods as follows:

1. *Isomass recrystallisation.* This is a change in surface shape or internal structure, usually resulting in a lower surface-area-to-volume ratio.
2. *Accretive recrystallisation.* Two adjacent ice crystals join together to form a larger crystal and cause an overall reduction in the number of crystals in the food.
3. *Migratory recrystallisation.* This is an increase in the average size and a reduction in the average number of crystals, caused by the growth of larger crystals at the expense of smaller crystals.

Migratory recrystallisation is the most important in most foods and is largely caused by fluctuations in the storage temperature. When heat is allowed to enter a freezer (for example, by opening a door and allowing warm air to enter), the surface of the food nearest to the source of heat warms slightly. This causes ice crystals to melt partially; the larger crystals become smaller and the smallest (less than $2\ \mu\text{m}$) disappear. The melting crystals increase the water vapour pressure, and moisture then moves to regions of lower

vapour pressure. This causes areas of the food nearest to the source of heat to become dehydrated. When the temperature falls again, water vapour does not form new nuclei but joins onto existing ice crystals, thereby increasing their size. There is therefore a gradual reduction in the numbers of small crystals and an increase in the size of larger crystals, resulting in loss of quality similar to that observed in slow freezing.

Cold stores have a low humidity because moisture is removed from the air by the refrigeration coils (see psychrometrics in Chapter 15). Moisture leaves the surface of the food to the storage atmosphere and produces areas of visible damage known as *freezer burn*. Such areas have a lighter colour due to microscopic cavities, previously occupied by ice crystals, which alter the wavelength of reflected light. Freezer burn is a particular problem in foods that have a large surface-area-to-volume ratio (for example IQF foods) but is minimised by packaging in moisture-proof materials (Chapter 24). The causes of dehydration during freezing and frozen storage are discussed in detail by Norwig and Thompson (1984).

Temperature fluctuations are minimised by:

- accurate control of storage temperature ($\pm 1.5^\circ\text{C}$)
- automatic doors and airtight curtains for loading refrigerated trucks
- rapid movement of foods between stores
- correct stock rotation and control.

These techniques, and technical improvements in handling, storage and display equipment, have substantially improved the quality of frozen foods (Jul, 1984).

Storage life

There is some confusion and lack of precise information on the storage life of frozen foods, caused in part by the use of different definitions. For example a European Community directive states that frozen storage must 'preserve the intrinsic characteristics' of foods, whereas the International Institute of Refrigeration defines storage life as 'the physical and biochemical reactions ... leading to a gradual, cumulative and irreversible reduction in product quality, such that after a period of time the product is no longer suitable for consumption ...'. Another definition by Bogh-Sorensen describes *practical storage life* (PSL) as 'the time the product can be stored and still be acceptable to the consumer' (Evans and James, 1993). These definitions differ in the extent to which a product is said to be acceptable and rely heavily on the ability of taste panellists to detect changes in flavour, aroma, etc. that can be used to measure acceptability.

The use of PSL and to a lesser extent, the concept of *high-quality life* (HQL), is used to establish storage life. PSL is defined as 'the time that a statistically significant difference ($P < 0.01$) in quality can be established by taste panellists'. These methods therefore measure the period that food remains essentially the same as when it was frozen. This should not be confused with a storage life that is acceptable to consumers as foods may be acceptable for three to six times longer than the PSL or HQL. Examples of PSL for meats and HQL for vegetables, stored at three temperatures are shown in Table 21.6.

The main causes of loss of storage life are fluctuating temperatures and the type of packaging used. Other factors, including type of raw material, pre-freezing treatments and processing conditions are discussed in detail by Evans and James (1993). Temperature fluctuation has a cumulative effect on food quality and the proportion of PSL or HQL lost can be found by integrating losses over time. *Time-temperature tolerance* (TTT) and *product-processing-packaging* (PPP) concepts are used to monitor

Table 21.6 Storage life of meats measured by PSL and vegetables measured by HQL

Product	Practical storage life (PSL) (months)		
	-12°C	-18°C	-24°C
Beef carcasses	8	15	24
Ground beef	6	10	15
Veal carcasses	6	12	15
Lamb carcasses	18	24	>24
Pork carcasses	6	10	15
Sliced bacon	12	12	12
Chicken, whole	9	18	>24
Turkey, whole	8	15	>24
Ducks, geese, whole	6	12	18
Liver	4	12	18

	High quality life (HQL) (months)		
	-7°C	-12°C	-18°C
Green beans	1	3.1	9.8
Cauliflower	0.4	2	9.7
Peas	1	3	10.1
Spinach	0.76	1.9	6.2

From Guadagni (1968) and Evans and James (1993).

and control the effects of temperature fluctuations on frozen food quality during production, distribution and storage (Olsson, 1984; Bogh-Sorensen, 1984).

Coloured indicators are being developed to:

- show the temperature of food (for example, liquid crystal coatings which change colour with storage temperature)
- indicate temperature abuse (for example wax melts and releases a coloured dye when an unacceptable increase in temperature occurs)
- integrate the time–temperature combination that a food has received after packaging and to give an indication of the remaining shelf life (Fig. 21.8).

In the last category, indicators may contain a material that polymerises as a function of time and temperature to produce a progressive, predictable and irreversible colour change. In another type, a printed label contains diacetylene in the centre of a ‘bull’s eye’, with the outer ring printed with a stable reference colour. The diacetylene gradually darkens in colour due to combined time and temperature and when it matches the reference ring the product has no remaining shelf life. An example of a time–temperature integrator, based on an enzymic reaction which changes the colour of a pH indicator, is described by Blixt (1984) and Selman (1995) has reviewed developments in this area. More recently a bar code system has been developed that is applied to a pack as the product is dispatched. The bar code contains three sections: a code giving information on the product identity, date of manufacture, batch number, etc. to identify each container uniquely. A second code identifies the reactivity of a time–temperature indicator and the third section contains the indicator material. When the bar code is scanned by a hand-held microcomputer, a display indicates the status and quality of the product with a variety of pre-programmed messages (for example: ‘Good’, ‘Don’t use’ or ‘Call QC’). A number of microcomputers can be linked via modems to a central control computer, to produce a portable monitoring system that can track individual containers throughout a distribution chain.

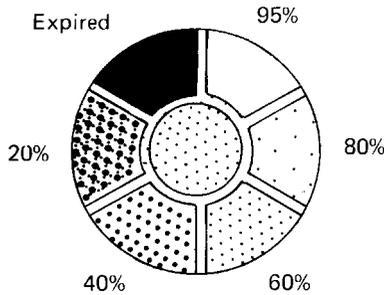


Fig. 21.8 Time–temperature integrator.
(After Fields and Prusik (1983).)

21.3.3 Thawing

When food is thawed in air or water, surface ice melts to form a layer of water. Water has a lower thermal conductivity and a lower thermal diffusivity than ice (Chapter 1) and the surface layer of water therefore reduces the rate at which heat is conducted to the frozen interior. This insulating effect increases as the layer of thawed food grows thicker. (In contrast, during freezing, the increase in thickness of ice causes heat transfer to accelerate.) Thawing is therefore a substantially longer process than freezing when temperature differences and other conditions are similar.

During thawing (Fig. 21.9), the initial rapid rise in temperature (AB) is due to the absence of a significant layer of water around the food. There is then a long period when the temperature of the food is near to that of melting ice (BC). During this period any cellular damage caused by slow freezing or recrystallisation, results in the release of cell constituents to form drip losses. This causes loss of water-soluble nutrients; for example beef loses 12% thiamine, 10% riboflavin, 14% niacin, 32% pyridoxine and 8% folic acid (Pearson *et al.*, 1951) and fruits lose 30% of the vitamin C. Details of changes to foods during thawing are described by Fennema (1975a).

In addition, drip losses form substrates for enzyme activity and microbial growth. Microbial contamination of foods, caused by inadequate cleaning or blanching (Chapters 3 and 10) has a pronounced effect during this period. In the home, food is often thawed using a small temperature difference (for example 25–40°C, compared with 50–80°C for commercial thawing). This further extends the thawing period and increases the risk of contamination by spoilage and pathogenic micro-organisms. Commercially, foods are often thawed to just below the freezing point, to retain a firm texture for subsequent processing.

Some foods are cooked immediately and are therefore heated rapidly to a temperature which is sufficient to destroy micro-organisms. Others (for example ice cream, cream and frozen cakes) are not cooked and should therefore be consumed within a short time of thawing.

When food is thawed by microwave or dielectric heaters (Chapter 18), heat is generated within the food, and the changes described above do not take place. The main considerations in thawing are:

- to avoid overheating
- to minimise thawing times
- to avoid excessive dehydration of the food.

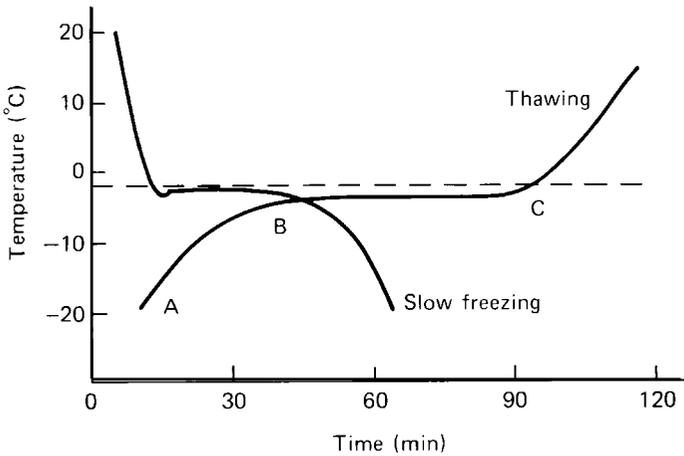


Fig. 21.9 Temperature changes during thawing.
(After Fennema and Powrie (1964).)

Commercially, foods are thawed in a vacuum chamber by condensing steam, at low temperatures by warm water (approximately 20°C) or by moist air which is recirculated over the food. Details of the types and method of operation of thawing equipment are described by Jason (1981).

21.4 Acknowledgements

Grateful acknowledgement is made for information supplied by: Air Products plc, Basingstoke, Hampshire RG24 8YP, UK; APV Jackstone Ltd, Thetford, Norfolk IP24 3RP, UK; Frigoscandia Equipment, Bedford MK42 7EF, UK; BOC Ltd, London SW19 3UF, UK; The Distillers Co. Ltd, Reigate, Surrey RH2 9QE, UK; LifeLines Technology Inc., USA.

21.5 References

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Freeze drying and freeze concentration

The advantages of dried and concentrated foods compared to other methods of preservation are described in Chapters 6, 13 and 15. The heat used to dry foods or concentrate liquids by boiling removes water and therefore preserves the food by a reduction in water activity (Chapter 1). However, the heat also causes a loss of sensory characteristics and nutritional qualities. In freeze drying and freeze concentration a similar preservative effect is achieved by reduction in water activity without heating the food, and as a result nutritional qualities and sensory characteristics are better retained. However, both operations are slower than conventional dehydration, evaporation or membrane concentration. Energy costs for refrigeration are high and, in freeze drying, the production of a high vacuum is an additional expense. This, together with a relatively high capital investment, results in high production costs for freeze-dried and freeze-concentrated foods. Nijhuis (1998) has reviewed the relative costs of freeze drying and radio frequency drying (Chapter 18). Freeze drying is the more important operation commercially and is used to dry expensive foods which have delicate aromas or textures (for example coffee, mushrooms, herbs and spices, fruit juices, meat, seafoods, vegetables and complete meals for military rations or expeditions) for which consumers are willing to pay higher prices for superior quality. In addition, microbial cultures for use in food processing (Chapter 7) are freeze dried for long-term storage prior to inoculum generation. Freeze concentration is not widely used in food processing but has found some applications such as pre-concentrating coffee extract prior to freeze drying, increasing the alcohol content of wine and preparation of fruit juices, vinegar and pickle liquors.

22.1 Freeze drying (lyophilisation)

The main differences between freeze drying and conventional hot air drying are shown in Table 22.1.

Table 22.1 Differences between conventional drying and freeze drying

Conventional drying	Freeze drying
Successful for easily dried foods (vegetables and grains)	Successful for most foods but limited to those that are difficult to dry by other methods
Meat generally unsatisfactory	Successful with cooked and raw meats
Temperature range 37–93°C	Temperatures below freezing point
Atmospheric pressures	Reduced pressures (27–133 Pa)
Evaporation of water from surface of food	Sublimation of water from ice front
Movement of solutes and sometimes case hardening	Minimal solute movement
Stresses in solid foods cause structural damage and shrinkage	Minimal structural changes or shrinkage
Slow, incomplete rehydration	Rapid complete rehydration
Solid or porous dried particles often having a higher density than the original food	Porous dried particles having a lower density than original food
Odour and flavour frequently abnormal	Odour and flavour usually normal
Colour frequently darker	Colour usually normal
Reduced nutritional value	Nutrients largely retained
Costs generally low	Costs generally high, up to four times those of conventional drying

22.1.1 Theory

The first stage of freeze drying is to freeze the food in conventional freezing equipment. Small pieces of food are frozen rapidly to produce small ice crystals and to reduce damage to the cell structure of the food (Chapter 21). In liquid foods, slow freezing is used to form an ice crystal lattice, which provides channels for the movement of water vapour. The next stage is to remove water during subsequent drying and hence dry the food.

If the water vapour pressure of a food is held below 4.58 Torr (610.5 Pa) and the water is frozen, when the food is heated the solid ice sublimates directly to vapour without melting (Fig. 22.1). The water vapour is continuously removed from the food by keeping the pressure in the freeze drier cabinet below the vapour pressure at the surface of the ice, removing vapour with a vacuum pump and condensing it on refrigeration coils. As drying proceeds a sublimation front moves into the frozen food, leaving partly dried food behind it.

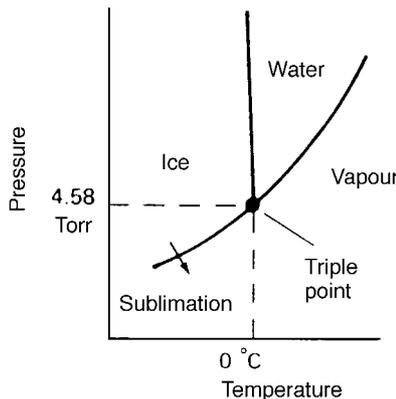


Fig. 22.1 Phase diagram for water showing sublimation of ice.

The heat needed to drive the sublimation front (the latent heat of sublimation) is either conducted through the food or produced in the food by microwaves (Chapter 18). Water vapour travels out of the food through channels formed by the sublimed ice and is removed. Foods are dried in two stages: first by sublimation to approximately 15% moisture content and then by evaporative drying (desorption) of unfrozen water to 2% moisture content. Desorption is achieved by raising the temperature in the drier to near ambient temperature whilst retaining the low pressure.

In some liquid foods (for example fruit juices and concentrated coffee extract), the formation of a glassy vitreous state on freezing causes difficulties in vapour transfer. Therefore the liquid is either frozen as a foam (vacuum puff freeze drying), or the juice is dried together with the pulp. Both methods produce channels through the food for the vapour to escape. In a third method, frozen juice is ground to produce granules, which both dry faster and allow better control over the particle size of the dried food.

The rate of drying depends mostly on the resistance of the food to heat transfer and to a lesser extent on the resistances to vapour flow (mass transfer) from the sublimation front (Fig. 22.2).

Rate of heat transfer

There are three methods of transferring heat to the sublimation front.

1. Heat transfer through the frozen layer (Fig. 22.2(a)).
The rate of heat transfer depends on the thickness and thermal conductivity of the ice layer. As drying proceeds, the thickness of the ice is reduced and the rate of heat transfer increases. The heater surface temperature is limited to avoid melting the ice.
2. Heat transfer through the dried layer (Fig. 22.2(b)).
The rate of heat transfer to the sublimation front depends on the thickness and area of the food, the thermal conductivity of the dry layer and the temperature difference between the surface of the food and ice front. At a constant cabinet pressure the temperature of the ice front remains constant. These factors are discussed in detail in Chapter 1 and related in equation (1.12). The dried layer of food has a very low thermal conductivity (similar to insulation materials (Chapter 1, Table 1.5)) and therefore offers a high resistance to heat flow. As drying proceeds, this layer becomes thicker and the resistance increases. As in other unit operations, a reduction in the size or thickness of food and an increase in the temperature difference increase the rate of heat transfer. However, in freeze drying, the surface temperature is limited to 40–65°C, to avoid denaturation of proteins and other chemical changes that would reduce the quality of the food.
3. Heating by microwaves (Fig. 22.2(c)).
Heat is generated at the ice front, and the rate of heat transfer is not influenced by the thermal conductivity of ice or dry food, or the thickness of the dry layer. However, microwave heating is less easily controlled (Chapter 18) and there is a risk of localised runaway overheating if any ice is melted.

Rate of mass transfer

When heat reaches the sublimation front, it raises the temperature and the water vapour pressure of the ice. Vapour then moves through the dried food to a region of low vapour pressure in the drying chamber. 1 g of ice forms 2 m³ of vapour at 67 Pa and, in commercial freeze drying, it is therefore necessary to remove several hundred cubic

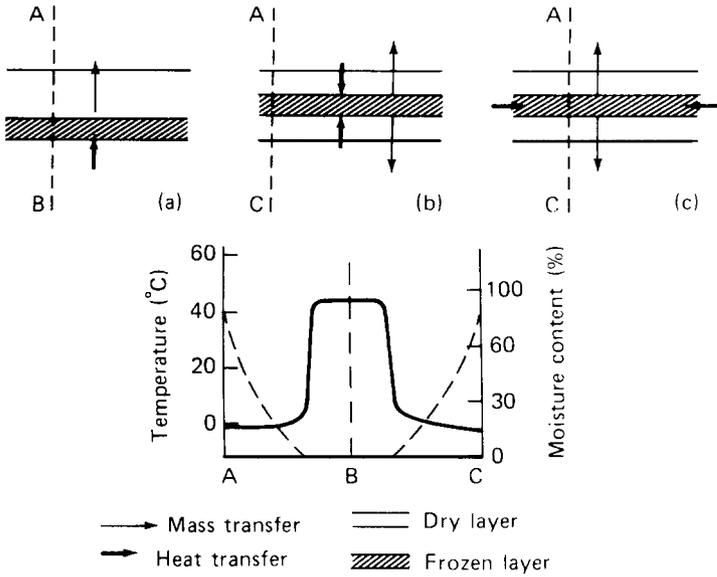


Fig. 22.2 Heat and moisture transfer during freeze drying: (a) heat transfer through the frozen layer; (b) heat transfer from hot surfaces or radiant heaters through the dry layer; (c) heat generated in the ice by microwaves. The graphs show changes in temperature (- -) and moisture content (—) along the line A→B→C through each sample.

metres of vapour per second through the pores in the dry food. The factors that control the water vapour pressure gradient are:

- the pressure in the drying chamber
- the temperature of the vapour condenser, both of which should be as low as economically possible
- the temperature of ice at the sublimation front, which should be as high as possible, without melting.

In practice, the lowest economical chamber pressure is approximately 13 Pa and the lowest condenser temperature is approximately -35°C .

Theoretically the temperature of the ice could be raised to just below the freezing point. However, above a certain critical *collapse temperature* (Table 22.2) the

Table 22.2 Collapse temperatures for selected foods in freeze drying

Food	Collapse temperature ($^{\circ}\text{C}$)
Coffee extract (25%)	-20
Apple juice (22%)	-41.5
Grape juice (16%)	-46
Tomato	-41
Sweetcorn	-8 to -15
Potato	-12
Ice cream	-31 to -33
Cheddar cheese	-24
Fish	-6 to -12
Beef	-12

Adapted from Bellows and King (1972) and Fennema (1996).

concentrated solutes in the food are sufficiently mobile to flow under the forces operating within the food structure. When this occurs, there is an instantaneous irreversible collapse of the food structure, which restricts the rate of vapour transfer and effectively ends the drying operation. In practice, there is therefore a maximum ice temperature, a minimum condenser temperature and a minimum chamber pressure, and these control the rate of mass transfer.

During drying, the moisture content falls from the initial high level in the frozen zone to a lower level in the dried layer (Fig. 22.2), which depends on the water vapour pressure in the cabinet. When heat is transferred through the dry layer, the relationship between the pressure in the cabinet and the pressure at the ice surface is:

$$P_i = P_s + \frac{k_d}{b\lambda_s}(\theta_s - \theta_i) \quad \boxed{22.1}$$

where P_i (Pa) is the partial pressure of water at the sublimation front, P_s (Pa) the partial pressure of water at the surface, k_d ($\text{W m}^{-1} \text{K}^{-1}$) the thermal conductivity of the dry layer, b ($\text{kg s}^{-1} \text{m}^{-1}$) the permeability of the dry layer, λ_s (J kg^{-1}) the latent heat of sublimation, θ_s ($^{\circ}\text{C}$) the surface temperature and θ_i ($^{\circ}\text{C}$) the temperature at the sublimation front ($^{\circ}\text{C}$). The factors that control the drying time are described by Karel (1974).

$$t_d = \frac{x^2 \rho (M_1 - M_2) \lambda_s}{8 k_d (\theta_s - \theta_i)} \quad \boxed{22.2}$$

where t_d (s) is the drying time, x (m) the thickness of food, ρ (kg m^{-3}) the bulk density of dry food, M_1 the initial moisture content and M_2 the final moisture content in dry layer. Note that drying time is proportional to the square of the food thickness: doubling the thickness will therefore increase the drying time by a factor of four.

Sample problem 22.1

Food with an initial moisture content of 400% (dry-weight basis) is poured into 0.5 cm layers in a tray placed in a freeze drier operating at 40 Pa. It is to be dried to 8% moisture (dry-weight basis) at a maximum surface temperature of 55°C . Assuming that the pressure at the ice front remains constant at 78 Pa, calculate (a) the drying time and (b) the drying time if the layer of food is increased to 0.9 cm and dried under similar conditions. (Additional data: the dried food has a thermal conductivity of $0.03 \text{ W m}^{-1} \text{K}^{-1}$, a density of 470 kg m^{-3} , a permeability of $2.4 \times 10^{-8} \text{ kg s}^{-1}$, and the latent heat of sublimation is $2.95 \times 10^3 \text{ kJ kg}^{-1}$.)

Solution to Sample problem 22.1

(a): From equation (22.1),

$$78 = 40 + \frac{0.03}{2.4 \times 10^{-8} \times 2.95 \times 10^6} (55 - \theta_i)$$

$$78 = 40 + 0.42(55 - \theta_i)$$

Therefore,

$$\theta_i = -35.7^{\circ}\text{C}$$

From equation (22.2),

$$t_d = \frac{(0.005)^2 470(4 - 0.08) 2.95 \times 10^6}{8 \times 0.03[55 - (-35.7)]}$$

$$= 6238.5 \text{ s}$$

$$\approx 1.7 \text{ h}$$

(b): From equation (22.2),

$$t_d = \frac{(0.009)^2 470(4 - 0.08) 2.95 \times 10^6}{8 \times 0.03[55 - (-35.7)]}$$

$$= 20224 \text{ s}$$

$$\approx 5.6 \text{ h}$$

Therefore increasing the thickness of the layer of food from 0.5 to 0.9 cm results in an increase of 3.9 h to the drying time.

22.1.2 Equipment

Freeze driers consist of a vacuum chamber which contains trays to hold the food during drying, and heaters to supply latent heat of sublimation. Refrigeration coils are used to condense the vapours directly to ice (i.e. reverse sublimation). They are fitted with automatic defrosting devices to keep the maximum area of coils free of ice for vapour condensation. This is necessary because the major part of the energy input is used in refrigeration of the condensers, and the economics of freeze drying are therefore determined by the efficiency of the condenser:

$$\text{efficiency} = \frac{\text{temperature of sublimation}}{\text{refrigerant temperature in the condenser}}$$

22.3

Vacuum pumps remove non condensible vapours. Different types of drier are characterised by the method used to supply heat to the surface of the food. Conduction and radiation types are used commercially (convection heating is not important in the partial vacuum of the freeze drier cabinet) and microwave freeze drying is also now used. Both batch and continuous versions are found for each type of drier. In batch drying, the product is sealed into the drying chamber, the heater temperature is maintained at 100–120°C for initial drying and then gradually reduced over a drying period of 6–8 hours. The precise drying conditions are determined for individual foods, but the surface temperature of the food does not exceed 60°C. In continuous freeze drying, trays of food enter and leave the drier through vacuum locks. A stack of trays, interspersed by heater plates is moved on guide rails through heating zones in a long vacuum chamber. Heater temperatures and product residence times in each zone are pre-programmed for individual foods, and microprocessors are used to monitor and control process time, temperature and pressure in the chamber, and the temperature at the product surface (also Chapter 2). Further details of freeze drying equipment are given by Lorentzen (1981).

Contact (or conduction) freeze driers

Food is placed onto ribbed trays which rest on heater plates (Fig. 22.3(a)). This type of equipment dries more slowly than other designs because heat is transferred by conduction

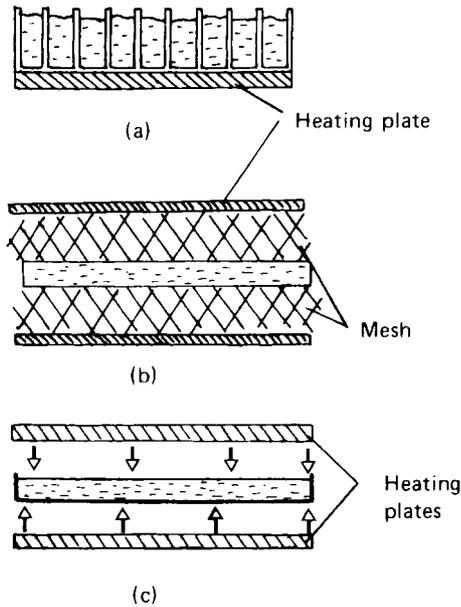


Fig. 22.3 Freeze-drying methods: (a) conduction through ribbed tray; (b) expanded mesh for accelerated freeze drying; (c) radiant heating of flat trays. (After Rolfgaard (1987).)

to only one side of the food. There is uneven contact between the frozen food and the heated surface, which further reduces the rate of heat transfer. There is also a pressure drop through the food which results in differences between the drying rates of the top and bottom layers. The vapour velocity is of the order of 3 m s^{-1} and fine particles of product may be carried over in the vapour and lost. However, contact freeze driers have higher capacity than other types.

Accelerated freeze driers

In this equipment, food is held between two layers of expanded metal mesh and subjected to a slight pressure on both sides (Fig. 22.3(b)). Heating is by conduction, but heat is transferred more rapidly into food by the mesh than by solid plates, and vapour escapes more easily from the surface of the food. Both mechanisms cause a reduction in drying times compared with contact methods.

Radiation freeze driers

Infrared radiation from radiant heaters (Chapter 18) is used to heat shallow layers of food on flat trays (Fig. 22.3(c)). Heating is more uniform than in conduction types, because surface irregularities on the food have a smaller effect on the rate of heat transfer. There is no pressure drop through the food and constant drying conditions are therefore created. Vapour movement is approximately 1 m s^{-1} and there is little risk of product carryover. Close contact between the food and heaters is not necessary and flat trays are used, which are cheaper and easier to clean.

Microwave and dielectric freeze driers

Radio frequency heaters have potential use in freeze drying but are not widely used on a commercial scale. They are difficult to control because water has a higher loss factor than



Fig. 22.4 Porous structure of freeze-dried food.

ice and any local melting of the ice causes 'runaway' overheating in a chain reaction (Chapter 18).

A modification of freeze drying is named *reversible freeze-dried compression*. Food is freeze dried to remove 90% of the moisture and it is then compressed into bars using a pressure of 69 000 kPa. The residual moisture keeps the food elastic during compression, and the food is then vacuum dried. When packaged in inert gas these foods are reported to have a shelf life of five years. They are used in military rations (for example a meal consisting of separate bars of pepperoni, stew, granola dessert and an orange drink). The bars reconstitute rapidly, during which time the compressed food 'groans, rumbles, quivers and eventually assumes its normal shape and size' (Unger, 1982).

22.1.3 Effect on foods

Freeze-dried foods have a very high retention of sensory characteristics and nutritional qualities and a shelf life of longer than 12 months when correctly packaged. Volatile aroma compounds are not entrained in the water vapour produced by sublimation and are trapped in the food matrix. As a result, aroma retention of 80–100% is possible. Theories of volatile retention are discussed in detail by Karel (1975) and Mellor (1978).

The texture of freeze-dried foods is well maintained; there is little shrinkage and no case hardening (Chapter 15). The open porous structure (Fig. 22.4) allows rapid and full rehydration, but it is fragile and requires protection from mechanical damage. There are only minor changes to proteins, starches or other carbohydrates. However, the open porous structure of the food may allow oxygen to enter and cause oxidative deterioration of lipids. Food is therefore packaged in an inert gas (Chapter 20). Changes in thiamin and ascorbic acid content during freeze drying are moderate and there are negligible losses of other vitamins (Table 22.3). However, losses of nutrients due to preparation procedures,

Table 22.3 Vitamin losses during freeze drying

Food	Loss (%)						
	Vitamin C	Vitamin A	Thiamin	Riboflavin	Folic acid	Niacin	Pantothenic acid
Beans (green)	26–60	0–24	–	0	–	10	–
Peas	8–30	5	0	–	–	0	10
Orange juice	3	3–5	–	–	–	–	–
Beef	–	–	2	0	+	0	13
Pork	–	–	< 10	0	–	0	56

+, apparent increase.

Adapted from Flink (1982).

especially blanching of vegetables, may substantially affect the final nutritional quality of a freeze-dried food.

22.2 Freeze concentration

Freeze concentration of liquid foods involves the fractional crystallisation of water to ice and subsequent removal of the ice. This is achieved by freezing, followed by mechanical separation techniques (Chapter 6) or washing columns. Freeze concentration comes closest to the ideal of selectively removing water from a food without alteration of other components. In particular, the low temperatures used in the process cause a high retention of volatile aroma compounds. However, the process has high refrigeration costs, high capital costs for equipment required to handle the frozen solids, high operating costs and low production rates, compared with concentration by boiling (Chapter 13). The degree of concentration achieved is higher than in membrane processes (Chapter 6), but lower than concentration by boiling. As a result of these limitations, freeze concentration is only used for high-value juices or extracts (Thijssen, 1982).

22.2.1 Theory

The factors that control the rate of nucleation and ice crystal growth are described in Chapter 21. In freeze concentration it is desirable for ice crystals to grow as large as is economically possible, to reduce the amount of concentrated liquor entrained with the crystals. This is achieved in a *paddle crystalliser* by slowly stirring a thick slurry of ice crystals and allowing the large crystals to grow at the expense of smaller ones (Muller, 1967). Details of the effect of solute concentration and supercooling on the rate of nucleation and crystal growth are described by Thijssen (1974). Calculations of the degree of solute concentration obtained by a given reduction in the freezing point of a solution are used to produce *freezing point curves* for different products (Fig. 22.5).

The efficiency of crystal separation from the concentrated liquor is determined by the degree of clumping of the crystals, and amount of liquor entrained. Efficiency of separation is calculated using:

$$\eta_{\text{sep}} = x_{\text{mix}} \frac{x_1 - x_i}{x_1 - x_j}$$

22.4

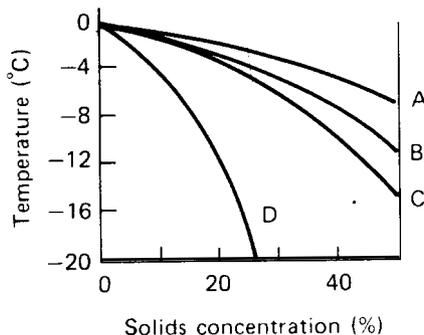


Fig. 22.5 Freezing point curves: curve A, coffee extract; curve B, apple juice; curve C, blackcurrant juice; curve D, wine.

(After Kessler (1986).)

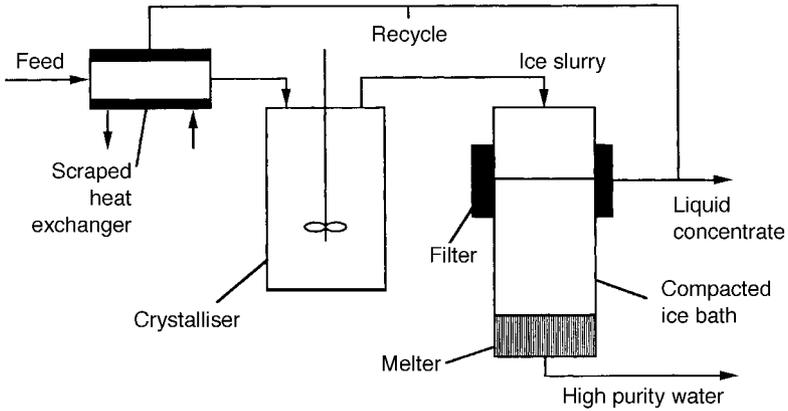


Fig. 22.6 Freeze concentration plant.
(After Rao (1989).)

where η_{sep} (%) = efficiency of separation, x_{mix} = weight fraction of ice in the frozen mixture before separation, x_1 = weight fraction of solids in liquor after freezing, x_i = weight fraction of solids in ice after separation and x_j = weight fraction of juice before freezing.

Separation efficiencies of 50% for centrifuging, 71% for vacuum filtration, 89–95% for filter pressing and 99.5% for wash columns (Section 22.2.2) are reported (Mellor, 1978).

22.2.2 Equipment

The basic components of a freeze concentration unit are shown in Fig. 22.6. These are:

- a direct freezing system (for example solid carbon dioxide) or indirect equipment (for example a scraped surface heat exchanger (Chapters 12, 13, 21)) to freeze the liquid food
- a mixing vessel to allow the ice crystals to grow
- a separator to remove the crystals from the concentrated solution.

Separation is achieved by centrifugation, filtration, filter pressing (Chapter 6) or wash columns. Wash columns operate by feeding the ice-concentrate slurry into the bottom of a vertical enclosed cylinder. The majority of the concentrate drains through the crystals and is removed. The ice crystals are melted by a heater at the top of the column and some of the melt water drains through the bed of ice crystals to remove entrained concentrate. Detailed descriptions of wash columns are given by Mellor (1978).

Concentration takes place in either single-stage or, more commonly, multi-stage equipment. Multi-stage concentrators have lower energy consumption and higher production rates. Improvements in techniques for generating large ice crystals and more efficient washing have increased the maximum obtainable concentration to 45% solids (Kessler, 1986). The energy consumption and the degree of concentration achieved by freeze concentration, in comparison with other methods of concentration, are shown in Chapter 13 (Table 13.3).

22.3 Acknowledgements

Grateful acknowledgement is made for information supplied by Atlas Industries A/S, DK-2750 Ballerup, Denmark.

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Part V

Post-processing operations

The unit operations described in preceding chapters are used to prepare foods for processing (Part II) or process them to extend their shelf life and/or alter their sensory characteristics (Parts II, III and IV). In this Part, the unit operations may be integral to previous operations (for example coating chilled or frozen foods, confectionery, etc. (Chapter 23)) or packaging foods to extend their shelf life and assist in promotion (Chapters 24 and 25). Other ancillary operations, including materials handling within a factory or warehouse, storage and distribution technologies and waste management and disposal (Chapter 26) are all critical to the success of commercial food processing.

Coating or enrobing

Coatings of batter or breadcrumbs are applied to fish, meats or vegetables, chocolate or compound coatings are applied to biscuits, cakes, confectionery and coatings of salt, sugar, flavourings or colourants are also applied to snackfoods, baked goods and confectionery. In each case, the aim is to improve the appearance and eating quality of foods, and to increase their variety. In some cases coatings also provide a barrier to the movement of moisture and gases, or protect the food against mechanical damage. Coatings are also applied to foods:

- to improve appearance
- to modify the texture
- to enhance flavours
- to improve convenience
- to increase variety and add value to basic products.

Coating operations have a minimal effect on the nutritional quality of foods, except in terms of the ingredients added to food in the coatings.

Methods of coating particles of food to encapsulate flavours or other ingredients are described by Dewettinck and Huyghebaert (1999).

There are three main methods of coating foods. The selection of an appropriate method depends on the type of coating material to be used and the intended effect of coating. The main methods are:

1. enrobing with chocolate, compound coatings, glazes or batters
2. dusting with spices, breadcrumbs, flour, sugar, flavourings, colourings, salt, etc.
3. pan coating with sugar or sugarless coatings.

23.1 Coating materials

There are two main types of coating material that are used to enrobe foods:

1. batters, breadcrumbs and powders for savoury foods and
2. chocolate, sugar or compound coatings for sweet foods such as confectionery, ice cream and baked goods.

23.1.1 Batters, powders and breadcrumbs

Batters are a suspension of flour in water to which various amounts of sugar, salt, thickening, flavourings and colourings are added to achieve the required characteristics. They are applied for example to fish, poultry and potato products. A single layer of viscous batter (termed 'Tempura') is used for products that are not subsequently breaded. A thinner, adhesive batter is applied to products prior to coating with crumb. Both are applied either by passing the product through batter using submerged mesh conveyors or by passing food pieces through one or more 'curtains' of batter in similar equipment to enrobers. Both types of equipment are fitted with air knives to remove excess batter and to control the thickness of the coating.

Typical examples of powder and crumb coatings are dry mixtures of spices, salt and flavourings applied to savoury foods, or sugar powder on sweet products, biscuits or cakes. Many of the flavour coatings, particularly barbecue dusts, are hygroscopic and require careful storage and handling in the dusting machine to prevent agglomeration and consequent depositing of large granules of dust onto the product.

Different types of crumb are available for breading fish, meat or vegetables, including wholemeal wheat or oats, sesame, and combinations of wheat, barley and rye. Maize crumb may be mixed with potato flakes to give a two-tone effect when applied to vegetables. Each are baked into a crumb with a known range of particle sizes and are flavoured or coloured if required. All are fragile and require delicate handling. Recent product developments include a fresh breadcrumb, which has a softer eating texture and enhanced colour definition, and coatings based on Asian or Oriental foods. One such example is satay, where a specially formulated coating is sprinkled onto pieces of meat or poultry and then grilled to produce a hot, spicy, peanut flavoured sauce (Marriott, 1989).

23.1.2 Chocolate and compound coatings

There are two main types of sweet coatings: chocolate and compound coatings. Chocolate manufacture is described in detail by Beckett (1994). Cocoa butter is a polymorphic fat (it crystallises in different forms or 'polymorphs'). Some forms are unstable and change from one to another if the temperature changes, resulting in a white 'bloom' on the surface of the product. There are four polymorphs:

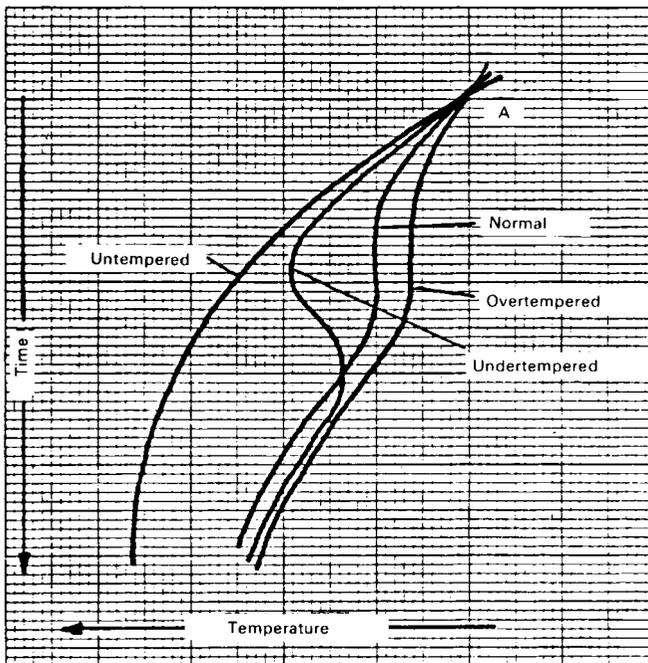
1. γ form, melting at 17°C
2. α form, melting at 21–24°C (very unstable, formed by rapid cooling of liquid fat)
3. β^1 form, melting at 27–29°C (from γ form. Unstable and most likely to be present, will slowly change back to γ form)
4. β form, melting at 34–35°C (the stable form, correct tempering should maximise this form).

It is therefore necessary to temper and cool chocolate under controlled conditions to ensure that only the stable form of cocoa butter is present. Dark chocolate is tempered by first melting it at 46–49°C and then cooling with constant stirring to 28–29°C to form nuclei for growth of predominantly β crystals, although β^1 forms are also still present. It is then reheated to 31–32°C to melt unstable β^1 crystals and it is held at that temperature during production (Minifie, 1988). Subsequent cooling is controlled so that it is not too rapid to produce only stable fat crystals and avoid the development of *bloom*. Milk chocolate is tempered at temperatures about 2°C lower than those above. If higher ratios of cocoa butter are used to make chocolate thinner, there is a greater risk of bloom formation and small amounts of lecithin (up to 0.5%) are added to reduce this risk. The

use of lecithin and other additives during enrobing is described in detail by Lees and Jackson (1973) and Talbot (1994) gives further details of chocolate tempering.

Tempering machines are either tubular or plate heat exchangers (see Chapters 11 and 13) that have accurate temperature control of the heating water. A portable 'temper meter' can be used to routinely test the state of temper of chocolate on a production line by plotting a cooling curve and comparing it to a standard for the particular type of chocolate being tested (Fig. 23.1). The first part of the curve indicates removal of sensible heat and this is followed by a change in the slope (point of inflexion) as latent heat of crystallisation is released. Differences in the angle of the initial slope and the point of inflexion can be used to assess the degree of temper.

Owing to the relatively high price of cocoa butter, a number of fats have been developed which are termed 'cocoa butter equivalents' (or CBEs) and have similar properties to cocoa butter. They are permitted at levels of up to 5% in many countries. Compound coatings are made from other fats and cannot legally be used in chocolate. These do not require tempering as the fats are not polymorphic. The principal ingredients in a compound coating are fat, sugar, corn syrup, flavourings, fat-soluble colourings and emulsifiers, which are mixed in different formulations to achieve the desired properties. Corn syrup and starch are used to reduce the sweetness and cost of coatings. The particle size of the starch has an important effect on the texture and is closely controlled. The thickness of a coating is controlled by the fat content (more fat produces a lower viscosity), and the type and amount of emulsifier (Appendix C). The ratios of sugar, starch and fat are carefully controlled to achieve the required flow characteristics for application of the coating and the desired mouthfeel and taste in the final product. An



Cooling curves

Fig. 23.1 Temper graph.
(Courtesy of Baker Perkins Ltd.)

example of the use of compound coatings is on cakes, such as Swiss roll, where the coating is more flexible than chocolate and will not chip off.

23.2 Enrobers

There are two types of enrober: in the ‘submerger’ type, food passes through batter on a stainless steel wire conveyor, held below the surface by a second mesh belt. In the second type, foods pass beneath a single or double curtain of hot liquid coating (Fig. 23.2). The coating is applied:

- by passing it through a slit in the base of a reservoir tank
- over the edge of the tank (spillway enrobers)
- by coating rollers.

A pan beneath the conveyor collects the excess coating and a pump recirculates it through a heater, back to the enrobing curtain. Excess coating is removed by air knives, shakers, licking rolls and ‘anti-tailer’ rollers to give a clean edge to the product. Discs, rollers or wires may be used to decorate the surface of the coating. A more detailed description of enrobers is given by Nelson (1994).

When enrobing products in chocolate, a separate first stage is termed ‘pre-bottoming’, in which the centres (e.g. peanuts) are passed on a wire belt through tempered chocolate.

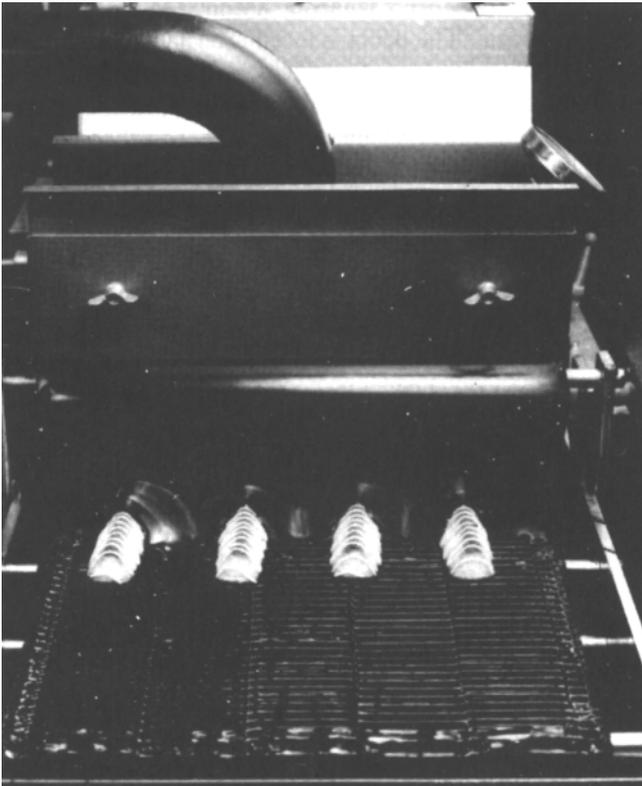


Fig. 23.2 Enrober.
(Courtesy of Sollich Ltd.)

The pre-bottomed centre then passes over a cooling plate to partially set the chocolate before passing through an enrober. This ensures that there is a sufficiently thick coating on the base of each centre to prevent it sinking through the chocolate. The centre is thus protected by the chocolate from moisture pickup or loss. The type and composition of centres can have a significant effect on the shelf life of enrobed confectionery. For example, centres should not be hotter than the enrobing temperature as this will cause a loss of temper. Nut centres should be sealed to prevent nut oil seeping into the casing and causing bloom formation (Lees and Jackson, 1973).

After enrobing, the coating is cooled by recirculated air in a cooling tunnel. Latent heat of crystallisation is removed from the product to prevent fat crystals from re-melting and coated foods are then held at 22°C for 48 h to allow fat crystallisation to continue (Matz, 1972). Temperature zones are used to cool the product rapidly but not too rapidly to cause overcooling which in chocolate would produce surface bloom. The thickness of the coating is determined by:

- the temperature of both the food and the coating
- the viscosity of the coating
- the speed of the air in air blowers
- the rate of cooling.

23.3 Dusting or breading

Dusting or breading equipment consists of a hopper fitted with a mesh base, located over a conveyor. The mesh screen is changeable for different types of crumb, seasoning, flavourings, etc. In breading, foods that are coated with a thin batter (Section 23.1) pass on a stainless steel wire belt through a bed of breadcrumbs to coat the base and then through a curtain of crumb to coat the upper surface. Excess material is collected and conveyed back to the hopper by an auger or an elevator (Chapter 26).

Most coatings and dusts can be readily recirculated, but care is needed when handling crumbs to avoid damage and changes to the average particle size. Breaded foods are gently pressed between ‘tamping’ rollers to drive the crumb into the batter and to absorb batter into the material to create a strong bond. Excess crumb is removed by air knives and reused. After breading, the products are then frozen (Chapter 21) or fried and chilled (Chapters 17 and 19). Similar designs of applicator are used to coat confectionery and baked goods with sugar, flaked nuts or dried fruits.

In another design of coating equipment, a rotating stainless steel drum, slightly inclined from the horizontal, is fitted internally with angled flights or ribs to tumble the food gently and to coat all surfaces with seasoning. The angle and speed of rotation are adjusted to control the product throughput. Similar equipment is used for spraying products with oil or liquid flavourings. In other designs, flavours or salt are blown directly into the drum by compressed air. Fluidised beds and Torbed equipment (Chapter 15) are also used as flavour applicators.

23.4 Pan coating

Panning is the process of building up in a controlled way layers of sugar, sweetener or chocolate coating on cores of fondant, fruit, nuts, etc., using a revolving copper or

stainless steel pan. These products are characterised by a smooth, regular surface obtained by the polishing action in the pan. Panning is a slow process involving small batches, but with automatic operation one operator can monitor a bank of ten or more pans. Pan speeds vary according to the size of the centre: large nuts for example requiring speeds of 15 rpm and sugar grains ('hundreds and thousands') speeds of 30–35 rpm. Air at 35–65°C is blown into the pan to give rapid drying of sugar layers, to remove dust and to remove frictional heat. During panning, the pieces are periodically removed and sieved to remove waste and break up any clumps. Additionally a small block of smooth wood in the pan helps to prevent clumping. There are three main types of pan-coated products, depending on the type of coating used.

23.4.1 Hard coatings

Centres are coated with a sweetener solution (termed 'wetting') which is added at a rate of 10–15% of the weight of the centres. This crystallises in successive layers and a hard coating is built up around the centres (termed 'engrossing'). If nuts are used, they should first be sealed with gum arabic/wheat flour mixture to prevent oil seepage during storage. Coatings are traditionally made from 60–65% sucrose or dextrose syrups. More recently sugarless coatings have been made from sorbitol syrup, described in detail by Le Bot (1993). Flavouring is added to each charge of wetting syrup and colouring is added in increasing concentration to the last five or six wettings. Cornflour may be added after each wetting to reduce sticking of the pieces but over-use results in agglomeration of the product. Separate glass-lined polishing pans are located away from the humid conditions in a pan room and are kept free of dust. Beeswax, paraffin oil or canauba wax are used to coat polishing pans and to shine hard pan products. Alternatively, they may be glazed using a mixture of shellac in isopropanol.

23.4.2 Soft coatings

Complex mixtures of liquid syrup and crystalline sugar are prepared as the centres for soft-coated confectionery such as jelly beans, 'Dolly Mixtures', etc. Because of the use of anti-crystallising agents in the liquid phase, the outer layers will only partially crystallise when added during pan-coating. Successive wettings of 60% glucose syrup are therefore followed by addition of fine castor sugar until the surfaces dry and produce an amorphous soft coating. The hardness of the coating is determined by the ratio of anti-crystallising agents in the syrup. The process should be stopped after two or three stages and the partially coated centres removed and allowed to dry for 2–3 hours. The final coating is dried using icing sugar and the products are then dried for two days at 20°C in a dust-free room (Lees and Jackson, 1973). Sugarless soft coatings made from sorbitol, mannitol, maltitol and xylitol are described by Le Bot (1993).

23.4.3 Chocolate coating

This type of panning is similar to that used for hard coatings. Pans are rotated at around 20 rpm and held at 16°C for plain chocolate and 14°C for milk chocolate. Tempered chocolate may be poured or spray-coated onto confectionery centres with successive layers being built up and finished with a hard glaze, or polished with a 50% solution of gum arabic. A summary of the properties of this and other hydrocolloids used in confectionery is shown in Table 23.1.

Table 23.1 Some characteristics of hydrocolloids used in confectionery products

	Agar	Gelatin	Gum arabic	Pectin	Starch
Characteristic/ source	From red seaweed	From animal tissues	From tree products	From apple pomace or citrus peel	From maize
Usage levels in confectionery products	1–2	6–10	20–50	1–2	10–30
Solubilisation temperature (°C)	90–95	50–60	20–25	70–85	70–85
Setting temperature (°C)	35–40	30–35	20–35	75–85	20–35
Setting time (h)	12–16	12–16	24	1	12
Textural characteristics	short, tender	elastic, firm	very firm	short, tender, clean bite	soft to firm, chewy
Can be used in combination with	starch, gelatin	pectin, starch, gum arabic	starch, gelatin	starch, gelatin	gelatin, gum arabic, pectin

From Carr *et al.* (1995).

23.5 Acknowledgements

Grateful acknowledgement is made for information supplied by: Coat and Fry Ltd, Derby DE2 8JD, UK; Allen Machinery Systems, Stourbridge, West Midlands DY9 7NB, UK; Baker Perkins Ltd, Peterborough PE3 6TA, UK; Torrftech Ltd, Mortimer, Reading, Berkshire RG7 3PG, UK; Interfood Ltd, Hemel Hempstead, Hertfordshire HP2 7DU, UK; Robinson's of Derby, Derby DE2 6JL, UK; Sollich GmbH and Co. KG, D-4902 Bad Salzuflen, West Germany; Sandvik Jahn, Huntingdon PE18 7EW, UK; Neilsen Ltd, c/o Robinson's of Derby Ltd, Derby DE2 6JL, UK; MOPA S.r.l., 1-44044 Cassana (FE), Italy; Spray Dynamics, Costa Mesa, CA, USA.

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Packaging

Packaging is an important part of all food processing operations and with some (for example canning (Chapter 12) and MAP (Chapter 20)), it is integral to the operation itself. There have been substantial developments in both materials and packaging systems over the last ten years, which have been instrumental in both reducing packaging costs and the development of novel and minimally processed foods (Chapters 9, 19 and 20). Packaging may be defined in terms of its protective role as in 'packaging is a means of achieving safe delivery of products in sound condition to the final user at a minimum cost' or it can be defined in business terms as 'a techno-economic function for optimising the costs of delivering goods whilst maximising sales and profits'.

The functions of packaging are:

- containment – to hold the contents and keep them secure until they are used
- protection – against mechanical and environmental hazards encountered during distribution and use
- communication – to identify the contents and assist in selling the product. Shipping containers should also inform the carrier about the destination and any special handling or storage instructions. Some packages inform the user about method of opening and/or using the contents
- machinability – to have good performance on production lines for high speed filling, closing and collating (1000 packs per min or more), without too many stoppages
- convenience – throughout the production, storage and distribution system, including easy opening, dispensing and/or after-use retail containers for consumers (Paine, 1991).

The main marketing considerations for a package are:

- the brand image and style of presentation required for the food
- flexibility to change the size and design of the containers
- compatibility with methods of handling and distribution, and with the requirements of retailers.

The package should be aesthetically pleasing, have a functional size and shape, retain the food in a convenient form for the customer without leakage, possibly act as a

dispenser which opens easily and recloses securely, and be suitable for easy disposal, recycling or re-use. The package design should also meet any legislative requirements concerning labelling of foods.

The factors that influence the success of a package in advertising a product have been described by Head and Stewart (1989) using the acronym SCIDASL:

- Standout
- Content identification
- Imagery
- Distinctiveness
- Adaptability
- Suitability
- Legality

The most important of these is standout – the ability of a pack to compete with up to 6000 similar products, each vying for the attention of the consumer. Others, such as correct imagery, distinctiveness and suitability are each important to create, build and sustain an image for the product that is different from its competitors. Details of the advertising and promotional functions of packaging are given by Paine (1991).

The technical factors that should be taken into account when selecting a packaging material for a particular product are described by Briston (1988). The requirements of packaging to protect foods for their expected shelf life are discussed in more detail in Section 24.1. The shelf life of packaged foods is controlled by the properties of the food (including water activity, pH, susceptibility to enzymic or microbiological deterioration and the requirement for, or sensitivity to, oxygen, light, carbon dioxide and moisture) and the barrier properties of the package. A summary of the packaging requirements of selected food groups is shown in Table 24.1.

Packaging materials can be grouped into two main types:

1. *Shipping containers* which contain and protect the contents during transport and distribution, but have no marketing function. Corrugated fibreboard cases are the most widely used shipping container for 5–20 kg loads, although they are steadily being replaced by shrinkwrapped or stretch wrapped corrugated trays. Other types of shipping containers include wooden or metal cases, crates, barrels, drums and sacks. More recently, *intermediate bulk containers* (IBCs), including combi-bins, large boxes made from metal, plastic or corrugated fibreboard, and large bags made from woven plastic fabric, have been introduced to increase handling efficiencies and have largely displaced wooden crates and cases (see also Section 24.1.5 and Chapter 26). IBCs have a capacity between that of a bulk road tanker and 220 l drums (e.g. 1000 l containers with integral pallet and bottom discharge valve), and are mainly used for powders and liquids. Many shipping containers are expensive and therefore made to be returnable (e.g. plastic crates for milk, beer and soft drink bottles). Others (for example expanded polystyrene shipping containers) provide insulation and mechanical protection for tomatoes and grapes or cured and wet fish and are used once. The requirements of shipping containers are to:
 - contain products efficiently throughout the journey
 - protect against the climate and contamination
 - be compatible with the product
 - be easily and efficiently filled and sealed
 - be easily handled

Packaging	Glass				Metal		Paper/paperboard					Plastic							
Product type	Jar	Bottle	Can	Tin/push on lid	Foil	Tube	Bag/wrap	Pot	Drum/tube	Carton ^a	Bottle	Pot	Tray/overwrap	Carton	Cellulose	LDPE/HDPE film	OPP ^b film	Laminated film	Co-extruded film
wines/spirits	*									*									
beers	*	*																	
carbonated drinks	*	*																	
Cheese spread						*					*	*							
Cooking oils		*									*								
Dairy products																			
cheese													*			*	*	*	*
butter					*		*											*	
Essences/flavours		*																	
Frozen foods																			
vegetables,																			
meat/fish products										*									
ice cream										*		*		*					
ready meals								*		*		*	*	*					
Margarine			*		*		*					*	*						
Mayonnaise	*																		
Pastes and purées																			
tomato/garlic	*		*				*												
peanut butter	*						*					*							
yeast extract	*																		
Snackfoods																			
fried, extruded																*	*	*	*
Sugar																			
confectionery ^d	*			*						*		*			*		*	*	*
chocolate	*			*	*					*		*			*		*	*	*
Sterilised foods																			
canned			*																
bottled	*	*																	
Syrups/honey	*	*		*							*								
UHT																			
milk, soups										*								*	*

^aAs outer containers, often laminated cartons with polythene and/or foil.

^bOriented polypropylene.

^cReady to eat.

^dToffee/fondant/fudge/jellies, hard boiled.

¹Perforated.

²Oxygen permeable.

From Fellows and Axtell (1993).

- remain securely closed in transit, open easily when required (e.g. customs inspection) and reclose securely
 - carry information for carriers, wholesalers, and manufacturers about contents, destination, and how to handle and open the pack.
 - have minimum cost
 - be readily disposable, re-usable or have another use.
2. *Retail containers* (or *consumer units*) which protect and advertise the food in convenient quantities for retail sale and home storage (for example metal cans, glass bottles, jars, rigid and semi-rigid plastic tubs, collapsible tubes, paperboard cartons, and flexible plastic bags, sachets and overwraps).

For convenience, this section describes both shipping and retail containers in categories that reflect their material of construction. A summary of the applications of different packaging materials to food products is shown in Table 24.1.

24.1 Theory

The main factors that cause deterioration of foods during storage are:

- climatic influences that cause physical or chemical changes (UV light, moisture vapour, oxygen, temperature changes)
- contamination (by micro-organisms, insects or soils)
- mechanical forces (damage caused by impact, vibration, compression or abrasion)
- pilferage, tampering or adulteration (Chapter 25).

Packaging provides a barrier between the food and the environment. It controls light transmission, the rate of transfer of heat, moisture and gases, and movement of micro-organisms or insects. In addition the package should not influence the product (for example by migration of toxic compounds, by reactions between the pack and the food (Section 24.4.1) or by selection of harmful micro-organisms in the packaged food (e.g. selection of anaerobic pathogens in MAP products, Chapter 20)). Other requirements of packaging are smooth, efficient and economical operation on the production line, resistance to damage such as fractures, tears or dents caused by filling and closing equipment, loading/unloading or transportation, and not least, minimum total cost.

24.1.1 Light

Light transmission is required in packages that are intended to display the contents, but is restricted when foods are susceptible to deterioration by light (for example by oxidation of lipids, destruction of riboflavin and natural pigments). The amount of light absorbed by food in a package is found using:

$$I_a = I_i T_p \frac{1 - R_f}{1 - R_f R_p} \quad \boxed{24.1}$$

where I_a (Cd) = intensity of light absorbed by the food, I_i (Cd) = intensity of incident light, T_p = fractional transmission by packaging material, R_p = the fraction reflected by the packaging material and R_f = the fraction reflected by the food.

The fraction of light transmitted by a packaging material is found using the Beer-Lambert law:

$$I_t = I_i e^{-\alpha x}$$

24.2

where I_t (Cd) = intensity of light transmitted by the packaging, α = the characteristic absorbance of the packaging material and x (m) = thickness of the packaging material.

The amount of light that is absorbed or transmitted varies with the packaging material and with the wavelength of incident light. Some materials (for example low-density polyethylene) transmit both visible and ultraviolet light to a similar extent, whereas others (for example polyvinylidene chloride) transmit visible light but absorb ultraviolet light. Pigments may be incorporated into glass containers or polymer films, they may be over-wrapped with paper labels to reduce light transmission to sensitive products (Chapter 25), or they may be printed (Section 24.3). Alternatively, clear packs may be contained in fibreboard boxes for distribution and storage.

24.1.2 Heat

The insulating effect of a package is determined by its thermal conductivity (Chapter 1) and its reflectivity. Materials which have a low thermal conductivity (for example paperboard, polystyrene or polyurethane) reduce conductive heat transfer, and reflective materials (for example aluminium foil) reflect radiant heat. However, control over the temperature of storage is more important than reliance on the packaging to protect foods from heat. In applications where the package is heated (e.g. in-container sterilisation or microwaveable ready meals), the packaging material must be able to withstand the processing conditions without damage and without interaction with the food.

24.1.3 Moisture and gases

Moisture loss or uptake is one of the most important factors that controls the shelf life of foods. There is a micro-climate within a package, which is determined by the vapour pressure of moisture in the food at the temperature of storage and the permeability of the packaging. Control of moisture exchange is necessary to prevent microbiological or enzymic spoilage, drying out or softening of the food, condensation on the inside of packages and resulting mould growth (for example in fresh vegetables and bread), or to prevent freezer burn in frozen foods (Chapter 21). The effect of changes in moisture content is shown by a water sorption isotherm of the food (Chapter 1) and this depends on the water vapour transmission rate of the package. Foods that have a low equilibrium relative humidity, such as dehydrated foods, biscuits and snackfoods, require packaging that has a low permeability to moisture or they will gain moisture from the atmosphere and lose their crispness. If the water activity rises above a level that permits microbial growth they will spoil. Similarly, foods that contain appreciable quantities of lipids or other oxygen-sensitive components are spoiled if the package has an inadequate barrier to oxygen. Conversely, fresh foods that are respiring and have a high equilibrium relative humidity, require a high degree of permeability to allow exchange of oxygen and carbon dioxide with the atmosphere, without excessive loss of moisture that would cause a loss of weight and shrivelling. Chilled foods (Chapter 19) require controlled movement of water vapour out of the pack to prevent fogging in display packs when the storage temperature changes, and foods packaged in modified atmospheres (Chapter 20) require careful control over both the gas composition and water vapour movement to achieve the expected shelf life.

Table 24.2 Selected properties of packaging films

Film	Thickness (μm)	Yield ($\text{m}^2 \text{kg}^{-1}$)	Moisture vapour transmission rate (ml m^{-2} per 24 h)		Oxygen transmission rate (ml m^{-2} per 24 h)			Barrier
			38°C	23°C	23°C	25°C	25°C	
			90% RH	85% RH	85% RH	0% RH	45% RH	
Cellulose								
Uncoated	21–40	30–18	1500–1800	400–275	25–20			10–8
Nitrocellulose coated	22–24	31–29	12–8	1.8	15–9	10–8		8–6
Polyvinylidene chloride coated	19–42	36–17	7–4	1.7		7–5.5		7–5
Metallised polyvinylidene chloride coated	21–42	31–17	5–4	0.8		3		3–2
Vinyl chloride coated			400–320	80–70				9
Polyethylene								
Low density	25–200	43–5	19–14	3000	120			8000
Stretch-wrap	17–38							
Shrink-wrap	25–200	43–11						
High density	350–1000		6.4					2000–500
Polypropylene								
Oriented	20–30	24	7–5	1.4–1.0	2200–1100			2000–1600
Biaxially oriented	20–40	55–27	7–3	1.2–0.6	1500			
Polyvinylidene chloride coated	18–34	53–30	8–4	1.4–0.6	6–10	13–6		
MG	20–40	55–27	7–4	1.4–0.6	2200–1100	2300–900		
Metallised	20–30	55–36	1.3	0.3–0.2	300–80	300		
Polyester								
Plain	12–23	59–31	40–20	8				110–53
850	12–30	60–24	40–17					120–48
Metallised			2.0–0.8					1.5–0.5
Polyvinylidene chloride coated and metallised			1.3–0.3					0.1
Polyvinylidene chloride	10–50	35–17	4–1	1.7	17–7			2

RH, relative humidity; TP, transparent.

^aWill not heat seal.

properties				Mechanical properties		Optical properties		
Nitrogen transmission rate (ml m ⁻² per 24 h)		Carbon dioxide transmission rate (ml m ⁻² per 24 h)		Tensile strength machine direction (MN m ⁻²)	Tensile strength transverse direction (MN m ⁻²)	Total light transmission (%)	Gloss (%)	Sealing temperature (°C)
25°C 0% RH	30°C 0% RH	25°C 0% RH	25°C 45% RH					
	28	40–30		33		TP	110	^a
		30–20		35		TP	130	90–130
		15		32–60		TP	150	100–130
		20–15		28–60		0	130	90–130
		30		120–130		TP		100–160
	19		40000	16–7				121–170
			8000–7000	61–24				135–170
285		3250		145–200	0.4–0.6		75–85	145
				118–260			80–85	117–124
		30–20				TP		
650–270		7000–3000		210	0.3–0.4	TP	75–85	120–145
85		900		215	0.5–0.6	0.5–3.1		120–145
25–7			500–150				87	100–200
25–10			500–200				88	100–200
1.8	0.0094	20		120–130			90	100–160

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Assuming that a packaging material has no defects (for example pinholes in can seams, or splits and poor seams in flexible films) and that there is no interaction between the material and the gas or vapour, the mass transfer rate m (usually expressed as: $\text{cm}^3 \text{m}^{-2}$ per 24 h) of gas or vapour through a packaging material is found using

$$m = \frac{bAt\Delta P}{x} \quad \boxed{24.3}$$

where b = permeability of the material, A (m^2) = the area of the material, t (h) = time, ΔP (Pa) = difference in pressure or concentration of gases between the two sides of the material and x (m) = thickness of the material.

Packaging should be sufficiently impermeable to retain desirable odours (for example in coffee or snackfoods) or prevent odour pick-up (for example by powders or fatty foods). There should also be negligible odour pickup from the plasticisers,¹ printing inks, adhesives or solvents used in the manufacture of the packaging material. Whereas glass and metal packaging is almost totally impermeable to gases and vapours, plastic films have a range of permeabilities, depending on the thickness, chemical composition and structure and orientation of molecules in the film. Plasticisers and pigments also loosen the film structure and increase its permeability. Permeability is related to both the type of film and the type of gas or vapour, and is not simply a property of the film. For example, the permeability of cellulose, nylon and polyvinyl alcohol changes with variations in humidity, owing to interaction of moisture with the film. These factors are discussed further by Pascat (1986) and Jasse (1986) and details of the mechanisms of movement of gases, vapours and flavour/odour compounds through packaging materials are described by Zobel (1988). The rate of gas or moisture transfer is found using

$$m = \frac{b\Delta P}{x} \quad \boxed{24.4}$$

Permeability is also related exponentially to temperature and it is therefore necessary to quote both the temperature and relative humidity of the atmosphere in which permeability measurements are made (Table 24.2). Methods for testing the permeability and mechanical properties of packaging materials are described by Robertson (1990), White (1990), Paine (1991) and Paine and Paine (1992).

A method to calculate the shelf life of packaged dry foods, based on the permeability of the pack, the water activity and equilibrium moisture content of the food (Chapter 1) is described by Robertson (1993), using the following equation:

$$\ln(M_e - M_i)/(M_e - M_c) = (P/X) \times (A/W_s) \times (P_o/b) \times (t_s) \quad \boxed{24.5}$$

where: M_e = equilibrium moisture content of the food, M_i = initial moisture content of the food, M_c = critical moisture content of the food, P/X = permeability of the packaging material ($\text{g water day}^{-1} \text{m}^2 (\text{mm Hg})^{-1}$), A = area of package (m^2), W_s = weight of dry solids in the food, P_o = vapour pressure of pure water at the storage temperature (Torr), b = slope of the moisture sorption isotherm ($\text{g H}_2\text{O/g solids per unit } a_w$ (Chapter 1, Fig. 1.16)) and t_s = time to the end of the shelf life (days).

The calculation of shelf life where oxygen permeability is the critical factor is found using the following equation:

$$t_s = (Q \times X)/(P \times A \times \Delta P) \quad \boxed{24.6}$$

1. Chemicals added to plastic films to make them more flexible.

where Q = the maximum quantity of oxygen that is permissible in the package (ml) and ΔP = difference between the partial pressure of oxygen inside and outside the container.

Sample problem 24.1

Potato crisps having 300 g of dry solids are to be packaged in a 0.2m^2 sealed bag made from barrier film having a water vapour transmission rate of $0.009\text{ ml day}^{-1}\text{ m}^2$. From studies of the sorption isotherm of the crisps, the equilibrium moisture content = 0.05 g per g of solids, the initial moisture content = 0.015 g per g of solids, the critical moisture content = 0.04 g per g of solids and the slope of the moisture sorption isotherm = $0.04\text{ g H}_2\text{O/g solids per units } a_w$. The crisps are expected to be stored at 20°C and the vapour pressure of pure water at the storage temperature = 17.53 Torr. Calculate the expected shelf life using this film, i.e. when the moisture content reaches the critical moisture content.

Solution to Sample problem 24.1:

Using Equation 24.5:

$$\begin{aligned} t_s &= \frac{\ln(0.05 - 0.015)/(0.05 - 0.04)}{0.009 \times (0.2/300) \times (17.53/0.04)} \\ &= \frac{1.2527}{2.6295 \times 10^{-3}} \\ &= 476.4 \text{ days (approx. 16 months)} \end{aligned}$$

24.1.4 Micro-organisms, insects, animals and soils

Metal, glass and polymer packaging materials are barriers to micro-organisms, but their seals are a potential source of contamination. Packs that are folded, stapled or twist-wrapped are not truly sealed. The main causes of microbial contamination of adequately processed foods are:

- contaminated air or water drawn through pinholes in hermetically sealed containers as the head space vacuum forms (Chapter 12)
- inadequate heat seals in polymer films caused by contamination of the seal with product or faulty heat sealer settings
- poorly sealed lids or caps
- damage such as tears or creases to the packaging material.

Processes such as heat sterilisation, irradiation and ohmic heating rely on packaging to maintain the sterility of the products. Whereas in other processes low temperatures and moisture contents or preservatives restrict microbial growth and the role of the package is less critical, although a high level of protection is still required. The effect of differences in gas permeability of packaging materials on the growth of micro-organisms is discussed by Bureau (1986). This is particularly important where low oxygen levels in a package risk selection of anaerobic pathogens (see also MAP, Chapter 20).

All types of pack should protect food from dust, and other soils that could contaminate the product. Insect infestation is prevented by metal, glass and some of the stronger flexible films (Highland, 1978), but only metal and glass containers can protect foods against rodents and birds.

24.1.5 Mechanical strength

The suitability of a package to protect foods from mechanical damage depends on its ability to withstand *crushing*, caused by stacking in warehouses or vehicles, *abrasion* caused by rubbing against equipment or during handling, *puncturing* or *fracturing* caused by impacts during handling or by *vibration* during transport. Some foods (for example fresh fruits, eggs, biscuits, etc.) are easily damaged and require a higher level of protection from a package, including cushioning using tissue paper, foamed polymer sheets, or from paperpulp that is formed into shaped containers for individual pieces (e.g. egg cartons, fruit trays). For other foods, protection is provided by a rigid container and/or restricted movement by shrink- or stretch-wrapping or by using plastic packages that are tightly formed around the product (see Chapter 25).

Wooden crates and barrels or metal drums have a long history of use as shipping containers as they provide good mechanical protection. These are now being replaced by cheaper composite intermediate bulk containers (IBCs) made from fibreboard and polypropylene. Examples of IBCs include a seamless, 6–9 ply corrugated fibreboard container, capable of withstanding 20 tonnes compression. It can be lined with a multi-ply film for liquids and, because no metal or wood is used in the construction, it is biodegradable and more easily recyclable (Anon., 1998). IBCs are claimed to carry 20% more product than drums in a given space and because they are flat when empty, save 80% on storage space. The rapid expansion in the use of polymer pots, trays and multi-layer cartons (Sections 24.2.5 and 24.2.6) has also increased the degree of protection that is available for specific foods.

The strength of polymer and paper or board materials can be assessed by measuring the stress that results from an applied force to give the following (Fig. 24.1):

- the tensile strength
- Young's modulus
- the tensile elongation
- the yield strength
- the impact strength

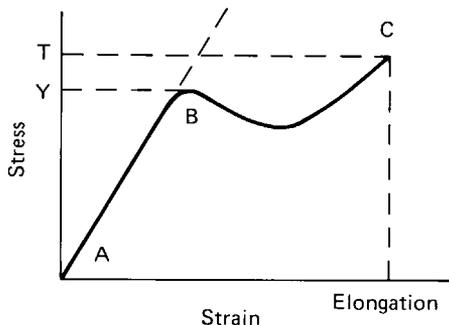


Fig. 24.1 Stress–strain curve for flexible packaging: T, tensile strength; Y, yield strength; slope of curve AB = Young's modulus; C, breaking point. (After Briston (1980).)

Table 24.3 Mechanical properties of some unoriented and bioriented polymers

	Unoriented polymer			Bioriented polymer		
	PVC	PP	PET	PVC	PP	PET
Young's modulus (kg cm ⁻²)	27–30 × 10 ³	15 × 10 ³	22 × 10 ³	30–37 × 10 ³	17–19 × 10 ³	55–95 × 10 ³
Impact strength (kg cm cm ⁻²)	200–400	200	200	1000–1500	1200–2500	2000–2500
Creep resistance ¹ (kg cm ⁻²)	200–250	150	300	400–600	200–300	700–1000

PVC: polyvinyl chloride, PP: polypropylene, PET: polyethylene terephthalate.

¹ Stress maximum allowance at 40°C.

Each of these factors is influenced by the temperature of the material and the length of time that the force is applied (Briston and Katan, 1974a). The molecular structure of polymer films may be aligned in different ways depending on the type of film and method of manufacture. Orientation of molecules in one direction (uniaxial) or in both directions (biaxial) improves the mechanical properties of some films (for example polyethylene, polypropylene, polyethylene terephthalate and polystyrene (Table 24.3)). Each of the properties described in Fig. 24.1 is therefore measured in both the axial (or machine) direction and the lateral (or transverse) direction of the film. Experimental studies are described by Jasse (1986) and examples of the tensile strength of selected films are given in Table 24.3.

24.2 Types of packaging materials

24.2.1 Textiles and wood

Textile containers have poor gas and moisture barrier properties, they are not suited to high-speed filling, have a poorer appearance than plastics and are a poor barrier to insects and micro-organisms. They are therefore only used as shipping containers or in a few niche markets as over-wraps for other packaging. Woven jute sacks (named 'burlap' in the United States), which are chemically treated to prevent rotting and to reduce their flammability, are non-slip which permits safe stacking, have a high resistance to tearing, low extensibility and good durability. Jute is a hessian type of weave (plain weave, single yarn); others include tarpaulin (double weave) and twill. They are still used to transport a variety of bulk foods including grain, flour, sugar and salt, although they are steadily being replaced by polypropylene sacks or bulk containers.

Wooden shipping containers have traditionally been used for a range of solid and liquid foods including fruits, vegetables, tea, wines, spirits and beers. They offer good mechanical protection, good stacking characteristics and a high vertical compression strength-to-weight ratio. However, polypropylene and polyethylene drums, crates and boxes have a lower cost and have largely replaced wood in many applications. The use of wood continues for some wines and spirits because the transfer of flavour compounds from the wooden barrels improves the quality of the product. Wooden tea chests are produced more cheaply than other containers in tea-producing countries and these are still widely used (Fellows and Axtell, 1993).

24.2.2 Metal

Hermetically sealed metal cans have advantages over other types of container in that they can withstand high temperature processing and low temperatures; they are impermeable to light, moisture, odours and micro-organisms to provide total protection of the contents; they are inherently tamperproof and the steel can be recycled by extraction from solid wastes. However, the high cost of metal and relatively high manufacturing costs make cans expensive. They are heavier than other materials, except glass, and therefore incur higher transport costs.

Three-piece cans

Three-piece 'sanitary' cans, consisting of a can body and two end pieces, are used to hermetically seal heat-sterilised foods (Chapter 12) and also to package powders, syrups and cooking oils. They are made from mild steel that is rolled to a strip 1.8 mm thick, and

then dipped into hot dilute sulphuric acid, cold-rolled to 0.15–0.50 mm thick, and then temper-rolled to give required hardness and surface finish. Further cold reduction produces steel with greater stiffness and so thinner sheet can be used (known as ‘double cold-reduction’ steel). Tin is applied by electroplating to a different thickness of tin coatings on each side of the steel (e.g. 2.8–1.2 g m⁻² or 0.1–0.3 mm thick). However, this produces a dull surface, due to the porous finish and it is heated quickly in a bath of hot oil or by electric induction (known as ‘flow brightening’) to slightly melt the tin and improve surface brightness and resistance to corrosion. It is then treated with chromate solution to stabilise the finish. The tin may be coated with the following lacquers to prevent interactions with foods (also Section 24.4.1):

- Epoxy-phenolic compounds are widely used, are resistant to acids, and have good heat resistance and flexibility. They are used in canned meat, fish, fruit, pasta and vegetable products. They are also coated with zinc oxide or metallic aluminium powder to prevent sulphide staining with meat, fish and vegetables.
- Vinyl compounds have good adhesion and flexibility, are resistant to acids and alkalis, but do not withstand the high temperatures used in heat sterilisation. They are used for canned beers, wines, fruit juices and carbonated beverages and as a clear exterior coating.
- Phenolic lacquers are resistant to acids and sulphide compounds and are used for canned meat or fish products, fruits, soups and vegetables.
- Butadiene lacquers prevent discolouration and have high heat resistance. They are used for beer and soft drinks.
- Acrylic lacquers are white and are used both internally and externally for fruit products. They are more expensive than other types and can cause flavour problems in some products.
- Epoxy amine lacquers are expensive, but have good adhesion, heat and abrasion resistance, flexibility and no off-flavours. They are used for beers, soft drinks, dairy products, fish and meats.
- Alkyd lacquers are low cost and used externally as a varnish over inks. They are not used internally due to off-flavour problems.
- Oleoresinous lacquers are low cost, general purpose, gold coloured coatings, used for beers, fruit drinks, and vegetables. They can incorporate zinc oxide (‘C’ enamel) for use with beans, vegetables, soups, meats and other sulphur-containing foods.

Methods of can manufacture are described in detail by Malin (1980) and are summarised in Fig. 24.2. Changes in materials and manufacturing technology have reduced the cost of cans as in the following examples (also Section 24.5):

- steel is made thinner by additional rolling in a double-reduction process
- beading (corrugations in the metal) around the can body maintains the can strength using thinner steel
- different thicknesses of tin are applied on each side of the steel (differential coating)
- welded side seams, made by forge welding or ‘lost-wire’ welding, have a better appearance and greater integrity than the traditional soldered seams
- side seams are bonded by thermoplastic polyamide (nylon) adhesives
- the tin coating is replaced by a chromium–chromium dioxide surface (tin-free steel), which has better compatibility with food products. However, external corrosion may occur if it is not protected by a lacquer.

These developments are described in detail by Malin (1980). Methods of filling and sealing cans are described in Chapter 25.

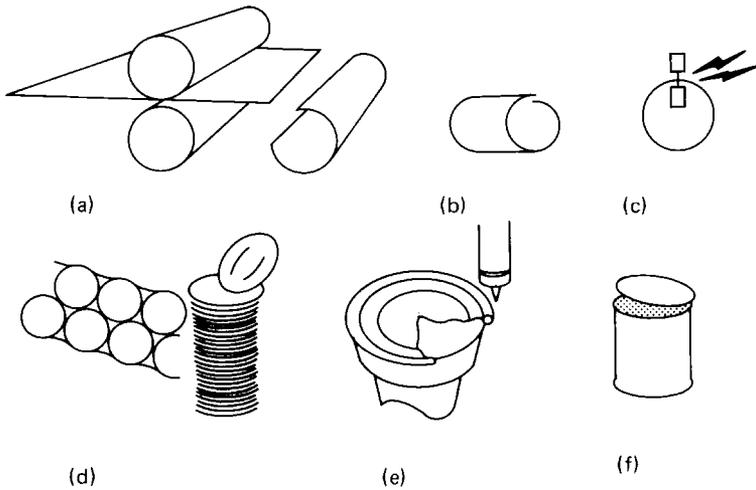


Fig. 24.2 Manufacture of three-piece electrically welded cans: (a) tinplate rolled into cylinders; (b) edges overlapped; (c) edges welded and seam lacquered; (d) base stamped out; (e) rims curled and sealing compound injected; (f) base seamed onto body.
(Courtesy of Metal Box plc.)

Two-piece cans

Two-piece aluminium cans are made by the *draw-and-wall-iron* (DWI) process or *draw-and-redraw* (DRD) process. The DWI process (Fig. 24.3) produces thinner walls than the DRD process and is used to produce aluminium cans for carbonated beverages where the gas pressure supports the container. DRD cans are thicker and are able to withstand the head-space vacuum produced during cooling after heat sterilisation (Chapter 12). The advantages of two-piece cans include greater integrity, more uniform lacquer coverage, savings in metal and greater consumer appeal.

In the DWI process a disc-shaped blank is cut and formed (drawn) into a cup. This is forced through a number of annular rings (wall ironed), to reduce the thickness of the wall metal and to increase the can height to the required extent (Fig. 24.3). The process permits good control over the wall thickness and therefore saves metal. Modifications to the basic two-piece design include:

- a reduced diameter at the neck of the can which improves the appearance and ability to stack the cans and saves metal
- ring-pull tabs or full-aperture easy-open ends for greater convenience (Chapter 25)
- computer-aided print design and abrasion-resistant inks allow the blank to be printed before the can is formed. The ink is then stretched with the metal during the DWI process, to produce the required design on the finished can.

The DRD process is similar to the initial stages of the DWI process but, instead of ironing to reduce the wall thickness, metal is moved from the base of the container to the wall by reducing the diameter of the container (Fig. 24.3). In both processes, epoxy, phenolic or vinyl-based lacquers are applied internally to prevent interactions between the metal and the product. Future developments of cans are likely to include plastic laminated thin sheet steel to produce two-piece containers, and other composite flexible materials made by electrolytic deposition of iron to produce pouches using form-fill-seal machines (Chapter 25) (Louis, 1998).

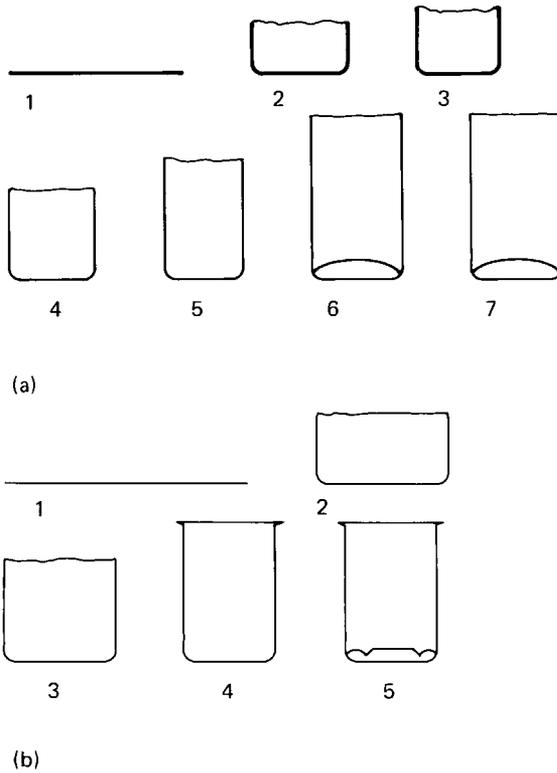


Fig. 24.3 Two-piece can manufacture: (a) DWI cans: 1, body blank; 2+3, drawn and redrawn cups; 4–6, three stages of wall ironing and base formation; 7, finished can trimmed to the required height; (b) DRD cans: 1, body blank; 2, drawn cup; 3+4, stages in re-drawn cups; 5, finished trimmed can with profiled base.

(After Malin (1980).)

Aerosol cans

Aerosol cans are two- or three-piece lacquered tinplate or aluminium cans fitted with a valve through which the product is dispensed. The propellant gas is either mixed with the product or kept separate by a plastic bag or a piston device. The pressure strength of the can should be 1.5 times the maximum vapour pressure of the filled aerosol at 55°C, with a minimum of 1 MPa. Nitrous oxide propellant is used for ultra high-temperature sterilised cream (Woollen, 1984), but other gases (for example argon, nitrogen and carbon dioxide) are approved for use with foods, including cheese spreads and oil sprays for baking pans.

Other aluminium packaging

In addition to its use in can-making, aluminium is used for foil wrappers, lids, cups and trays, laminated pouches, collapsible tubes, barrels and closures. Aluminium is the third most abundant element in the earth's crust, and is most economically recovered from bauxite (40–60% alumina (hydrated aluminium oxide)). 1 kg of aluminium can be made from about 4 kg of bauxite by dissolving the bauxite in cryolite (potassium aluminium fluoride) and applying 50 000–150 000 amps to electrolytically reduce the oxide to aluminium and oxygen. The oxygen combines with carbon of the anode to form CO₂ and the aluminium is drawn off into crucibles. Foil is produced by a cold reduction process in which pure aluminium (purity, greater than 99.4%) is passed through rollers to reduce the

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thickness to less than 0.152 mm and then annealed (heated to control its ductility) to give it dead-folding properties. The advantages of foil include:

- good appearance
- odourless and tasteless
- good dead-folding properties
- the ability to reflect radiant energy
- an excellent barrier to moisture and gases
- good weight:strength ratio
- impermeable to light, moisture, odours and micro-organisms
- high quality surface for decorating or printing
- lacquers not needed because a protective thin layer of oxide forms on the surface as soon as it is exposed to air
- can be laminated with paper or plastics
- compatible with a wide range of sealing resins and coatings for different closure systems
- has value as scrap.

A potential disadvantage of aluminium is the widely reported incompatibility with use in microwave ovens. Paine (1991) reports a study by the Aluminium Association of Washington and Aluminium Foil Containers Association of Wisconsin into the effects of aluminium packaging on the performance of microwave ovens and concluded:

- in most instances results of food heating were as good as with microwave transparent materials and in many cases heating was more uniform
- foil containers had no effect on the magnetron
- in approximately 400 tests, arcing between the foil and oven wall occurred only once.

Other tests showed that foil containers did not cause the magnetron to operate outside its allowable ratings and only in earliest microwaves, before 1969, has any damage to magnetrons occurred.

Foil is widely used for wraps (0.009 mm), bottle caps (0.05 mm) and trays for frozen and ready meals (0.05–0.1 mm). If foil is to be used to contain acid or salty foods it is normally coated with nitrocellulose. Aluminium is also used as the barrier material in laminated films, to 'metallise' flexible films (Section 24.2.4) and to make collapsible tubes for viscous products (for example tomato purée and garlic paste). Collapsible tubes are supplied pre-formed, with an internal epoxy-phenolic or acrylic lacquer, a sealed nozzle and an open end ready for filling. Aluminium tubes are preferred to polyethylene for food applications because they permanently collapse as they are squeezed, unlike plastic tubes, and thus prevent air and potential contaminants from being drawn into the part-used product. Aluminium packaging is reviewed by Severus and Wirth (1989).

24.2.3 Glass

Glass jars and bottles are made by heating a mixture of sand (73%), the main constituent being silica (99% SiO₂), broken glass or 'cullet' (15–30% of total weight), soda ash (Na₂CO₃) and limestone (CaCO₃ or CaCO₃.MgCO₃) to a temperature of 1350–1600°C. Alumina (Al₂O₃) improves the chemical durability of the glass, and refining agents reduce the temperature and time required for melting, and also help remove gas bubbles from the glass. Colourants include chromic oxide (green), iron, sulphur and carbon

(amber), and cobalt oxide (blue). Flint (clear) glass contains decolourisers (nickel and cobalt) to mask any colour produced by trace amounts of impurities (e.g. iron).

The molten glass is shaped in a mould by the *blow-and-blow process* or the *press-and-blow process* (Fig. 24.4). The 'independent section (IS)' machine is now used universally for bottle-making. Narrow neck containers are made by the blow-and-blow process in which a gob of glass at 1000°C is placed in a parison mould where a bubble is formed, and the moulding of the finish (the part that supports the closure) is done. The parison is then inverted and the body is formed by compressed air in the mould. Wide neck containers are made by press-and-blow process where gob is shaped into a parison and the finish is moulded by the upwards action of a plunger. It is then transferred for blow-moulding as in the blow-and-blow process.

When bottles leave the moulds, the temperature is about 450°C. If they were allowed to cool on their own, their low thermal conductivity (Chapter 1) would cause the inside to cool more slowly than the outside, and the different rates of contraction would cause internal stresses which would make the glass unstable. Glass is therefore *annealed* at 540–570°C to remove stresses and then cooled under carefully controlled conditions in an annealing lehr (a long (30 m) tunnel) to prevent distortion or fracturing. Details of glass manufacturing techniques are given by Osborne (1980) and Paine and Paine (1992). Paine (1991) describes developments in glass-making technology to improve the strength of glass, reduce the risk of fracturing and maintain container strength with light-weighting.

Glass containers have the following advantages:

- they are impervious to moisture, gases, odours and micro-organisms
- they are inert and do not react with or migrate into food products
- they have filling speeds comparable with those of cans
- they are suitable for heat processing when hermetically sealed

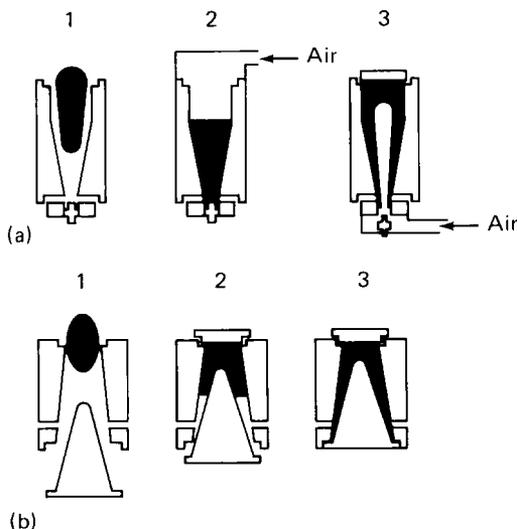


Fig. 24.4 Glass-blowing techniques: (a) blow-and-blow process: 1, gob drops into parison mould; 2, settle blow to form finish; 3, counter-blow to complete parison; (b) press-and-blow process: 1, gob drops into parison mould; 2, plunger presses parison; 3, parison completed.

(After Osborne (1980).)

Table 24.4 Relative strengths of different shaped glass containers

Container shape	Ratio of relative strengths
Cylindrical	10
Elliptical (2:1)	5
Square with round corners	2.5
Square with sharp corners	1

From Ramsland (1989).

- they are transparent to microwaves
- they are re-useable and recyclable
- they are resealable
- they are transparent to display the contents and can be decorated
- they can be moulded into a wide variety of shapes and colours
- they are perceived by the customer to add value to the product
- they are rigid, having good vertical strength to allow stacking without damage to the container.

The main disadvantages of glass include:

- higher weight which incurs higher transport costs than other types of packaging
- lower resistance than other materials to fracturing and thermal shock
- more variable dimensions than other containers
- potentially serious hazards from glass splinters or fragments in foods.

Although glass can be made into a wide variety of shapes, particularly for marketing high-value products such as liqueurs and spirits, simple cylindrical shapes are stronger and more durable (Table 24.4). Sharp corners and abrasion of glass surfaces weaken the container, and design features such as a protruding ‘shoulder’ (Fig. 24.5) which

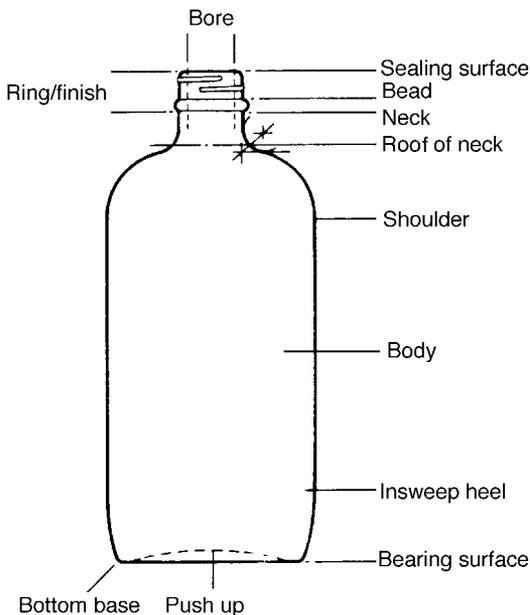


Fig. 24.5 Glass container terminology.
(From Paine (1991).)

minimises contact between containers during handling, or protection by a plastic sleeve are used to reduce the risk of damage.

Alternatively glass surfaces may be treated with titanium, aluminium or zirconium compounds to increase their strength and also enable lighter containers to be used. Developments in glass-making technology, including reductions in wall thickness (light-weighting) and computer design of containers, are described by Lomax (1987). Louis (1998) describes potential advances in glass-making technology using plasma-arc crucibles to melt raw ingredients. The molten glass could then be co-extruded in a similar way to that currently used for plastic containers to produce jars or bottles of any shape, size or thickness.

24.2.4 Flexible films

Flexible packaging describes any type of material that is not rigid, but the term 'flexible film' is usually reserved for non-fibrous plastic polymers (from Greek: *plastikos* = to form), which are less than 0.25 mm thick. The ability to shape plastics is due to long polymers formed by addition reactions (e.g. for polyethylene, the $\text{CH}_2=\text{CH}_2$ group splits at the double bond to form $\text{CH}_2-\text{CH}_2-\text{CH}_2$), or by condensation reactions (e.g. PET, where water is eliminated between ethylene glycol and terephthalic acid) to form long polymer molecules. Thermoplastic materials are able to undergo repeated softening on heating and hardening again on cooling, whereas thermosetting plastics cross-link the long molecules when heated or treated with chemicals and they do not resoften.

In general, flexible films have the following properties:

- they have relatively low cost
- they can be produced with a range of barrier properties against moisture and gases
- they are heat sealable to prevent leakage of contents, and can be laminated to paper, aluminium or other plastics
- they are suitable for high-speed filling
- they have wet and dry tensile and impact strength
- they are easy to handle and print and are convenient for the manufacturer, retailer and consumer
- they add little weight to the product and fit closely to the shape of the food, thereby wasting little space during storage and distribution.

Ranges of mechanical, optical, thermal and barrier properties are produced for each type of polymer by variation in film thickness, orientation of polymer molecules, amount and type of additives and in the type and thickness of coatings. Films may be used singly, coated with polymer or aluminium, or produced as multi-layered laminates or co-extrusions. Plasticisers are added to soften the film and to make it more flexible, especially for use in cold climates or for frozen foods. Pigments may be added to avoid the need for large areas of printing. Details of the chemical structure of films and additives are given by Briston and Katan (1974a). There are thus a very large number of possible combinations of polymer and treatment, to meet the varied requirements of foods.

Single films

Most polymer films are made by *extrusion*, in which pellets of the polymer are melted and extruded under pressure as a sheet or tube. Other methods are *callandering*, where the polymer is passed through heated rollers until the required thickness is achieved, and

casting, in which the extruded polymer is cooled on chilled rollers. The most important types of film for food packaging are described below and a selection of their properties is shown in Table 24.2.

Cellulose films are produced by mixing sulphite paper pulp (Section 24.2.5) with caustic soda to dissolve it and it is allowed to 'ripen' for 2–3 days to reduce the length of polymer chains and form sodium cellulose. This is then converted to cellulose xanthate by treatment with carbon disulphide, ripened for 4–5 days to form 'viscose', and then cellulose is regenerated by extrusion or casting into an acid–salt bath to form cellulose hydrate. Glycerol is added as a softener and the film is then dried on heated rollers. Higher quantities of softener and longer residence times in the acid–salt bath produce more flexible and more permeable films. Plain cellulose is a glossy transparent film which is odourless, tasteless and biodegradable within approximately 100 days. It is tough and puncture resistant, although it tears easily. It has low-slip and dead-folding properties and is unaffected by static buildup, which make it suitable for twist-wrapping. However, it is not heat sealable, and the dimensions and permeability of the film vary with changes in humidity. It is used for foods that do not require a complete moisture or gas barrier, including fresh bread and some types of confectionery (Table 24.2). An international code is used to identify the various types of cellulose film (Table 24.5).

Oriented *polypropylene* (OPP) is a clear glossy film with good optical properties and a high tensile strength and puncture resistance. It has moderate permeability to moisture, gases and odours, which is not affected by changes in humidity. It is thermoplastic and therefore stretches, although less than polyethylene, and has low friction, which minimises static buildup and makes it suitable for high-speed filling equipment (Chapter 25). Biaxially oriented polypropylene (BOPP) has similar properties to oriented polypropylene but is much stronger. PP and OPP are used for bottles, jars, crisp packets, biscuit wrappers and boil-in-bag films among many other applications.

Polyethylene terephthalate (PET) is a very strong transparent glossy film which has good moisture and gas barrier properties. It is flexible at temperatures from -70°C to 135°C and undergoes little shrinkage with variations in temperature or humidity. There are two types of PET: amorphous (APET) which is clear, and crystalline (CPET) which is

Table 24.5 Codes for cellulose films

Code	Explanation
A	Anchored (describes lacquer coating)
/A	Copolymer coated from aqueous dispersion
B	Opaque
C	Coloured
D	Coated one side only
F	For twist wrapping
M	Moisture-proof
P	Plain (non-moisture-proof)
Q	Semi-moisture-proof
S	Heat sealable
/S	Copolymer coated from solvent
T	Transparent
U	For adhesive tape manufacture
W	Winter quality (withstands low temperatures)
X	Copolymer coated on one side
XX	Copolymer coated on both sides

opaque and used for microwave trays and semi-rigid containers, such as tubs. APET is oriented to develop the full tensile strength for bottles (e.g. carbonated drinks) or films (e.g. boil-in-bag). It has been described in detail by Turtle (1990).

Low-density *polyethylene* (LDPE) is used as a copolymer in some tubs and trays. LDPE film is heat sealable, chemically inert, odour free and shrinks when heated. It is a good moisture barrier but has a relatively high gas permeability, sensitivity to oils and poor odour resistance. Low-slip properties can be introduced for safe stacking, or conversely high-slip properties permit easy filling of packs into an outer container. It is less expensive than most films and is therefore widely used, including applications in shrink- or stretch-wrapping (Chapter 25). Stretch-wrapping uses either thinner LDPE than shrink-wrapping does (25–38 μm compared with 45–75 μm), or alternatively, linear low-density polyethylene (LLDPE) is used at thicknesses of 17–24 μm . This material has a highly linear arrangement of molecules and the distribution of molecular weights is smaller than for LDPE. It therefore has greater strength and a higher restraining force. The cling properties of both films are biased on one side, to maximise adhesion between layers of the film but to minimise adhesion to adjacent packages.

High-density polyethylene (HDPE) is stronger, thicker, less flexible and more brittle than low-density polyethylene and has lower permeability to gases and moisture. It has a higher softening temperature (121°C) and can therefore be heat sterilised. Sacks made from 0.03–0.15 mm HDPE have a high tear strength, tensile strength, penetration resistance and seal strength. They are waterproof and chemically resistant and are used instead of multi-wall paper sacks for shipping containers (Section 24.2.5). A foamed HDPE film is thicker and stiffer than conventional film and has dead-folding properties (Anon., 1980). It can be perforated with up to 80 holes cm^{-1} for use with fresh foods or bakery products. When unperforated, it is used for edible fats. Both types are suitable for shrink-wrapping.

Uncoated *polyvinylidene chloride* (PVdC) film has very good moisture, odour and gas barrier properties. It is fat resistant and does not melt in contact with hot fats, making it suitable for ‘freezer-to-oven’ foods. PVdC is also used as a coating for films and bottles to improve the barrier properties.

Polystyrene is a brittle clear sparkling film which has high gas permeability. It may be oriented to improve the barrier properties. *Rubber hydrochloride* is similar to polyvinyl chloride but becomes brittle in ultraviolet light and at low temperatures and is penetrated by some oils. *Polyvinyl chloride–vinylidene chloride* copolymer is very strong and is therefore used in thin films. It has very low gas and water vapour permeabilities and is heat shrinkable and heat sealable. However, it has a brown tint which limits its use in some applications. *Nylon* has good mechanical properties in a wide temperature range (from –60°C to 200°C). However, the film is expensive to produce, it requires high temperatures to form a heat seal, and the permeability changes at different storage humidities.

Ethylene vinyl acetate (EA) is low-density polyethylene, polymerised with vinyl acetate. It has high mechanical strength, and flexibility at low temperatures. EA is as flexible as PVC without plasticisers, has greater resilience than PVC and greater flexibility than LDPE. Ethylene vinyl acetate which contains less than 5% vinyl acetate, is used for deep-freeze applications. Films with 6–10% vinyl acetate are used in bag-in-box applications and milk pouches, and above 10% vinyl acetate the material is used as a hot-melt adhesive. *High-nitrile resins* are acrylonitrile-methyl acrylate and acrylonitrile-styrene copolymers. They are moulded to form containers which have very good barrier

properties and are used to package processed meat, cheese, margarine and peanut butter (Briston, 1987).

The properties of single films are reviewed by Driscoll and Patterson (1999), who also quote the relative costs of films as follows: PET: 1.00, HIPS: 0.82, EVOH: 1.58, Nylon: 2.00, HDPE: 0.75, PP: 0.85, LDPE: 0.70.

Coated films

Films are coated with other polymers or aluminium to improve their barrier properties or to impart heat sealability. For example, *nitrocellulose* is coated on one side of cellulose film to provide a moisture barrier but to retain oxygen permeability. A nitrocellulose coating on both sides of the film improves the barrier to oxygen, moisture and odours and enables the film to be heat sealed when broad seals are used. A *polyvinylidene chloride* coating is applied to cellulose, using either an aqueous dispersion (MXXT/A cellulose) or an organic solvent (MXXT/S cellulose). In each case the film is made heat sealable and the barrier properties are improved (Table 24.2). A coating of vinyl chloride or vinyl acetate gives a stiffer film which has intermediate permeability. Sleeves of this material are tough, stretchable and permeable to air, smoke and moisture. They are used, for example, for packaging meats before smoking and cooking.

A thin coating of aluminium (termed *metallisation*) produces a very good barrier to oils, gases, moisture, odours and light. Metallised film is less expensive and more flexible than foil laminates which have similar barrier properties, and it is therefore suitable for high-speed filling on form-fill-seal equipment (Chapter 25) (Guise, 1984). Cellulose, polypropylene or polyester are metallised by depositing vaporised aluminium particles onto the surface of a film under vacuum. The degree of metallisation is expressed in optical density units, up to a maximum of 4 units. Metallised polyester has higher barrier properties than metallised polypropylene, but polypropylene is used more widely as it is less expensive (Guise, 1987).

Laminated films

Lamination of two or more films improves the appearance, barrier properties and/or mechanical strength of a package. Commonly used laminates are described in Table 24.6 and recent developments in MAP (Chapter 20) have included laminates of nylon-LDPE, nylon-PVdC-LDPE and nylon-EVOH-LDPE for non-respiring products. The nylon provides strength to the pack, EVOH or PVdC provide the correct gas and moisture barrier properties and LDPE gives heat-sealability. PVC and LDPE are also commonly used for respiring MAP products (Smith *et al.*, 1990).

The most versatile method of lamination is *adhesive laminating* (or dry bonding) in which an adhesive is first applied to the surface of one film and dried. The two films are then pressure bonded by passing between rollers. Synthetic adhesives are mostly aqueous dispersions or suspensions of polyvinyl acetate with other compounds (e.g. polyvinyl alcohol, 2-hydroxycellulose ether) to give a wide range of properties. Two-part urethane adhesives, consisting of a polyester or polyether resin with an isocyanate cross-linking agent, are also widely used. Co-polymerised vinyl acetate and ethylene or acrylic esters give improved adhesion to plastics, to produce laminated films, and are also used for case sealing, spiral tube winding, pressure sensitive coatings and labelling of plastic bottles (Section 24.2.6). Solvent-based systems have a number of problems including environmental considerations, clean air regulations, higher cost, safety from fire hazards, toxicity and production difficulties, which mean that these are now being used only when other systems are not suitable and are likely to be phased out altogether.

Table 24.6 Selected laminated films used for food packaging

Type of laminate	Typical food application
Polyvinylidene chloride-coated polypropylene–polyvinylidene chloride-coated polypropylene	Crisps, snackfoods, confectionery, ice cream, biscuits, chocolate confectionery
Polyvinylidene chloride-coated polypropylene–polyethylene	Bakery products, cheese, confectionery, dried fruit, frozen vegetables
Polypropylene–ethylene vinyl acetate	Modified-atmosphere-packaged (Chapter 19) bacon, cheese, cooked meats
Biaxially oriented polypropylene–nylon–polyethylene	Retort pouches
Cellulose–polyethylene–cellulose	Pies, crusty bread, bacon, coffee, cooked meats, cheese
Cellulose acetate–paper–foil–polyethylene	Dried soups
Metallised polyester–polyethylene	Coffee, dried milk, bag-in-box packaging, potato flakes, frozen foods, modified-atmosphere-packaged (Chapter 19) foods
Polyethylene terephthalate aluminium–polypropylene	Retort pouches
Polyethylene–nylon	Vacuum packs for bulk fresh meat, cheese
Polyethylene–aluminium–paper	Dried soup, dried vegetables, chocolate
Nylon–polyvinylidene chloride–polyethylene–aluminium–polyethylene	Bag-in-box packaging
Nylon–medium-density ethylene–butene copolymer	Boil-in-bag packaging

The type of laminate reads from the outside to the inside of the package. All examples of polyethylene are low-density polyethylene.

Not all polymer films can be successfully laminated; the two films should have similar characteristics and the film tension, adhesive application and drying conditions should be accurately controlled to prevent the laminate from blocking (not unwinding smoothly), curling (edges of the roll curl up) or delaminating (separation of the layers).

Coextruded films

Coextrusion is the simultaneous extrusion of two or more layers of different polymers to form a single film. Coextruded films have three main advantages over other types of film:

1. they have very high barrier properties, similar to multi-layer laminates but produced at a lower cost
2. they are thinner than laminates and closer to mono-layer films and are therefore easier to use on forming and filling equipment
3. the layers cannot separate.

To achieve strong adhesion, the copolymers used in coextruded films should have similar chemical structures, flow characteristics and viscosities when melted. There are three main groups of polymers:

1. olefins (low-density and high-density polyethylene, and polypropylene)

2. styrenes (polystyrene and acrylonitrile-butadiene-styrene)
3. polyvinyl chloride polymers.

All materials in each group adhere to each other, as does acrylonitrile-butadiene-styrene with polyvinyl chloride, but other combinations must be bonded with ethylene vinyl acetate. There are two main methods of producing coextrusions: blown films and flat-sheet coextrusion.

Blown-film coextrusions are thinner than flat-sheet types and are suitable for high-speed form-fill-seal and pouch or sachet equipment (Chapter 25). Typically a three-layer coextrusion has an outside presentation layer, which has a high gloss and printability, a middle bulk layer which provides stiffness, strength and split resistance, and an inner layer which is suitable for heat sealing. These films have good barrier properties and are more cost effective than laminated films or wax-coated paper. They are used, for example, for confectionery, snackfoods, cereals and dry mixes. A five-layer coextrusion is used to replace metallised polyester for bag-in-box applications. *Flat-sheet coextrusions* (75–3000 μm thick) are formed into pots, tubs or trays (Table 24.7).

Edible and biodegradable films

Concern over environmental pollution from packaging materials (Section 24.5) has led to research into edible or biodegradable films for general food packaging and films that can be used to coat fresh fruit to control the rate of respiration. Examples of edible forming materials include corn zein (a prolamine derived from corn gluten), wheat gluten, soy protein, peanut protein, cottonseed protein, casein, milk whey proteins, alginates and collagen (Gontard *et al.*, 1992a, 1992b, and 1993 and Baldwin, 1999). Collagen casings for meat products was one of the first films. The properties of some edible films are shown in Table 24.8. Details of edible coatings and active edible coatings, including gums, waxes, oils, resins and carbohydrate-based coatings, are given by a number of authors, including Arvanitoyannis and Gorris (1999), Guilbert and Gontard (1995), Baldwin (1994 and 1999) and Debeaufort *et al.* (1998).

Development of novel polymers that biodegrade slowly has focused on thermoplastic polyesters (e.g. poly (ϵ -caprolactone), poly (ϵ -methyl-valerolactone) polylactide), α -amino acids and polyamides, and copolymerisation of lactams and lactones, as each has a low glass transition and low melting point. However, most natural polymers have mechanical properties that are inferior to synthetic materials, and this together with processing problems is restricting their widespread use. One method of overcoming these problems is to blend a natural and a synthetic polymer to improve the film properties

Table 24.7 Selected applications of flat-sheet coextrusions

Type of coextrusion	Properties	Applications
High impact polystyrene–polyethylene terephthalate		Margarine, butter
Polystyrene–polystyrene–polyvinylidene chloride–polystyrene	Ultraviolet and odour barrier	Juices, meats, milk products
Polystyrene–polystyrene–polyvinylidene chloride–polyethylene	Ultraviolet and odour barrier	Butter, cheese, margarine, coffee, mayonnaise, sauce
Polypropylene–saran–polypropylene	Retortable trays	Sterilised foods
Polystyrene–ethylene vinyl acetate–polyethylene	Modified-atmosphere packs	Meats, fruits

Table 24.8 Properties of some edible films, compared to some synthetic films

Type of film	Thickness (mm)	Conditions (°C, %RH)	Permeability (g/mm/m ² /day)
Collagen	–	23, 0	1.2
Collagen		23, 63	23.3
Collagen		23, 93	890
Zein:glycerin	0.10–0.31	30, 0	13.0–44.9
Gluten:glycerin	0.23–0.42	30, 0	9.6–24.2
AM:gluten:glycerin	0.066	23, 0	2.67
Soy protein isolate:glycerin	0.064–0.089	25, 0	4.75
Whey protein:sorbitol	0.118	23, 30	1.03
Whey protein:sorbitol	0.118	23, 75	144.92
MC:PEG	–	30, 0	149–226
HPC:PEG	–	30, 0	910
M:BW/MC:PEG	–	25, 0	960
S:BW/MC:PEG	–	25, 0	319
Starch	–	24, –	13 130
Amylomaize	–	25, –	1 480
Gliadins and glycerol	0.01	–	1.03
Gluten and beeswax	0.09	–	0.005
Gluten and glycerol	0.011	–	0.18
Gluten and glycerol	0.05	–	1.05
Pectin	0.036	–	8.2
Starch	0.790	–	4.86
Starch:cellulose acetate	1.19	–	29.3
LDPE	0.04–0.07	23, 50	1 870
Cellulose	0.10	23, 50	16
Cellulose	0.05	23, 95	252
EVOH	0.05	23, 0	0.1
Polyester	0.054	23, 0	17.3

MC = methylcellulose, PEG = polyethylene glycol, HPC = hydroxypropyl cellulose, BW = beeswax, M = beeswax applied molten, S = beeswax applied in solvent, LDPE = low density polyethylene, EVOH = ethylene vinyl alcohol.

Adapted from Gontard *et al.* (1992b) and McHugh and Krochta (1994).

while retaining biodegradability. Starch and LDPE polymers have been in use since the 1980s and other natural polymers, including Gutta-percha (1,4 trans-polyisoprene), are being investigated (Arvanitoyannis and Gorris, 1999). Applications of gluten films on glass jars, starch/LDPE films and laminated chitosan-cellulose-polycaprolactone films are described by Petersen *et al.* (1999).

24.2.5 Rigid and semi-rigid plastic containers

Trays, cups, tubs, bottles and jars are made from single or coextruded polymers. The main advantages, compared with glass and metal, are as follows:

- they have a lower weight, resulting in savings of up to 40% in transport and distribution costs compared to glass or metal
- they are produced at a lower temperature than glass (300°C compared to 800°C) and therefore incur lower energy costs
- they are precisely moulded into a wider range of shapes than glass
- they are tough, unbreakable (impact and pressure resistance)
- they are easy to seal

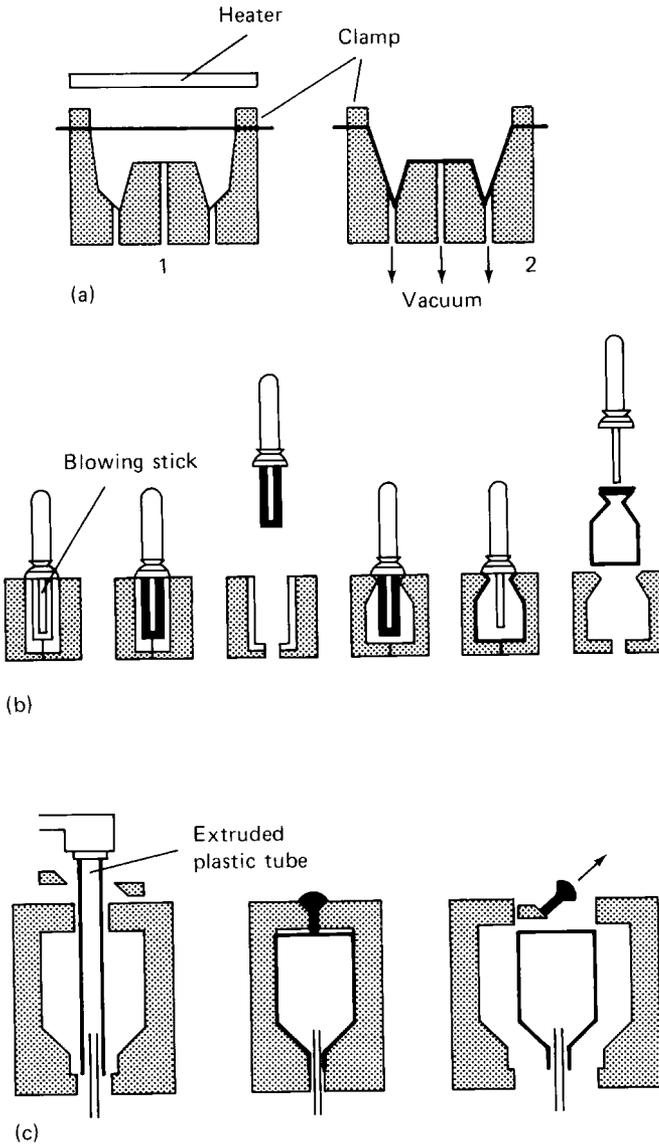


Fig. 24.6 Manufacture of rigid containers: (a) thermoforming; (b) injection blow moulding; (c) extrusion blow moulding.
(After Briston (1987).)

- they can be easily coloured for aesthetic appeal and UV-light protection
- they are produced at relatively low cost
- they have a greater chemical resistance than metals.

However, they are not re-usable, have a lower heat resistance and are less rigid than glass or metal. Cups, tubs and trays are tapered (a wider rim than base) to facilitate removal from the mould and are made without sharp corners, which would become thin during the moulding process and be a potential source of leakage. In general the height of the container should not exceed the diameter of the rim in order to maintain a uniform thickness of material.

There are six methods of container manufacture:

1. *Thermoforming* in which the film is softened over a mould, and a vacuum and/or pressure is applied (Fig. 24.6(a)). More complex systems, which prevent the sheet from thinning at the edges, are described by Briston (1980, 1987). Thermoforming can be by either vacuum or pressure, and each can have positive or negative pressure applied, or have mechanical pre-stretching to give a total of eight different methods. The six main materials used for thermoforming are: PVC, PS, PP, PVC-PVDC, PVC-PVF or PVC-PE-PVDC (Paine, 1991). These containers are thin walled and possess relatively poor mechanical properties. Examples include trays or punnets for chocolates, eggs or soft fruit, and cups or tubs for dairy products, margarine, dried foods or ice cream.
2. *Blow moulding* is similar to glass making (Section 24.2.3) and is used in either a single- or two-stage process for producing bottles, jars or pots. Containers are used for cooking oils, vinegar beverages and sauces.
3. In *injection moulding*, grains of polymer are mixed and heated by a screw in a moulding machine and injected under high pressure into a cool mould. This method is used for wide-mouthed containers (for example tubs and jars) and for lids.
4. In *injection blow moulding* (Fig. 24.6(b)), polymer is injection moulded around a blowing stick and, while molten, this is transferred to a blowing mould. Compressed air is then used to form the final shape of the container. Injection blow moulding of HDPE, PP and PS bottles gives accurate control of the container weight and precise neck finishes. It is more efficient than extrusion blow moulding and is used for small bottles (<500 ml), but it is not possible to produce containers with handles and capital costs are high (Paine, 1991).
5. *Extrusion blow moulding* (Fig. 24.6(c)). A continuously extruded tube of softened polymer is trapped between two halves of a mould and both ends are sealed as the mould closes. The trapped part is inflated by compressed air to the shape of the mould. It is used for bottles from >200 ml up to 4500 l tanks and can be used to form handles and offset necks. In both types of blow-moulding, careful control is needed to ensure uniform thickness in the container wall.
6. *Stretch blow moulding*. A pre-form (or parison) is made by injection, extrusion or extrusion blow moulding. It is brought to correct temperature and rapidly stretched and cooled in both directions by compressed air. The biaxial orientation of the molecules produces a glass clear container which has increased stiffness, tensile strength, surface gloss, impact resistance, barrier properties to moisture and gases and stability over a wide temperature range. It is mainly used for PET but also for PVC and PP bottles between 450 ml and 1.8 l. Multilayer blow moulding using poly (ethylene-vinyl alcohol) (EVOH) is high cost but has excellent oxygen barrier properties, and can be used as a thin layer, sandwiched between two layers of PE or PP (HDPE/adhesive/EVOH/adhesive/HDPE). An important development is PVC blow-moulded bottles for wine, oils and juice concentrates. Previously, this was difficult because thermal degradation of PVC occurs at a temperature a little above the melting point, but the technology to overcome this problem has now been solved.

High impact polystyrene (HIPS) and acrylonitrile butadiene styrene (ABS) are widely used for thermoformed trays, tubs and cups to contain yoghurt, margarine, cheeses, spreads, ice cream and desserts. In its natural state it is translucent but it can easily be coloured. Polyvinyl chloride (PVC) trays, tubs and bottles are made by extrusion- or

injection-stretch blow moulding. Food-grade PVC is tough, clear and easy to colour. It has good oil resistance and low gas permeability and is therefore used in trays for meat products and chocolates, in tubs for margarine or jams, and in bottles for edible oils, fruit juices, squashes and concentrates. However, it has lower strength than PET and is not used for carbonated beverages as it cannot withstand the pressure of carbonation. It also has a relatively low temperature resistance (65–70°C). Polypropylene is currently more expensive than HIPS or PVC and is less widely used for rigid/semi-rigid containers. However, it is resistant to a wider temperature range (deep-freeze temperatures to 120–140°C) and also provides a good barrier to water vapour and oxygen.

High-density polyethylene is at present the most common material used for bottles and jars. It is used for vinegar, milk, syrups and as drums for salt and bulk fruit juices (Briston, 1987). Polypropylene coextrusions, in which ethylene–vinyl alcohol copolymer is a central barrier material, are used for mustard, mayonnaise, jams, tomato ketchup and other sauces to give a shelf life of 18 months. They are shatterproof, oxygen and moisture resistant, squeezable and suitable for hot filling.

Multi-chamber PET trays have a hygienic smooth white finish. They are fat and grease resistant, heat sealable and lightweight. They are used, for example, for chilled or frozen ready meals (Chapters 19 and 21), where the cover is left on during either microwave or conventional cooking and then peeled off to give an attractive table dish. Details of the materials, methods of production and processing are given by Faithfull (1988). A coextruded five-layer sheet of polypropylene or polycarbonate, with polyvinylidene chloride or ethylene–vinyl alcohol barrier layers, is used to form heat-sterilisable trays and pots, by either injection moulding, blow moulding or thermoforming (Briston, 1980). *Plastic cans* are made from similar material which is thermoformed or injection blow moulded to form the can body. They are sealed using easy-open aluminium ends and processed on existing canning lines with considerably reduced noise levels (Louis, 1986 and Darrington, 1980). Brody (1992) has reviewed the development of both retortable trays and plastic cans.

24.2.6 Paper and board

Paper has a number of advantages as a food packaging material:

- it is produced in many grades and converted to many different forms, especially boxes or cartons
- it is recyclable and biodegradable
- it is easily combined with other materials to make coated or laminated packs
- it can be produced with different degrees of opacity.

Paper pulp is produced from wood chips by acid or alkaline hydrolysis, in which lignin in wood pulp is dissolved and removed by washing to leave cellulose fibres. There are two processes: the kraft (Swedish for ‘strong’) and sulphite process. The kraft process is more important as it retains more strength in the fibres, gives higher yields and process chemicals are more completely and economically recovered (Paine, 1991). Wood (mostly spruce) chips are digested in sodium hydroxide and sodium sulphate for several hours. In the sulphite process sulphur dioxide and calcium bisulphite are heated with wood chips at 140°C, washed and then bleached with calcium hypochlorite, to give very pure cellulose fibres. Additives in paper include:

- fillers (‘loading agents’) such as china clay, to increase the opacity and brightness of paper and improve surface smoothness and printability

- binders, including starches, vegetable gums, and synthetic resins to improve the strength (tensile, tear and burst strength)
- resin or wax emulsions are used as sizing agents to reduce penetration by water or printing inks
- pigments
- other chemicals to assist in the manufacturing process (e.g. anti-foaming agents).

Both types of pulp then undergo a beating process to brush individual cellulose fibres and make them split down their length. This produces a mass of thin fibrils (termed fibrillation) that hold together more strongly to give increased burst, tensile and tear strength. The fibres are suspended in water and then transferred to a *Fourdrinier wire*, on which water is removed by suction to reduce moisture content of the pulp to 75–80%, and produces a mat of fibres which is strong enough to transfer to felt (wool) sheets. These blot up more water from the paper and press it to reduce the water content to 60%. The paper is then dried using heated cylinders.

High gloss machine glazed (MG) papers produced using highly polished cylinders and machine finished (MF) papers are produced by passing them through a series of rollers (a *calender stack*), in which one roller is driven and the other is moved by friction with the paper, to create a smooth surface.

Papers

Kraft paper is a strong paper which is used for 25–50 kg multi-wall sacks for powders, flour, sugar, fruits and vegetables. It can be bleached white, printed or used unbleached (brown). It is usually used in several layers or ‘plies’, to give the required strength. Sack material is described from the outer ply inwards according to the number and weight (or ‘substance’ in g per m²) of the layers. For example 2/90, 1/80 means that there are three plies, the outer two having a weight of 90 gm⁻² and the inner having a weight of 80 gm⁻². *Vegetable parchment* is produced from sulphate pulp which is passed through a bath of concentrated sulphuric acid to swell and partly dissolve the cellulose fibres, to make them plasticised. This closes the pores and fills voids in the fibre network to make the surface more intact than kraft paper, and thus makes the paper resistant to grease and oils and gives greater wet strength properties. It is used to pack butter, cheese and fresh fish or meat. Both types of paper protect foods from dust and soils, but they have negligible water vapour or gas barrier properties and are not heat sealable.

Sulphite paper is lighter and weaker than sulphate papers. It is used for grocery bags and sweet wrappers, as an inner liner for biscuits and in laminations. It may be glazed to improve its wet strength and oil resistance, when it is known as MG (machine glazed) sulphite paper. *Greaseproof paper* is made from sulphite pulp in which the fibres are more thoroughly beaten to produce a closer structure. It is resistant to oils and fats, and although this property is lost when the paper becomes wet, it is widely used for wrapping fish, meat and dairy products. *Glassine* is similar to greaseproof paper, but is given additional calendaring to increase the density and produce a close-knit structure and a high gloss finish. It is more resistant to water when dry but loses the resistance once it becomes wet. *Tissue paper* is a soft non-resilient paper used for example to protect fruits against dust and bruising. Some properties of papers are given in Table 24.9.

Coated papers

Many papers are treated with wax by coating, dry waxing (in which wax penetrates the paper while hot) or wax sizing (in which the wax is added during the preparation of the

Table 24.9 Properties of main types of food papers

Paper	Weight range (g/m ²)	Tensile strength (kN/m)	Examples of uses
Kraft	70–300	MD 2.4–11.3 CD 1.2–5.2	Multi-wall sacks, liners for corrugated board
Sulphite	35–300	Variable	Small bags, pouches, waxed papers, labels, foil laminates
Greaseproof	70–150	MD 1.7–4.4 CD 0.85–2.1	Paper for bakery products, fatty foods
Glassine	40–150	MD 1.4–5.2 CD 0.85–2.8	Odour resistant and greaseproof bags, wrappers or liners for boxes, suitable for wax coating to make them water resistant – for dry cereals, potato crisps, dried soups, cake mixes, coffee, sugar
Vegetable parchment	60–370	2.1–14.0	High wet strength and grease resistant bags, wrappers or liners for boxes used for meat, fish, fats, etc.
Tissue	17–50	–	Soft wrapping paper for bread, fruits, etc.

MD = machine direction, CD = cross direction.

Adapted from Paine (1991).

pulp). Wax provides a moisture barrier and allows the paper to be heat sealed. However, a simple wax coating is easily damaged by folding or by abrasive foods, but this is overcome by laminating the wax between layers of paper and/or polyethylene. Waxed papers are used for bread wrappers and inner liners for cereal cartons.

The thickness of some plastic films that is needed to give the required degree of protection is less than that which can be handled on filling and forming machines. Therefore coating an expensive barrier film onto a thicker, cheaper paper substrate gives the desired strength and handling properties. Coatings can be applied:

- from aqueous solutions (cellulose ethers, polyvinyl alcohol) to make papers greaseproof
- from solvent solutions or lacquers
- from aqueous dispersions (e.g. polyvinylidene chloride)
- as hot-melts (e.g. microcrystalline wax, polyethylene and copolymers of ethylene and vinyl acetate) to increase gloss, durability, scuff and crease resistance and permit heat sealability)
- as extrusion coatings (e.g. polyethylene), which have been an area of major advances in the last 50 years.

Although they are not affected by temperature, all papers are sensitive to humidity variations, and coated papers in particular may lose moisture from one face and are therefore prone to curling. Smooth papers block if pressed together in a stack. The optimum storage conditions for papers are about 20°C and a relative humidity of approximately 50%.

Paperboard cartons

Paperboard is a generic term covering boxboard, chipboard and corrugated or solid fibreboards. Typical paperboard has the following structure:

- a top ply of bleached pulp to give surface strength and printability
- an underliner of white pulp to stop the grey/brown colour of middle plies showing through

- middle plies of lower grade material
- a back ply of either low grade pulp or better grade pulp if strength or printability are required.

All plies are glued together with hot-melt or aqueous adhesives.

Boards are made in a similar way to paper but are thicker to protect foods from mechanical damage. The main characteristics of board are:

- thickness
- stiffness
- the ability to crease without cracking
- the degree of whiteness
- surface properties
- suitability for printing.

White board is suitable for contact with food and is often coated with polyethylene, polyvinyl chloride or wax for heat sealability. It is used for ice cream, chocolate and frozen food cartons. *Chipboard* is made from recycled paper and is not used in contact with foods. It is used, for example, as the outer cartons for tea and cereals. It is often lined with white board to improve the appearance and strength. *Duplex board* has two layers: the liner is produced from bleached woodpulp and the outer is unbleached. Other types include paperboard (0.3–1.0 mm), boxboard (1.00–3.00 mm) and moulded paperboard trays (for example egg cartons).

Fibreboard (more than 0.11 mm thick) is either solid or corrugated. The solid type has an outer kraft layer and an inner bleached board. It is able to resist compression and to a lesser extent impact. Small fibreboard cylinders (or ‘composite cans’) are made using single ply board, either with or without a foil layer and LDPE inner layer. They are spirally wound around a mandrel in a helical pattern and bonded with an adhesive. The correct can length is cut, flanges are formed at each end and they are fitted with plastic or metal caps which may have an easy-open end or a pouring mechanism. Small tubs or cans are used for juice concentrates, snackfoods, confectionery, nuts, biscuit doughs, powders and spices. Larger drums (up to 375 l) are used as a cheaper alternative to metal drums for powders and other dry foods and, when lined or laminated with polyethylene, for fats. They are lightweight, resist compression and have recently been made water resistant for outside storage. Other products that are handled in drums include frozen fruits and vegetables, peanut butter, sauces and wine. A similar material, made from single ply board with a moisture-proof membrane below the surface is used to make cases to transport chilled foods. The membrane prevents the board absorbing moisture and retains its strength throughout the chill chain.

Corrugated board has an outer and inner lining of kraft paper with a central corrugating (or fluting) material. This is made by softening the fluting material with steam and passing it over corrugating rollers. The liners are then applied to each side using a suitable adhesive (Fig. 24.7). The board is formed into ‘cut-outs’ which are then assembled into cases at the filling line. Corrugated board resists impact, abrasion and compression damage, and is therefore used for shipping containers. Smaller more numerous corrugations (for example 164 flutes m^{-1} , with a flute height of 2.7 mm) give rigidity, whereas larger corrugations (for example 127 flutes m^{-1} , and a flute height of 3.4 mm) or double and triple walls give resistance to impact (Table 24.10). Twin-ply fluting, with a strengthening agent between the layers, has the same stacking strength but half the weight of solid board, and a space saving of 30% compared with double-

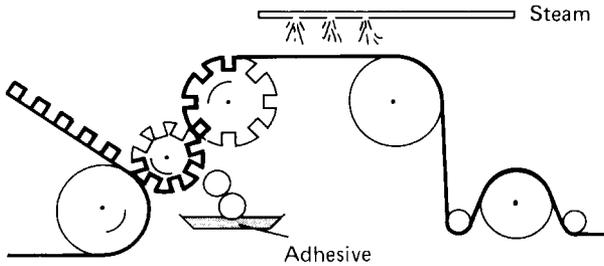


Fig. 24.7 Corrugated board manufacture.

corrugated boards of comparable strength. Boards should be stored in a dry atmosphere to retain their strength and prevent delamination of the corrugated material. Wet foods may be stored by lining the corrugated board with polyethylene, which also reduces moisture migration and tainting (for example for chilled bulk meat (Anon., 1982)). Alternatively the liner may be a laminate of greaseproof paper, coated with microcrystalline wax and polyethylene (for fresh fruit and vegetables, dairy products, meat and frozen food).

Laminated paperboard cartons are made from LDPE–paper–LDPE–aluminium–surlyn–LDPE and are used to make cartons for packaging aseptically sterilised (UHT) foods (Chapter 12). There are two systems: in one the material is supplied as individual pre-formed collapsed sleeves with the side seam formed by the manufacturer (Fig. 24.8). The cartons are erected at the filling line, filled and sealed (Chapter 25), with the top seal formed above the food. This allows a headspace to both enable the product to be mixed by shaking, and to create less risk of spillage on opening. In a second system, the laminate is supplied as a roll, and is formed into cartons on form–fill–seal equipment (Chapter 25). The advantages of this system include a lower space required for storage of packaging material and easier handling. Details of the production of cartons by both methods are given by Schraut (1989). Both types of carton have the following advantages. They:

- are unbreakable
- require no additional labelling or capping
- incur lower energy costs in manufacture and give a substantial saving in weight compared with cans and glass
- are easier to open and dispose of than cans
- save on shelf space and bold graphics give a ‘billboard effect’ on display shelves.

Natural and synthetic water-based adhesives are used to prepare paper and fibreboard containers. They are safe, low cost and have good strength. They are used for seams of bags, corrugated board, labelling cans and bottles and winding paper tubes. Starch pastes and dextrans are used for carton and case closing, tube winding and paperboard

Table 24.10 Fluting ranges for corrugated board

Flute configuration	No. flutes/m	Flute height (mm)	Minimum flat crush (N/m ²)
A (coarse)	104–125	4.5–4.7	140
B (fine)	150–184	2.1–2.9	180
C (medium)	120–145	3.5–3.7	165
E (very fine)	275–310	1.15–1.65	485

From Paine (1991).

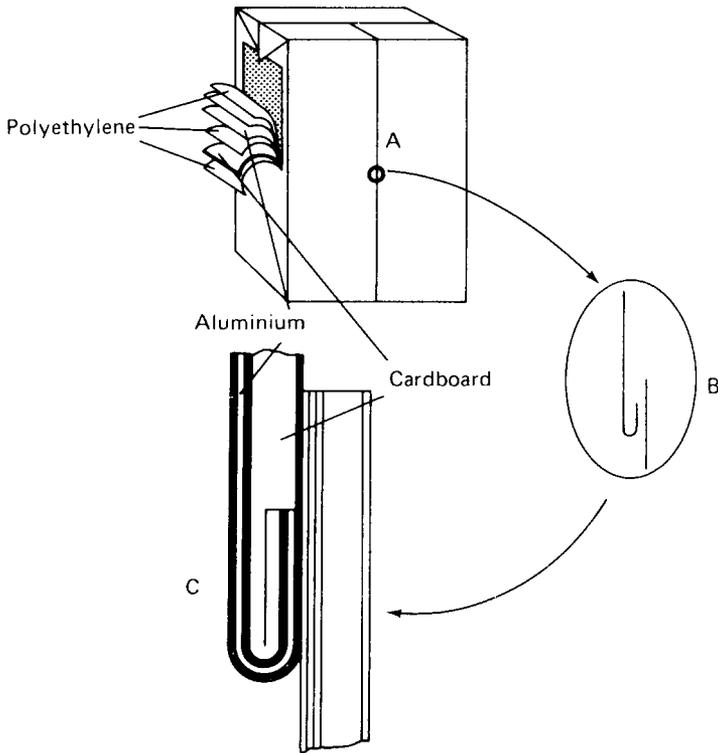


Fig. 24.8 (a) Construction of laminated paperboard carton for aseptic foods: A, side seam; B, folded to prevent leakage of contents into laminate; C, laminate chamfered to prevent seam bulging. (Courtesy of Bowater PKL (UK) Ltd.)

laminating and labelling. Latex is blended with acrylic resins and used for cold-seal coatings for confectionery wrappers, carton making, and water resistant labelling of drums cans and bottles. Hot melt adhesives contain no water or solvent and are heated to form a solution for application, and then set rapidly on cooling. EA copolymer is the most widely used and low molecular weight polyethylene is also used for case sealing and bag seaming.

Moulded paper pulp containers

These are lightweight containers, normally having 2.5 mm thick walls, that are able to absorb shocks by distortion and crushing at the point of impact, without transmitting them to the product. They are made from paper pulp using a mould instead of a wire screen, by either pressure injection or suction moulding. Pressure injection uses air at 480°C to form the pack. It leaves the mould having 45–50% moisture and is then dried. The suction process uses a perforated mould and the pack leaves the mould at 85% moisture before drying. The capital cost of suction moulding is higher than pressure moulding and it is therefore used for higher production rates. The main advantages of pulp, compared to expanded polystyrene and single- or double-wall corrugated board, include low fire risk and no static problems compared to polystyrene and the capacity to make more complex shapes than corrugated board. It is used for egg trays, bottle sleeves and trays for fruits, meats and fish.

Tetra-brik Aseptic,
layers of material,
starting from the outside

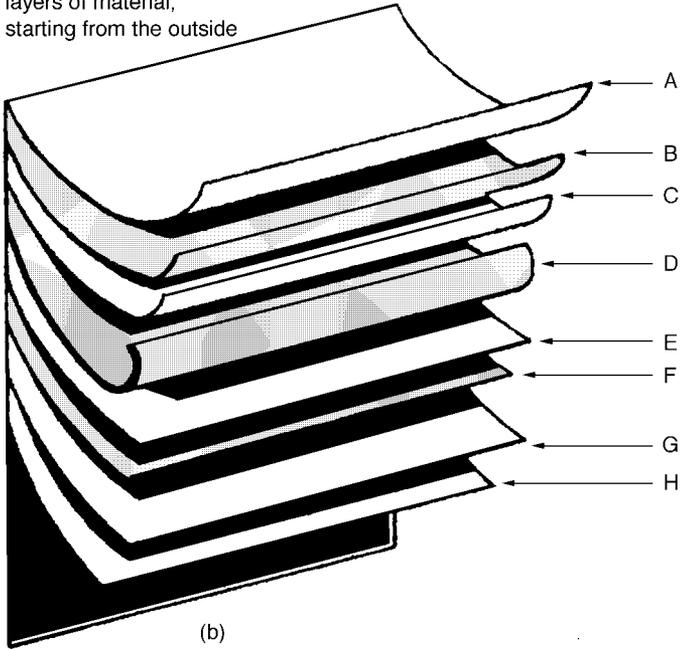


Fig. 24.8 (b) Construction of laminated packaging material used by Tetra-brik Aseptic machinery: A, polyethylene; B, printing ink; C and D, duplex paper; E, polyethylene; F, aluminium foil; G and H, polyethylene.
(Courtesy of Tetra Pak Inc.)

24.2.7 Combined packaging systems

A common combined packaging system is the use of cartons to contain multiple packs of food in flexible film. These in turn are shrink-wrapped or placed in corrugated board shipping containers. *Bag-in-box packaging* consists of a laminated or coextruded EVOH film bag, fitted with an integral tap, and contained within a solid or corrugated fibreboard display case (Briston, 1990), which in turn is packed into fibreboard shipping containers. The bag collapses evenly as liquid is withdrawn which prevents the product from becoming trapped in the folds of the bag and prevents oxidation of the product by air. It is a convenient lightweight secure container for liquid foods (for example wine, fruit juice, edible oils, syrups and milk). The design allows savings in weight and space compared with glass (for example a saving in weight from 5.13 kg to 3.24 kg and a saving in volume from 0.011 m³ to 0.004 m³ for containers of 31 capacity, compared with glass).

The technology for *modified atmosphere packaging* (MAP) is described in detail in Chapter 20. A wide range of different packaging systems are used to produce MAP packs and a summary of the main types is given in Chapter 25 (Table 25.2). Examples of films that are currently used include laminates of PET/PVdC/PE, PE/nylon/PE or PE/EVOH/PE. MAP packs frequently require high oxygen barriers and until recently, this has only been achievable at reasonable cost using either polyvinylidene chloride or aluminium foil, which does not let the consumer see the product. Developments in transparent low oxygen barrier materials include glass-coated microwaveable pouches, silica-coated

(SiO_x) films having oxygen transmission rates of <1 ml/m² and moisture vapour transmission rates of <1 g/m², aluminium oxide coatings and nylon-based co-extrusions having an oxygen permeability of 0.48 ml/m²/24 h/atm. (Church, 1994). The barrier properties of materials are described in Table 24.2. Although only one SiO_x/PET product is commercially available at present (2000), produced by plasma-enhanced chemical vapour deposition (PECVD), silica-coated films, trays and bottles are likely to become increasingly important as very high barrier, transparent, microwaveable containers.

24.2.8 Active packaging technologies

The rapid growth of chilled, MAP/CAP, and minimally processed foods during the 1990s has been accompanied by a number of developments in packaging technologies, which may be grouped under the term 'active' packaging. Details of active packaging for MAP products are given in Chapter 20. Active packaging has been described by Labuza (1996), Plaut (1995) and Rooney (1995) and includes:

- oxygen scavenging
- CO₂ production
- preservative release (e.g. ethanol production)
- antimicrobial action
- aroma release
- moisture removal
- removal of odours, off-flavours or ethylene
- time–temperature indicators
- gas indicators
- edible coatings and films (also Section 24.2.4)
- films to slow moisture transfer between ingredients that have different water activities
- microwave 'susceptor' films that create high temperature treatments. In contrast to most microwave packs, which do not heat up in a microwave oven, susceptors absorb a proportion of the microwave energy, become hot (up to 220°C) and therefore directly affect the rate and type of heating of the food. They are mostly used to impart crispness or browning to the surface of foods. The most common susceptor is a PET film that is lightly metallised with aluminium and laminated to a paperboard substrate. It is used in packs for popcorn, French fries, pizzas, pies, baked goods, etc. De-metallised susceptors have areas in which the metallisation is etched off during production. This enables heat to be directed to specific areas of a pack and also prevents carton glues from melting or producing volatiles that could contaminate the product (Woods, 1993)
- infrared films that radiate energy to inactivate micro-organisms
- steam release films
- time–temperature indicators to display loss of shelf life and extreme-temperature indicators to display temperature abuse conditions (Chapter 21)
- indicator labels that change colour when a specified level of CO₂ is attained in a modified atmosphere package
- tamper-evident labels that change colour when they are removed and leave behind a message on the pack that cannot be hidden.

Possible future developments in active packaging include self-venting microwave packs in which a vent opens at a pre-set temperature and closes on cooling, respiring trays that respond to changing atmospheric conditions to optimise respiration, materials that

generate electrical impulses when moved; their electrical conductivity may change when exposed to light and their opacity may change or they become softer or harder when subjected to small electrical charges (Louis, 1998).

24.3 Printing

Printing inks for films and papers consist of a dye which is dispersed in a blend of solvents, and a resin which forms a varnish. Solvents must be carefully removed after application of the ink to prevent odour contaminating the product and blocking the film during use. Other considerations include the cost of the ink, and compatibility with the film which is needed to achieve a high bond strength.

There are five processes used to print films and papers:

1. *Flexographic printing* (or relief or letterpress) in up to six colours, is high speed and suitable for lines or blocks of colour. A fast-drying ink is applied to the film by a flexible rubber plate with raised characters. The plate is pressed against an inked roller to cover the raised portions with ink and then against the film or paper (Fig. 24.9(a)). It is used, for example, for cartons that do not require high print quality.
2. *Photogravure printing* (or intaglio) is able to produce high-quality detail and realistic pictures and has been more expensive than flexographic printing, although new methods of making gravure cylinders have reduced the cost. It uses an engraved chromium-plated roller with the printing surfaces recessed in the metal. Ink is applied to the roller and the excess is wiped from all but the recesses. The remaining ink is then transferred to the packaging material (Fig. 24.9(b)).
3. *Offset lithography* (or planographic) is based on the incompatibility of grease and water. A greasy ink is repelled by moistened parts of a printing plate but remains on compatible parts which carry the design. This method produces a print of similar quality to that of rotogravure and is suitable for papers and boards that are too rough for rotogravure printing (Fig. 24.9(c)).
4. *Screen printing* in which ink passes through a porous surface of a printing screen (Fig. 24.9(d)).
5. *Ink-jet printing* (Fig. 24.9(e)) in which electrically charged droplets of ink are deflected by charged deflector plates to create the image.

Further details of different method of printing are given by Lentz (1986).

Printing may be on the inside of the film (reverse printing) which has the advantage of producing a high gloss finish. However, the ink should have negligible odour to prevent contamination of the product. Printing on the outer surface avoids the risk of contact between the ink and product, but the ink must have a high gloss and be scuff-resistant to prevent it from rubbing off during handling. The ink may also be located between two layers of a laminate. This is achieved by reverse printing onto one film and then laminating the two films. Alternatively the ink is overcoated with polyvinylidene chloride latex, which gives a surface gloss, protects the print and contributes to the barrier properties of the film.

Developments in printing for shipping containers include on-line ink-jet printing and in future this could develop into System Laser Decoration (SYLADEC), in which an ultra-fast laser produces photographic decoration on polymer materials that have special pigments or other additives that selectively change colour under tuned laser light. With microprocessor control, this would enable great flexibility in changes to a pack

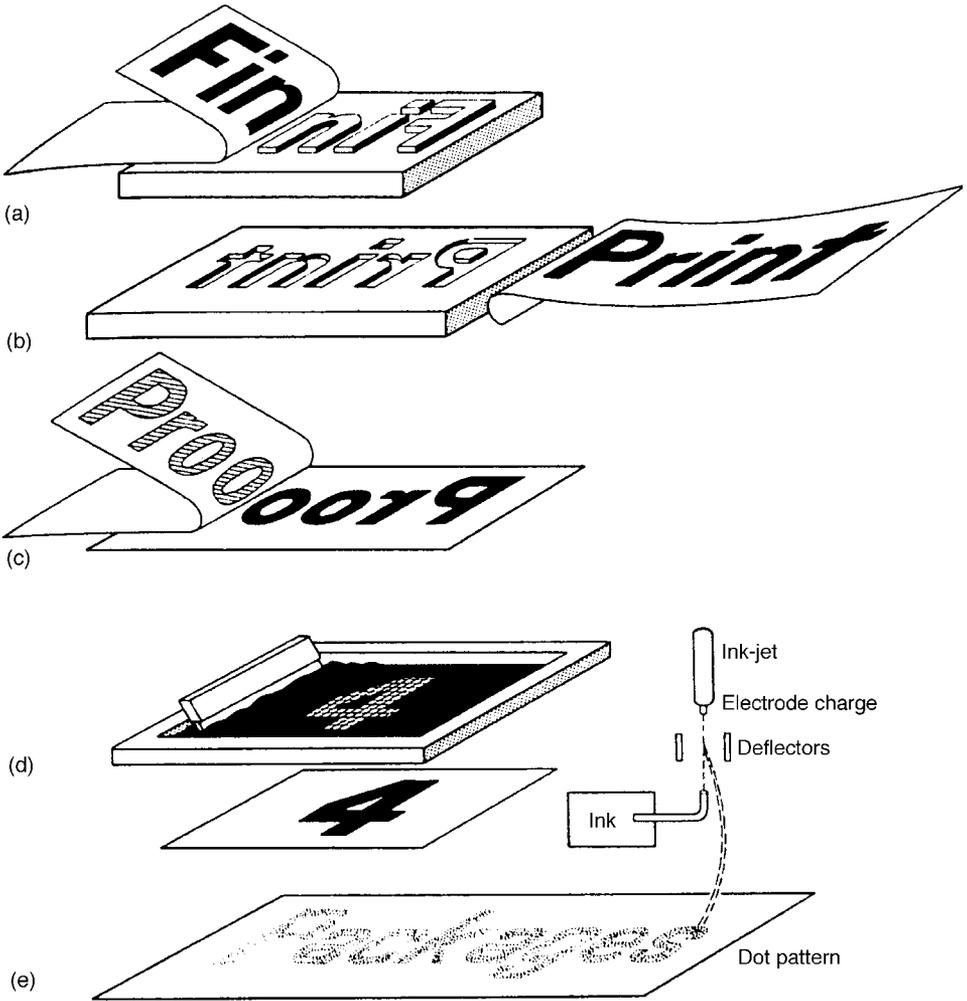


Fig. 24.9 Printing: (a) flexographic printing; (b) rotogravure printing; (c) lithographic printing; (d) screen printing; (e) ink-jet printing.

(From Lentz (1986).)

decoration, text language or design, leading to instant decoration, reduced stocks, absence of printing ink residues and enhanced recyclability of materials (Louis, 1998).

24.3.1 Bar codes and other markings

The Universal Print Code (UPC) or bar code (Fig. 24.10) is printed on consumer packs for laser reading at retail checkouts. It avoids the need for individual price labelling of packs and allows itemised bills to be produced for customers. The bar code information is fed to a computer which deducts the item from the store inventory and thus enables faster stock-taking, detection of pilferage and automatic re-ordering. The information is also collated into product sales reports, which can be used by store managers to adjust the shelf space allotment to specific items, or produce data on competitors' sales or the results of promotion and marketing strategies (also Chapter 2). Corrugated board

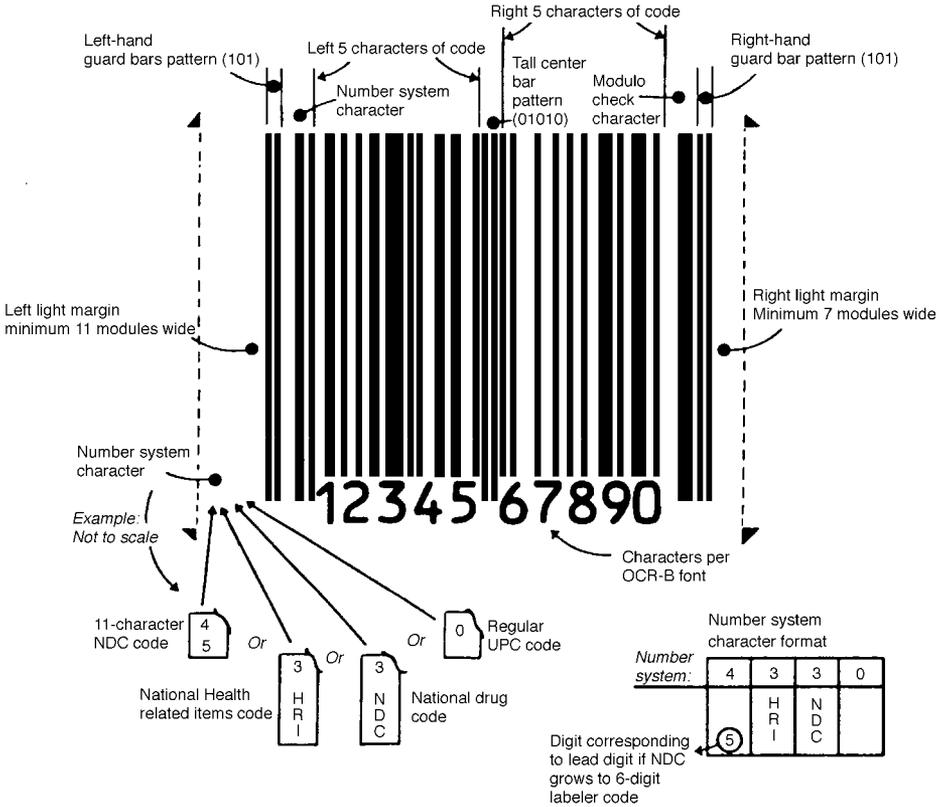


Fig. 24.10 UPC or bar code.
(From Hirsch (1991).)

shipping containers are also bar coded to inform the carrier about the destination, but this is not yet possible directly onto shrink-wrapping (Osborne, 1986).

Markings are also required on containers to show the 'sell-by' or 'use by' date in many countries. A manufacturer's code is printed onto containers to identify the factory, the production line and the shift during which the product was made. Coding lasers (Fig. 24.11) are non-contact and produce permanent marks without the use of inks and solvents. They are fully programmable to easily change the characters, and are capable of producing 400–2000 characters per second on paperboard, metal, glass, plastics and foil. They are described by Campey (1987).

Future developments in labelling, described by Louis (1998), may include an information micro-dot on the pack that contains all required label information in a number of languages, leaving the main area of the pack for graphic design and branding. The additional data storage capacity would allow more information to be included on, for example, nutritional composition and instructions for use. The information could be checked by equipment at the point of sale or by scanners operated by home computers. In a separate development, a label could be devised that contains micro-dots of electrically conducting polymer that are 'tuned' to respond to a particular gas or vapour that relates to the condition of the food. When the gas or vapour contacts the dots, the electrical conductivity changes and this could be measured by an analytical instrument, or later by electrochromic pigments or voice activation to produce instant visual or vocal warning of the condition of the food.



Fig. 24.11 Laser coding: (a) (above) operator interface and coding laser on a production line; (b) (overleaf) date and production codes positioned on a carton.
(Courtesy of Lumonics Ltd.)

24.4 Interactions between packaging and foods

Toxicological effects of interactions between food and packaging materials and also the effect of such interactions on the shelf life and sensory quality of the food are extremely complex. The main aspects that are being intensively studied are:

- lacquers and coatings for metal containers to prevent interaction of food acids, anthocyanins, sulphur compounds and other components with steel, tin or aluminium
- the migration of plasticisers, pigments, metal ions and other components of plastic packaging into foods
- the migration of oils from foods into plastics
- the interaction of the package and food under different processing conditions.

Research on these aspects is reviewed by Heidelbaugh and Karel (1982), Karel and Heidelbaugh (1975), Tice (1988) and Anon. (1971). International legislation on food



Fig. 24.11 Continued.

packaging is reviewed by Andrews (1980) and Briston and Katan (1974b). Blumenthal (1997) describes a selection of case studies in which the transfer of volatile organic compounds (VOCs) has caused serious quality problems for food manufacturers.

24.5 Environmental considerations

The value of packaging materials to protect foods against losses is illustrated by levels of food wastage of 2–3% in developed countries, compared to 30–50% in developing countries where sophisticated packaging, storage and distribution are not found. In industrialised countries, 67% of all packaging is used by the food industry and an average household uses around 200 different packaged items (INCPEN, undated). There have been a number of developments in both the types of materials used for packaging and the methods of handling and distribution of packaged foods that have affected the environmental impact of food packaging.

Table 24.11 Comparative packaging costs (\$US '000s) based on orders of 10–20M packages

	Primary package	Closure	Label	Corrugated box	Total
Glass jars	250	35	9.5	^a	294.5
Plastic jars	175	35	8.7	28	246.7
Metal cans	175	25	9.7	16.8	226.5
Composite cans	157	25	^b	16.8	198.8
Paperboard cartons	53	12.75	^c	14.6	80.5
Flexible foil bags	70	^d	^c	11.7	81.7

^a Price includes corrugated box.

^b Spiral wound cans are delivered with labels.

^c Pre-printed.

^d Heat sealed – closure not required.

From Leonard (1981).

24.5.1 Packaging costs

It is difficult to compare packaging costs without also including, for example, the costs of shipping containers, depreciation costs of packaging machinery, labour requirements, etc. It is also important to consider the cost of the package in relation to the value of the product: for example a 0.5 litre glass bottle and cap/label may cost 20p. If filled with mineral water valued at 2p, the ratio of packaging to cost of product is 10. If milk is filled with value of 30p, the ratio is approximately 0.7, whereas if whisky at £10 is filled, the ratio is 20/1000 or 0.02 (Paine, 1991). Comparative costs of some packaging materials are given in Table 24.11.

24.5.2 Manufacture of packaging materials

Retail packs have been subject to criticism by environmental groups on the following counts: packaging makes excessive use of resources in a wasteful way; it adds to waste disposal problems and uses large amounts of energy, particularly fossil fuels used for plastics. It has also been stated that over-packaging adds unnecessarily to the cost of products, limits consumer choice, may be used to deceive consumers, and forms a major part of litter and wastage due to poor design for re-use or recycling.

The main function of packaging is to enable consumers to receive foods in good condition at the lowest reasonable price. Manufacturers therefore have the responsibility to review the economies of the total production and distribution chain, re-use and disposal options, and marketing and commercial considerations should be reconciled with economy in the use of materials and energy, and the environment. A code of packaging described by Paine (1991) is as follows:

- packaging must comply with all legal requirements
- the pack must be designed to use materials as economically as possible while having regard to protection, preservation and presentation of the product
- packaging must adequately protect foods under normal conditions of distribution, retailing and home storage
- the packaging materials should have no adverse effects on the contents
- the pack must not contain any unnecessary void volume, nor mislead as to the amount, character or nature of the product it contains

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- the package should be convenient for the consumer to handle and use for opening and reclosing when required and be appropriate to the product and its use
- all relevant information about the product should be presented concisely and clearly on the pack
- the pack should be designed with regard to its possible effect on the environment, its ultimate disposal and to possible recycling and re-use.

A proportion of the cost of packaging is the energy required for their manufacture and the energy needed to make 1 kg of different packaging materials from their raw materials is shown in Table 24.12. It should be noted that these figures are produced on a weight basis, whereas packaging is used on an area or volume basis. The area from 1 kg of a film material will be much greater than that for 1 kg tinfoil (e.g. one million m² of polypropylene film requires 110 tonnes of oil as feedstock and energy, whereas one million 0.33 litre tinfoil cans require 75 tonnes of oil). Other factors that should be taken into account are the energy needed to procure raw materials, manufacture the packaging material, convert the material into packages, handle and use the packs, types of energy sources used (Chapter 1, Table 1.9) and their conversion efficiency, the distance that packaging raw materials are transported and the energy efficiency of the transport methods.

The total environmental impact of production of packaging takes into account the types and sources of raw materials, the cost of transporting them, the energy used to produce the packaging and the amount of wastage during production. There are strong economic incentives for manufacturers to reduce the costs of packaging. For example, 100% of scrap from can-making is recycled as 50% less energy is used compared to making steel from iron ore. Advances have been made in several areas first to reduce the cost of delivery of raw materials for packaging by using bulk handling, rather than small sacks of raw materials, second to reduce material and energy consumption by better design of production systems and control of production using microcomputers (Chapter 2), and lastly to switch from materials that require a high energy consumption for their manufacture, such as glass and metals, to plastics. This may, however, be a relatively short-term gain because plastics (with the exception of cellulose) are produced from non-renewable resources, whereas the raw materials for glass and metal packaging are relatively abundant and these materials are recyclable. Paper and board packaging is now

Table 24.12 Energy needed to make 1 kg of different packaging materials from their raw materials

Packaging material	Total energy	
	MJ/kg	Tonnes of oil equivalent (TOE)
Aluminium	293	8.8
Cellulose film	192	4.4
Shrinkwrap film	187	4.3
PET resin	183	4.2
Can sealing compound	180	4.17
Polypropylene film	173	4.0
LDPE resin	104	2.4
Paperboard	99	2.3
Kraft paper	82	1.9
Tinfoil	50	1.2
Glass containers	22	0.5

From Paine (1991).

Table 24.13 Levels of recycling of materials for packaging

Material	Weight used in typical container (g and year)	Amount recycled to production (%)	Notes
Aluminium	91 (1950) 17 (1990)	40	Scrap used in aluminium production for all purposes. Plentiful supply of raw material
Glass	538 (pre 1939) 245 (1990)	35–50	Cullet from glass production and recycled containers from consumer 'bottle banks'. Abundant supplies of raw materials
Paper and board	N/A	55	Recycled material used in production of all paper and board products. Renewable supply of raw materials
PET	66 (1983) 42 (1990)	N/A	Scrap used for non-food applications. Non-renewable supplies of oil for raw materials
PVC	N/A	N/A	Scrap used for non-food applications. Abundant supplies of sodium chloride raw material. Non-renewable supplies of oil raw material but coal, shale or vegetable material could be substituted
Tinplate	68.9 (1970) 56.6 (1990)	44	Scrap used in ferrous metal production for all purposes. Abundant supplies of all raw materials (iron ore, coal, limestone) except tin. Tin reserves estimated at 25–200 years. 10% of cans produced without tin and percentage increasing

N/A – data not available.

Adapted from the data of INCPEN (undated).

mostly sourced from renewable forests and the proportion of recycled paper that is used in packaging is steadily increasing (Table 24.13), although there remain substantial variations in the amounts that are used in different countries. The amount of energy needed to produce a range of packaging materials, including paper, board, aluminium, steel, glass and a variety of plastic films is reviewed by Selke (1994).

A further area of environmental concern is the level of emissions and water pollution during the production of packaging materials. Selke (1994) has reviewed data on controlled and uncontrolled airborne emissions of polluting gases and lead, and waterborne emissions of suspended solids, acids, a range of organic chemicals their biological oxidation demand (BOD), and heavy metals for a range of packaging materials, including steel, aluminium, plastic films, paper, board and glass (also Chapter 26).

24.5.3 Distribution of packaging materials and ingredients for food production

Ingredients and packaging materials were previously delivered in small unit loads to food manufacturers, which not only increased fuel consumption for transportation, but also increased the number of packages that were required to protect both ingredients and packaging materials. The energy needed to transport goods or packs depends in part on the types of packaging used. Trucks are either filled before they reach their weight limit (e.g. plastics or paper) or reach their weight limit before they are full (e.g. glass). The energy consumption for a full load is reported by Selke (1994) as ranging from 9.61 MJ/vehicle-km (15.47 MJ/vehicle-mile) for vehicles below 1 tonne capacity to between 1.80 and 27.5 MJ/vehicle-km (2.90–44.32 MJ/vehicle-mile) for vehicles greater than 18 tonne

capacity, including the energy consumed in supplying the fuel. This compares with estimates of 0.58 MJ/tonne-km and 1.09–1.50 MJ/tonne-mile for rail transport and 0.17 MJ/tonne-mile for sea transport.

Developments in packaging technologies and design of materials, including rolls of material for form–fill–seal machines to replace pre-formed packs, and stackable pots to replace cans and jars, have substantially reduced the volume of packaging materials to be transported and hence the fuel and packaging consumed to deliver them to food manufacturers. The weight of packages has also fallen with almost 90% of plastic consumer packs now weighing less than 10 g – up to 80% lighter than they were ten years ago (Russotto, 1999). Light-weighting of metal, glass, paperboard and plastics has also been continuously improved for the last 60 years: tinsplate thicknesses may be as much as half the weight in the 1930s; and paperboard for corrugated cases is 30% lighter. Additionally, the materials used to transport packaging have also been made lighter, especially with the introduction of shrinkwrapping and so even though the area of packaging material has increased, the weight of materials used has decreased. Similarly, developments in bulk handling of ingredients (Chapter 26) in which tankers and large (1–2 tonne) combi-bins, tanks or polypropylene bags have replaced 50 kg bags and sacks, have reduced the energy and materials needed to supply ingredients.

24.5.4 Distribution to retailers and consumers

The development of improved barrier packaging materials has reduced the weight and cost of retail packaging. Examples described in Section 24.2 in which PET has replaced glass bottles, aluminium has replaced tinsplate cans for carbonated beverages and printed co-extruded polymers have replaced glass jars with metal lids and printed paper labels, are each good examples of such savings. Similarly, distribution and sales of biscuits, first in cellulose and then polypropylene film, has replaced tins, lined with corrugated paper. Although the tins were reused, they had to be steam-cleaned between uses and new labels applied each time. The additional weight of the tins also added to the cost of transporting the product as well as the cost of the return journey by the tins.

Changes in handling and distribution methods (Chapter 26) mean that few foods are now packaged in one material, and an additional one or more shipping containers are also now used. For example, although shrink-wrapped trays weighing 80–90 g, have largely replaced fibreboard cartons (weighing 300–350 g) for transporting carbonated beverages, the shipping container still accounts for 53% of the weight of the package, compared to 47% of the total weight for the retail container (INCPEN, undated). In other examples, in which polymer films have replaced metal or glass containers, the proportion of the total weight taken up by a retail display carton and an outer fibreboard shipping carton is even greater. However, shipping containers are mostly separated and collected at retail outlets and in principle, recycling or re-use should be easier. In an audit reported by Russotto (1999), a major European retailer found that it used 20 000 tonnes of shipping containers each year. The company introduced reusable trays and reduced this by 40% as part of an efficiency and environmental programme.

24.5.5 Consumer recycling

In contrast to most purchased goods, which begin their useful life upon purchase, most packaging materials cease their usefulness at this stage and apart from home storage, the consumer most often disposes of the package without further consideration. One

exception is the use of re-fillable bottles, which remain common in the UK for milk and beers. Such systems work well when the supplier is relatively close to the consumer or a closed system operates in which the delivery vehicle collects empty bottles. Because reusable bottles are made thicker (and hence heavier) than non-returnable bottles to withstand the re-use, this increases the energy needed for both production of the bottle and transportation. The environmental benefits only become apparent when a bottle has made several journeys and if a returnable bottle is not returned, the initial investment in energy and resources is wasted. Because of its chemical composition, glass is virtually unchanged by repeated heating and does not degrade on recycling as do papers and plastics, so glass-makers have traditionally used 15–30% cullet when making new containers (Section 24.2.3). In many European countries and in Japan, all new containers have 50–55% recycled glass, although in other regions, where collection is less well organised, the figures are much lower.

Progress has been made in many countries to encourage consumers to separate glass, metal and paper packaging for recycling. For example, cans from household waste are separated magnetically, cleaned to remove dirt and treated in a de-tinning plant to extract and re-use the tin. However, there are considerable difficulties in separating out the wide variety of different plastic packaging materials for recycling or re-use and even where this occurs, the materials are not suitable for food grade applications. A balance must therefore be made between the lower costs of production of plastic packaging versus the limited capacity for recycling and consequent disposal and pollution problems, compared with glass, metal and paper packaging. These issues are discussed in more detail by Perchard (1989), and White (1994) reviews the options for packaging disposal, and recycling of paper, metals, glass and plastics. Trends indicate increased use of plastics as a result of their perceived lower production and distribution costs and superior technical performance. Russotto (1999) has reported that 50% of all packaged goods in Europe use plastic packaging (representing 16% of the weight of all packaging). However, changes in thinking about the true costs of different alternatives, possible future changes in legislation in some countries and the introduction of ‘environmental’ or ‘pollution’ taxes, together with potential increases in the price of oil-based raw materials, may change the relative benefits of recyclable materials. Pressure from environmental groups to develop more ecologically sound packaging systems has already prompted changes to European legislation² to reduce packaging waste through reduction, re-use and recovery of packaging materials (Akre, 1991; Griffiths, 1991; Hall, 1991). In a study reported by de Kruijf (1997) the potential for re-using PET and polycarbonate beverage bottles was examined and it concluded that such schemes were feasible, without public health risks from contaminated bottles. Interpretation of the European regulations is given by Powell and Steele (1999).

24.6 Acknowledgements

Grateful acknowledgement is made for information supplied by: Rose Forgrove Ltd, Seacroft, Leeds LS14 2AN, UK; Bowater PKL Ltd, Houghton-le-Spring, Tyne and Wear DH4 6JN, UK; British Sidac, Wigton, Cumbria, UK; BCL Shorko Films, Swindon, Wiltshire SN2 2QF, UK; Tetra-Pak (UK), Kingston on Thames, Surrey KT1 1LF, UK; Bonar Cooke Cartons Ltd, Manchester M16 0NP, UK; Thames Case Ltd, Purfleet, Essex

2. The European Directive on Packaging and Packaging Waste, 1994.

RM16 1RD, UK; H. Erben Ltd, Ipswich IP7 6AS, UK; Reed Corrugated Cases, Uxbridge, Middlesex UB8 2JP, UK; J. Gosheron and Co. Ltd, Isleworth, Middlesex TW7 4DT, UK; BCL Plastic Films, Bridgewater, Somerset TA6 3UA, UK; Beatson Clark plc, Rotherham, South Yorkshire S60 2AA, UK; Star Aluminium plc, Bridgnorth, Shropshire WV15 6AW, UK; ICI plc, Welwyn Garden City, Hertfordshire AL7 1HD, UK; Metal Box plc, Reading, Berkshire, UK; Sonoco Products Co., Box 160, Hartsville, S. Carolina, 29550, USA; Lumonics Ltd, Hull HU7 0YE, UK.; Mac Millan Bloedel Bulk Packaging, Marietta, GA 30062, USA; BOC Gases, London SW19 3UF, UK.

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Filling and sealing of containers

There have been significant developments in packaging systems during the last ten years, prompted by a number of considerations, for example:

- marketing requirements for different, more attractive packs
- reductions in pack weight to reduce costs and meet environmental concerns over energy and material consumption (Chapter 24)
- new packaging requirements for minimally processed foods (Chapters 9, 18, 19) and modified atmosphere packaging (Chapter 20)
- the need for new types of tamper-resistant and tamper evident packs.

Packaging methods that have been developed to meet these requirements are described in subsequent sections.

Accurate filling of containers is important to ensure compliance with fill-weight legislation and to prevent ‘give-away’ by overfilling. The composition of some foods (for example meat products such as pies and canned mixed vegetables) is also subject to legislation in some countries, and accurate filling of multiple ingredients is therefore necessary.

The maintenance of food quality for the required shelf life depends largely on adequate sealing of containers. Seals are the weakest part of a container and also suffer more frequent faults during production, such as food trapped in a seal, incorrect sealing temperatures or can seamer settings. In this chapter the techniques used to fill and seal rigid and flexible containers are described. By themselves these operations have no effect on the quality or shelf life of foods, but incorrect filling or sealing has a substantial effect on foods during subsequent storage.

25.1 Rigid and semi-rigid containers

‘Commercially clean’ metal and glass containers are supplied as palletised batches, which are wrapped in shrink or stretch film (Section 25.1.3) to prevent contamination. They are depalletised and inverted over steam or water sprays to clean them and they

remain inverted until filling to prevent recontamination. Wide-mouthed plastic pots or tubs are supplied in stacks, fitted one inside another, contained in fibreboard cases or shrink film. They are cleaned by moist hot air unless they are to be filled with aseptically sterilised food (Chapter 12), when they are sterilised with hydrogen peroxide. Laminated paperboard cartons are supplied either as a continuous reel or as partly formed flat containers. Both are sterilised with hydrogen peroxide when used to package UHT products.

25.1.1 Filling

The selection of an appropriate filling machine depends on the nature of the product and the production rate required. Gravity, pressure and vacuum fillers are each used for liquid foods and are described in detail by Osborne (1980). In each case an airtight seal is made between the container and the filling head, and liquid is filled until it reaches a vent tube, which is set to give the correct fill-weight or volume.

Volumetric fillers (for example a piston filler (Fig. 25.1)) are commonly used for liquids, pastes, powders and particulate foods. The filling heads are either in line or in a ‘carousel’ (or rotary) arrangement.

Large particulate materials (e.g. confectionery, tablets, etc.) can be filled into containers, using a photo-electric device, similar to a sorter (Chapter 3) to count individual pieces. Alternatively, a disc fitted with recesses to hold an individual item rotates below a holding container and when each recess is filled the required number are deposited in the pack. Smith (1999) describes developments in multi-head weighers that are able to weigh different products simultaneously, prior to filling into the same container. Examples include pre-packed mixed salads, mixed nuts and mixed selections of confectionery.

Containers can also be filled by weight using either a net-weight or gross-weight system. In the former, the weighed product is filled into a container and sealed, whereas the latter system weighs the product plus package before sealing. Both systems use microprocessors to control the rate of filling and final fill-weight (also Chapter 2). A bulk feeder is used to quickly fill a pack to approximately 90% full, and it is then weighed. The controller calculates the exact weight of material remaining to be filled and activates a fine feed to top up the pack and re-weigh it. The microprocessor monitors the number of packs and their weights, to produce a statistical record of fill weight variation.

All fillers should accurately fill the container ($\pm 1\%$ of the filled volume) without spillage and without contamination of the seal. They should also have a ‘no container-no

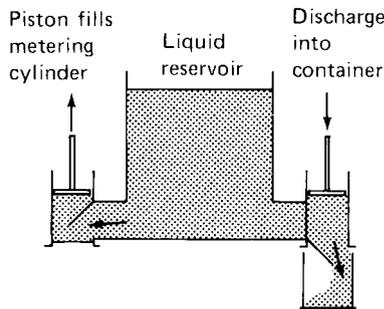


Fig. 25.1 Piston filler.

fill' device and be easily changed to accommodate different container sizes. Except for very low production rates or for difficult products (for example bean sprouts), fillers operate automatically to achieve the required filling speeds (for example up to 1000 cans per minute using rotary fillers).

Hermetically sealed containers are not filled completely. A headspace (or 'vacuity', 'expansion space' or 'ullage') is needed above the food to form a partial vacuum. This reduces pressure changes inside the container during processing and reduces oxidative deterioration of the product during storage (also Chapter 12). Glass containers and cans should have a head space of 6–10% of the container volume at normal sealing temperatures. Care is necessary when filling solid foods or pastes, to prevent air from becoming trapped in the product, which would reduce the head space vacuum. Viscous sauces or gravies are therefore added before solid pieces of food. This is less important with dilute brines or syrups, as air is able to escape before sealing. The functions of these added liquids are as follows:

- to improve the rate of heat transfer into solid pieces of food
- to displace air from the container
- to improve flavour and acceptability
- to act as a medium for adding colours or flavours.

The proportions of solid and liquid components in a container are also subject to legislation or trade standards in many countries.

25.1.2 Sealing

The requirements of closures for glass containers are described by Moody (1970) and Osborne (1980). Containers that are designed to enable consumers to use the contents a little at a time create a difficulty in ensuring that they are tamper-proof before opening and developments in tamper-evident closures are described in Section 25.3. Glass containers are sealed by one of the following types of seal (Fig 25.2).

- *Pressure seals* are used mostly for carbonated beverages. They include:

- screw in (internal screw) screw out, or screw on screw off
- crimp on lever off, crimp on screw off, or crimp on pull off
- roll on (or spin on) screw off.

Examples include cork or injection-moulded polyethylene stoppers or screw caps, crown caps (pressed tinfoil, lined with cork or polyvinyl chloride) or aluminium roll-on screw caps.

- *Normal seals* are used, for example, for pasteurised milk or wine bottles. There are many different types of seals including:

- one or two-piece pre-threaded, screw on, screw off
- lug type screw on, twist off
- roll on (or spin on), screw off
- press on, prise off
- crimp on prise off, or crimp on screw off
- push in pull out, or push on pull off.

Examples include cork or synthetic cork stoppers fitted with tinned lead, polythene or aluminium capsules, metal or plastic caps, and aluminium foil lids. Plug fittings

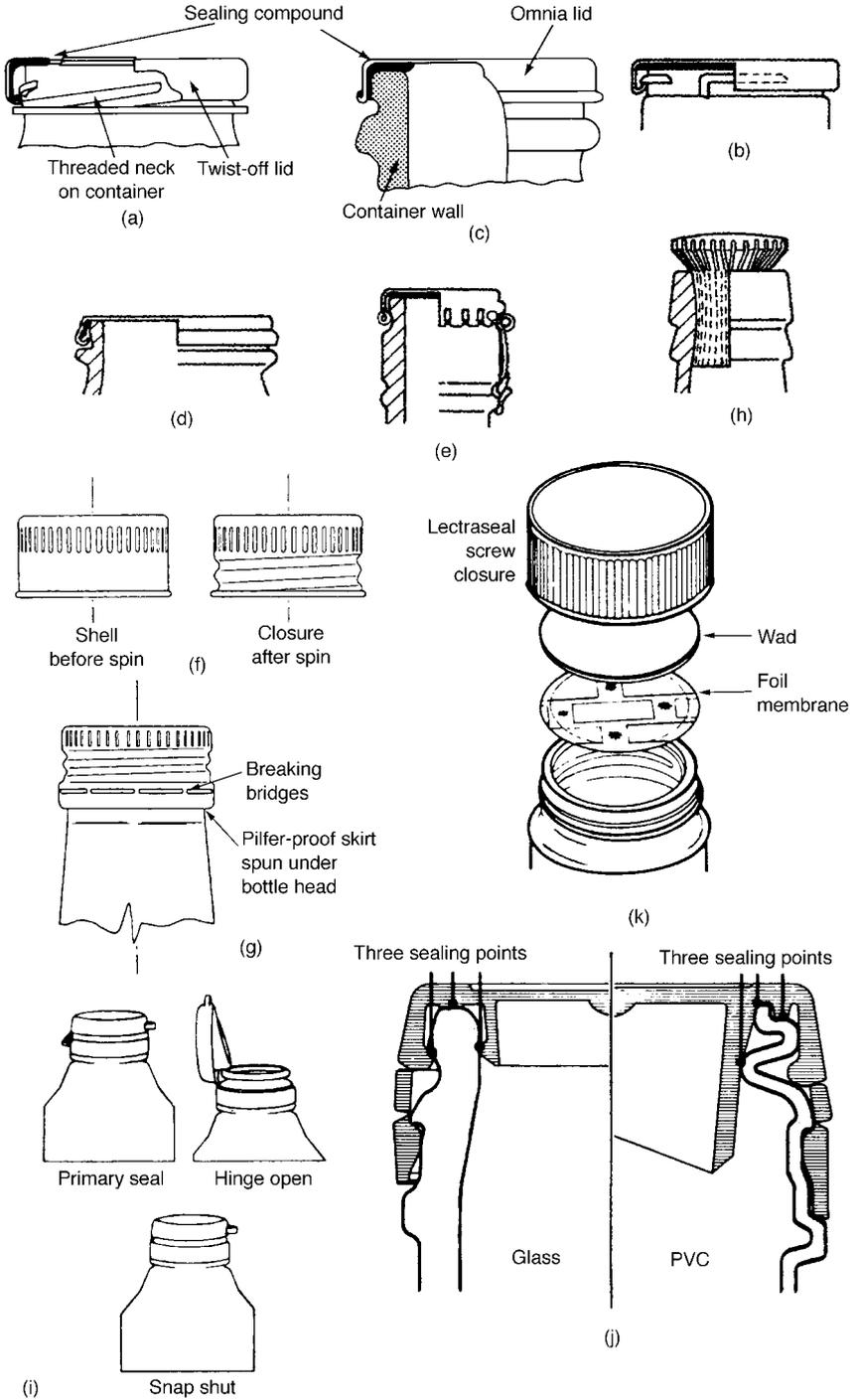


Fig. 25.2 Lids for glass and plastic containers: (a) twist-off; (b) lug cap; (c) Omnia; (d) pry-off; (e) lever cap; (f) screw cap; (g) ROPP; (h) flanged cork; (i) hinge-open, snap shut, (j) sealing points on hinge-open, snap shut lids, (k) pre-threaded closure. (After Hersom and Hulland (1980), Paine (1991) and Moody (1970).)

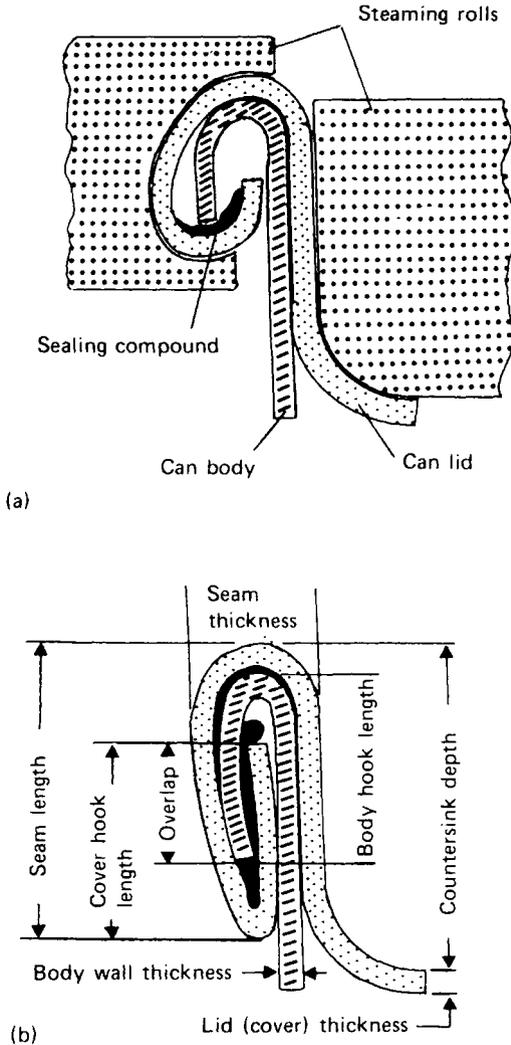


Fig. 25.3 Can seam formation: (a) first operation; (b) double seam. (After Hersom and Hulland (1980).)

are made from injection moulded LDPE and have the required softness and flexibility to form a good seal.

- *Vacuum seals* include
 - screw on twist off
 - press on prise off, or press on twist off
 - two-piece screw on screw off, or roll on screw off
 - crimp on prise off.

They are used, for example, for hermetically sealed containers for preserves or paste jars.

Can lids are sealed by a double seam in a seaming machine (or 'seamer'). The 'first operation roller' rolls the cover hook around the body hook (Fig. 25.3(a)) and the 'second operation roller' then tightens the two hooks to produce the double seam (Fig. 25.3(b)). A thermoplastic sealing compound melts during heat processing and fills the spaces in the

seam, to provide an additional barrier to contaminants. The can seam is the weakest point of the can and the seam dimensions are routinely examined by quality assurance staff to ensure that they comply with specifications (Table 25.1).

Free space is calculated using:

$$\text{Free space} = \text{seam thickness} - [2t_b + 3t_e] \quad \boxed{25.1}$$

and
$$\text{Percent Body Hook Butting} = [x - 1.1t_b]/[L - 1.1(2t_e + t_b)] \times 100 \quad \boxed{25.2}$$

$$\text{Actual overlap} = y + x + 1.1t_e - L \quad \boxed{25.3}$$

where x (mm) = the body hook length, y (mm) = the cover hook length, t_e (mm) = the thickness of the can end, t_b (mm) = the thickness of the can body, L (mm) = the seam length and c (mm) = the internal seam length.

Different types of easy-open end are fitted to cans, depending on the product: ring pull closures are used for beverages, and different designs retain the ring pull within the can after opening to reduce litter problems. Full-aperture ring pull closures are used, for example, for meat products, snackfoods and nuts. Both types are produced by scoring the metal lid and coating it with an internal lacquer. A metallised peelable plastic strip is used to close cans of non-carbonated non-pasteurised beverages (Malin, 1980). In aerosol cans, a pre-sterilised top is seamed on, and a pre-sterilised valve is fitted. The can is then dosed with gas and pressure checked. A cap is fitted onto the valve and finally an overcap covers the valve assembly.

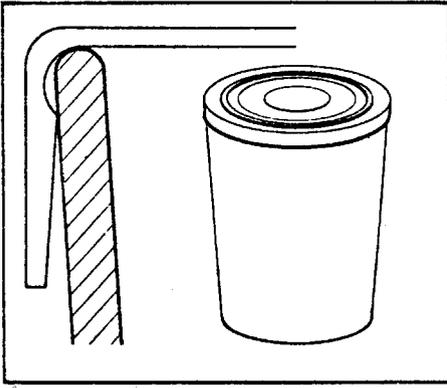
Aluminium collapsible tubes are sealed by folding and crimping the open end of the tube after filling. Polyethylene or laminated plastic tubes are sealed using a heat sealer, which may also cut a hanging slot in the tube for retail display.

Wide-mouthed rigid and semi-rigid plastic pots and tubs are sealed by a range of different closures, including push-on, snap-on or clip-on lids, membranes made from aluminium foil laminates or thermoplastic films, and push-on or crimp-on metal or plastic caps (Fig. 25.4). Push-on, crimp-on and snap-on lids require a bead at the rim of the container. These closures are not tamper-evident and, although the seal is sufficient to retain liquids, they do not provide a sufficient moisture barrier to protect hygroscopic foods. Membranes are sealed to pots by a combination of pressure and high frequency activation or heating of a heat-seal coating. They are tamper-evident and, depending on the material selected, can be made to provide a barrier to moisture and gases. Where a product is to be used over a period of time, or where additional protection is required for the membrane, a clip-on lid may also be fitted to the pot.

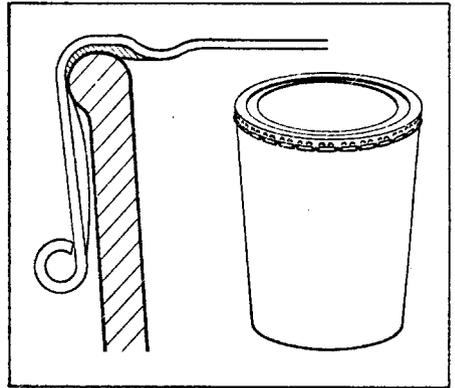
Table 25.1 Seam specifications for selected cylindrical cans

Type of can	Dimensions (mm)		Dimensions of seam (mm)		
	Diameter	Height	Length	Thickness	Hooks*
A1	65.3	101.6	2.97–3.17	1.40–1.45	1.90–2.16
A2	87.3	115.3	2.97–3.17	1.47–1.52	1.90–2.16
A21/2	103.2	115.3	2.97–3.17	1.52–1.57	1.90–2.16
A10	157.2	177.8	3.10–3.30	1.65–1.70	2.03–2.29
Actual overlap > 1.143 mm, % Body Hook Butting > 70%					

* Range of lengths for cover and body hooks.
Adapted from Lock (1969).



(a)



(c)



(b)

Fig. 25.4 Closures for sealing semi-rigid pots and tubs: (a) push-on; (b) snap-on; (c) crimp-on metal caps.

(Courtesy of UG Closures and Plastics.)

Thermoformed pots or trays are filled and then lidded with a web of material that is heat sealed to the top flanges (Fig. 25.5). Small containers such as those used for individual portions for ultra high-temperature sterilised milk, honey or jam, are formed–filled–sealed in a single machine at up to 50 000 containers per hour (Guise, 1985). The equipment can also be easily adapted to produce multi-packs of four to six pots (e.g. yoghurt).

Plastic bottles are sealed using a variety of closures that can be tamper-evident, recloseable or able to form a pouring spout. An example (Fig. 25.6) is suitable for push-on or screw thread bottle necks, for squeezeable bottles that are used to pack creams, oils, sauces or syrups. The caps are made from injection moulded polypropylene, polyethylene or polystyrene (Chapter 24) and have a positive ‘snap-open, snap-shut’ action with a profiled pin to clean the aperture on reclosing. This gives a product seal and also ensures that the aperture is cleaned of product to prevent microbial growth and potential contamination of the product.

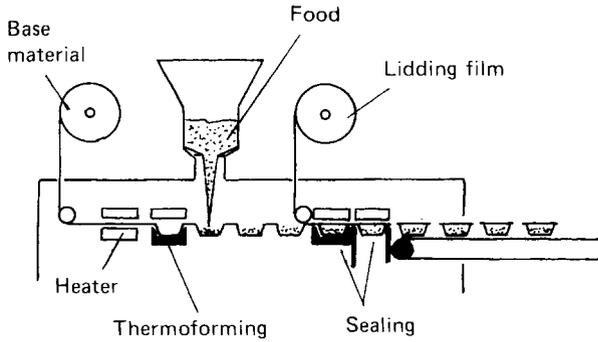


Fig. 25.5 Forming–filling–sealing of individual portion pots.
(After Briston and Katan (1974).)

In each case the seal is formed by causing a resilient material to press against the rim of a container; the pressure must be evenly distributed and maintained to give a uniform seal around the whole of the cushioning material that is in contact with the rim. Typically, a resilient material is stamped out of composite cork or pulpboard sheet, and protected with a facing material (e.g. PVC, PE, EVA) to prevent any interaction with contents (together these are termed the ‘liner’).

The tightness with which the cap is fitted to a container is known as the *tightening torque*, and with rolled-on, crimped-on and pressed-on caps, the effectiveness of the seal depends on pressure exerted on top of the cap during the sealing operation. To avoid the need for undue pressure, the width of the sealing edge is kept as narrow as possible. Glass bottles and jars have a narrow round sealing edge, whereas plastic bottles have flat sealing edges. Two other important considerations for caps are the *thread engagement* (the number of turns of a cap from the first engagement between the cap and rim, and the point where the liner is engaged with the rim). This should be at least one full turn to allow uniform engagement of liner and rim. The greater the thread engagement, the more effective is the cap tightening torque in keeping it in place. The *thread pitch* is the slope or steepness of the thread. The lower the number of turns, the steeper the slope of the thread and the more rapidly the cap will screw on or off (Paine, 1991).

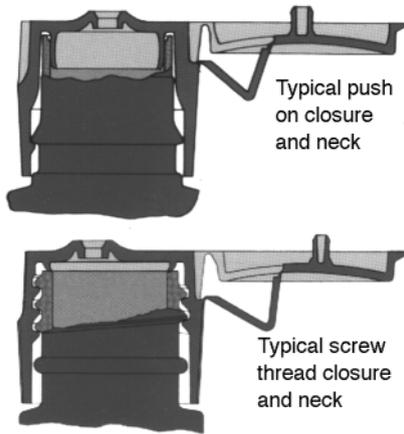


Fig. 25.6 Snap-on caps for squeezeable plastic bottles.
(Courtesy of Johnsen & Jorgensen (Plastics) Ltd.)

Push-on covers are used for injection moulded pots (for yoghurt, cream, etc.) and jars, often having a tamper-evident foil or diaphragm sealed to the top of the pot.

Cases and cartons

Plain or corrugated cases are first designed to give a flat 'blank', which is then cut, creased and folded to form the case or carton. It is important to fit as many blanks as possible to a sheet of paperboard to minimise wastage (Fig. 25.7(a)). Board is printed, cut out using a guillotine either on-site or by the case supplier, and then precisely creased and formed into a carton (Fig. 25.7(b)), which is then either glued or stapled. Different folding carton types are classified by the European Carton Makers Association using an ECMA Code, which also defines how the dimensions should be stated. Details are given by Ramsland (1989).

Multiple packs of cans or bottles are held together by paperboard, formed in a similar way to cartons. These have now been developed to have inter-locking lugs which dispense with the need for staples or glue (Fig. 25.7(c)).

Rigid laminated paperboard cartons have thermoplastic film on the inside. In one system a continuous roll of material is aseptically formed–filled–sealed (Section 25.1.2) whereas, in a second system, pre-formed cartons are erected, filled and sealed in an aseptic filler. In the second system the paperboard can be heavier than in form–fill–seal systems, because it does not require the flexibility needed for the forming machine. As a result the carton is more rigid and particulate foods may be filled without risk of contamination of the seam.

25.2 Flexible containers

Thermoplastic materials or coatings become fluid when heated and resolidify on cooling. A heat sealer heats the surfaces of two films (or 'webs') until the interface disappears and then applies pressure to fuse the films. The strength of the seal is determined by the temperature, pressure and time of sealing. The seal is weak until cool and should not therefore be stressed during cooling. Three common types of seal are as follows:

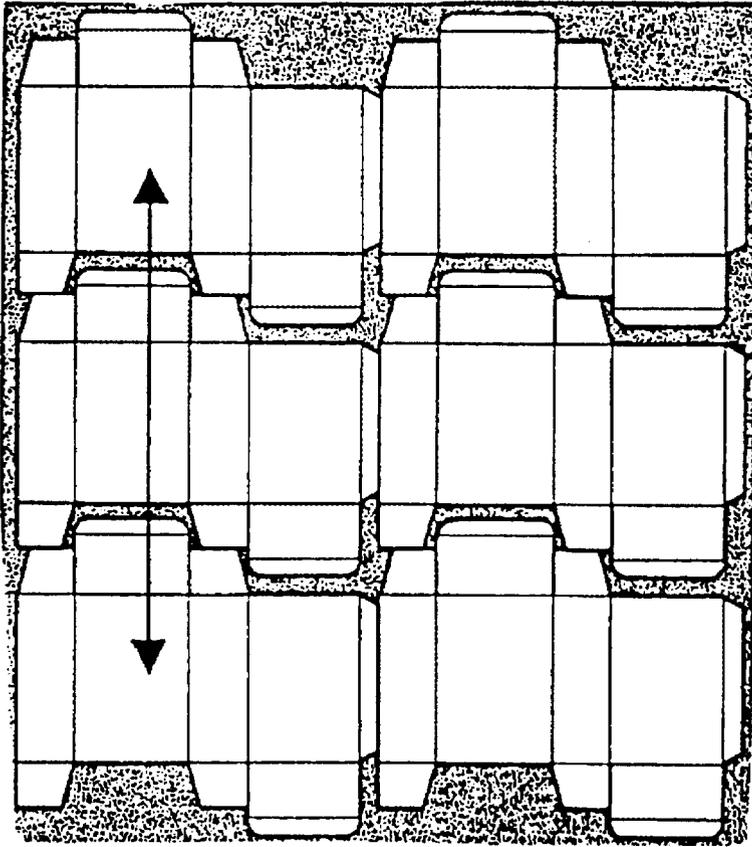
1. bead seals (Fig. 25.8(a))
2. lap seals (Fig. 25.8(b))
3. fin seals (Fig. 25.8(c)).

The bead seal is a narrow weld at the end of the pack. In a lap seal, opposite surfaces are sealed, and both should therefore be thermoplastic. In a fin seal, the same surface of a sheet is sealed and only one side of the film need be thermoplastic. Fin seals protrude from the pack and no pressure is exerted on the food during sealing. They are therefore suitable for fragile foods (for example biscuits and soft confectionery).

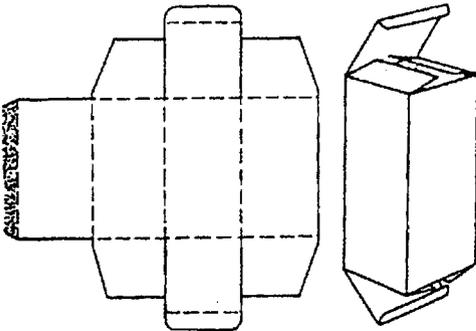
Other types of wrapper include aluminium foil for unusual shaped foods (e.g. chocolate Easter eggs) and twist wrapped cellulose film for confectionery.

25.3 Types of sealer

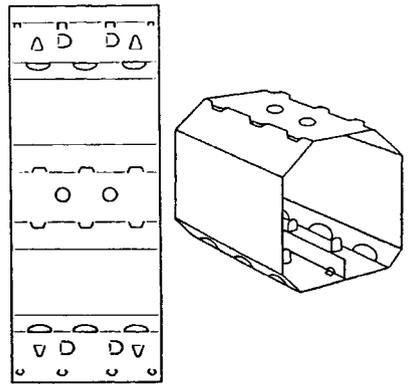
The *hot-wire sealer* is a metal wire, heated to red heat to form a bead seal and simultaneously to cut the film. A *hot-bar sealer* (or jaw sealer) holds the two webs in



(a)



(b)



(c)

Fig. 25.7 (a) Positioning blanks on a sheet of paperboard to minimise wastage; (b) board is creased and formed into a carton (Fellows and Axtell (1993)); (c) inter-locking lugs which dispense with the need for staples or glue in bottle-carrier carton (Paine (1991)).

place between heated jaws until the seal is formed. In the *impulse sealer*, films are clamped between two cold jaws, which each have a metal ribbon down the centre. The films are heated and fused, but the jaws remain in place until the seal cools and sets to

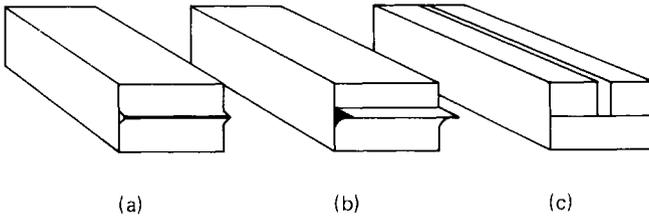


Fig. 25.8 Seals: (a) bead seal; (b) lap seal; (c) fin seal.

prevent shrinkage or wrinkling. These types of sealer conduct heat through the film and therefore risk causing heat damage to the film.

Rotary (or band) sealers are used for higher filling speeds. The centres of metal belts are heated by stationary shoes and the edges of the belts support the unsoftened film. The mouth of a package passes between the belts, and the two films are welded together. The seal then passes through cooling belts which clamp it until the seal sets. In the *high-frequency sealer*, an alternating electric field (1–50 MHz) induces molecular vibration in the film and thus heats and seals it. The film should have a high loss factor (Chapter 18) to ensure that the temperature is raised sufficiently by a relatively low voltage. The *ultrasonic sealer* produces high-frequency vibrations (20 kHz), which are transmitted through the film and dissipate as localised heat at the clamped surfaces. *Cold seals* (adhesive seals) are used to package heat sensitive products (for example chocolate, chocolate-coated biscuits or ice cream).

25.3.1 Form–fill–seal (FFS) equipment

FFS equipment has been one of the most significant growth areas in food packaging during the last 10–15 years. The advantages include reduced transport, handling and storage costs for materials compared to pre-formed containers, simpler and cheaper package production, lower labour costs and higher output (Robinson, 1992).

In *vertical form–fill–seal* (transwrap) equipment (Fig. 25.9), a web of film is pulled intermittently over a forming shoulder by the vertical movement of the sealing jaws. A fin seal is formed at the side. The bottom is sealed by jaw sealers and the product is filled. The second seal then closes the top of the package and also forms the next bottom seal. This type of equipment is suitable for powders and granular products, but liquids may contaminate the seal. Filling speeds are 30–90 min^{-1} . Films should have good slip characteristics and resistance to creasing or cracking, in order to pass over the filling tube, and a high melt strength to support the product on the hot seal.

The vertical *flow pack* (flow wrap) equipment differs from the transwrap design in two ways: first a forming shoulder is not used and the film is therefore less stressed; secondly, the action is continuous and not intermittent. The side seam is formed by heaters and crimp rollers, which pull the tube tightly around the product, make a fin seal and lay it flat against the pack.

In the horizontal form–fill–seal (HFFS) system (*pillow pack* or *flowwrap*), products are pushed into the tube of film as it is being formed (Fig. 25.10). In both types, the transverse seals are made by rotary sealers, which also separate the packs. Filling speeds are over 600 min^{-1} and films should therefore be thin and have a high melt strength, to produce a strong seal in the short heating time available (Briston and Katan, 1974).

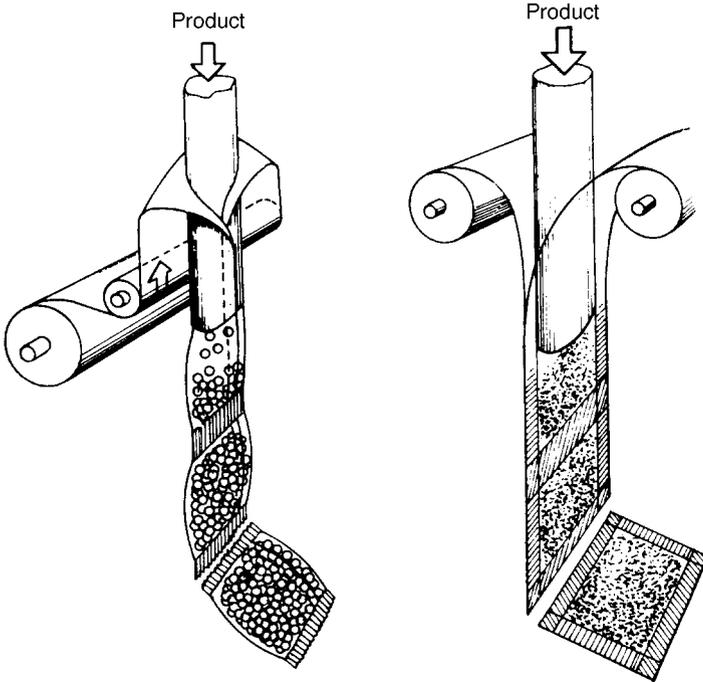


Fig. 25.9 Vertical form-fill-seal (transwrap).
(Courtesy of Flex Industries Ltd.)

HFFS equipment has gained in popularity due to its greater speed (up to 600 packs per minute) and flexibility: it can pack single pieces of food or multiple wrapped or unwrapped pieces; packs can accommodate irregular shaped foods that were previously difficult to pack using foil or glassine (Martin, 1991); it can be used for MAP products (Naylor, 1992) (Table 25.2), and the fin seals ensure a good gas and moisture barrier without risk of damage to the product from sealing head pressure (Fig. 25.8).

A modification of this equipment is used to fill laminated cartons aseptically. A web of material is sterilised in a bath of hydrogen peroxide and formed into a vertical tube. An internal heater vaporises any remaining hydrogen peroxide. The tube is then filled, sealed through the product, shaped into a carton and top sealed. The 'ears' on the base of the carton are folded flat and sealed into place.

In *sachet pack* machines, either horizontal or vertical packs are formed from single or double sheets of film. Horizontal single-web machines fold the film over a triangular shoulder and then form two side seams (Fig. 25.11). The sachets are then separated, opened by a jet of compressed air, filled and heat sealed across the top. The vertical single-web machine is similar to the transwrap machine. Horizontal machines have a smaller distance for the product to fall into the package and are therefore more suitable for sticky foods. Vertical machines have lower cost and take up less floor space.

On two-reel machines, one web forms the front and the second forms the back of the pack. Two blanks are cut from a roll of film, brought together and sealed on three sides. The package is filled and the final seal is made. Sachet machines are widely used for powders or granules (for example coffee, salt and sweeteners), liquids (for example cream) and sauces (for example ketchup and salad cream). Filling speeds are 70–1000

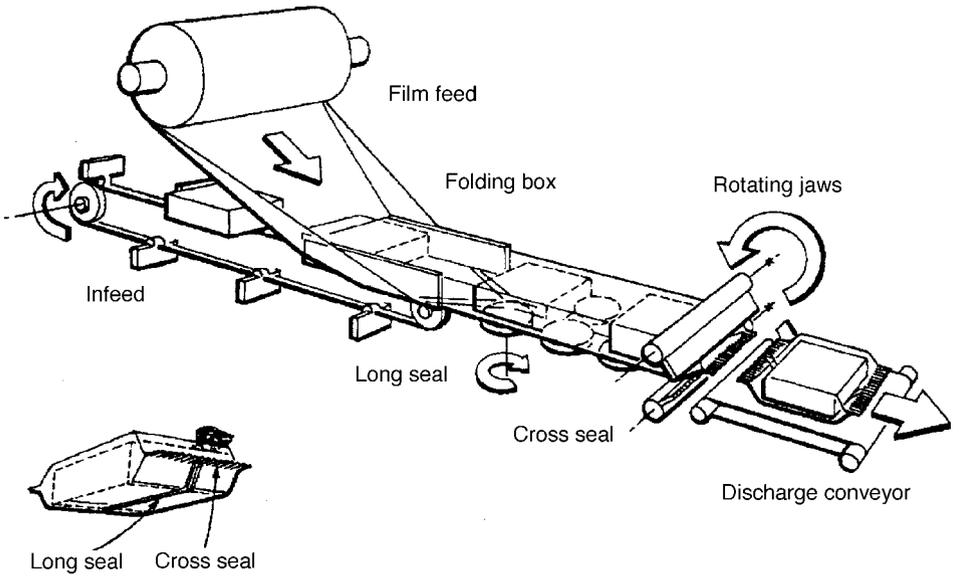


Fig. 25.10 Horizontal form-fill-seal (Flowpack) machine.
(After Naylor (1992) and Wolmsley and Bakker (1986).)

Table 25.2 Packaging systems for MAP products

Type of system	Description	Applications
Thermoforming	Heat forming of semi-rigid and flexible containers, vacuum with gas flushing	Meat, poultry, fish, cooked meats, bakery products, cheese, nuts
Horizontal and vertical form-fill-seal, pillow pack	Single flexible web, gas flushing by lance or tube, venting to atmosphere	Bakery products, snackfoods, cheese, coffee, nuts, meat, fish, salads, fruit, vegetables
Pre-formed tray or bag	Using HDPE, PET or HIPS trays or pre-formed plastic bags, vacuum with gas flushing	Meat, fish, nuts, prepared meals
Thermoforming, composite or pre-formed board/plastic tray	Carton blank and plastic tray form composite tray structure with in-line lidding and vacuum with gas flushing	Meat, poultry, fish, cooked meats, bakery products, cheese, salads, vegetables, prepared meals
Bag-in-box	Barrier or non-barrier bag into corrugated or solid board case, vacuum with gas flushing	Bulk meat, poultry, fruit, cheese, nuts, dried powders
Vacuum skin packs	Multi-layer film top web shrunk over product contained in 'easy-peel' forming bottom web. Gas in headspace before lidding	Meat, fish
Shrink vacuum system	Two webs of film, upper heated and shrunk over product on base web	Meat, fish
Vacuum skin system	Laminate top web shrunk over product on laminated board/film base	Meat, fish
Bag-in-carton	Lined carton, gas flushed	Powders, granular products

Adapted from Hastings (1998).

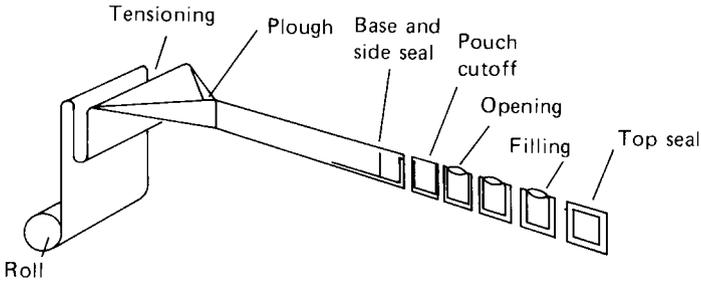


Fig. 25.11 Form-filling-sealing of sachets.
(Courtesy of Engelmann and Buckham Machinery Ltd.)

min^{-1} , depending on the size of the sachet and the type of product. Sachets are automatically cartoned, and the cartoning machine is therefore an integral part of sachet production (Guise, 1987a, and 1987b).

Various devices are used to assist in opening of flexible packs, particularly where a strong film is used. These include tear-tape applied longitudinally or transversely to the pack, slits or perforations that are either produced mechanically by the wrapping machine or cut by laser after wrapping.

Bag-in-box packaging is filled through the tap hole at up to 600 bags h^{-1} , after first removing air. The tap is then sterilised and refitted and the bag is placed into the outer carton.

25.4 Shrink-wrapping and stretch-wrapping

Low-density polyethylene is biaxially oriented to produce a range of films that shrink in two directions (Chapter 24). The shrink ratios are measured in both the machine direction (MD) and the transverse direction (TD). Films are *preferentially balanced* (shrink ratios are MD = 50%, TD = 20%), *fully balanced* (MD = 50%, TD = 50%) or *low balanced* (MD = 10%, TD = 10%). A small amount of shrinkage is usually required to tighten a loosely wrapped package, but contoured packages require a higher shrink ratio. The size of film required to shrink-wrap a sleeve-wrapped package is calculated using

$$\text{width} = A + \frac{3}{4}C$$

$$\text{length} = 2(B + C) + 10\% \text{ shrink allowance}$$

25.4

where A (m) = width of the package, B (m) = length of the package and C (m) = height of the package.

The total mass of film used equals the width multiplied by the length, divided by the yield (a measure of film density) ($\text{m}^2 \text{ kg}^{-1}$). The size of the film required to shrink-wrap an overwrap using centre-fold film is found using:

$$\text{width} = (B + C) + 10\% \text{ shrink allowance}$$

$$\text{length} = (A + C) + 10\% \text{ shrink allowance}$$

25.5

The total mass of film used equals twice the width (m) multiplied by the length (m) divided by the yield ($\text{m}^2 \text{ kg}^{-1}$).

The film is shrunk by passing through a hot-air tunnel or beneath radiant heaters. Alternatively a heat storage gun fires an intermittent pulse of hot air to shrink the film when a package passes beneath. This reduces energy consumption by 70%. Shrink-wrapped trays have now largely replaced fibreboard shipping cases for many products.

In stretch-wrapping, low-density polyethylene, polyvinyl chloride or linear low-density polyethylene (Chapter 24) is wrapped under tension around collated packages. The main advantages over shrink-wrapping include lower energy use than in shrink tunnels (1.5–6 kW compared with 20–30 kW), and lower film use. In shrink-wrapping, 5–10% extra film is used to allow for shrinkage, whereas stretch film is elongated by 2–5%. Together this gives a 10–15% saving in film.

25.5 Tamper-evident packaging

The habit of some consumers of *grazing* (opening packs, tasting the food, and returning it to the shelves) and a number of cases of deliberate poisoning of packaged foods in attempts to blackmail companies, have caused food manufacturers to modify package designs. Although total protection is not possible, tamper-resistant packaging delays entry into the package and tamper-evident packs indicate whether tampering has occurred (Box, 1986). The main problems occur with bottles and jars because they need to be re-closable. There are a number of options to make packs tamper evident (Table 25.3 and Fig. 25.2) including:

- heat-shrinkable polyvinyl chloride sleeves for bottle necks
- foil or membrane seals for wide-mouthed containers, cartons and plastic bottles
- rings or bridges to join a hinged cap to a lower section on bottles (the container cannot be opened without breaking the bridge or removing the ring)

Table 25.3 Tamper-evident packaging

Current tamper-evident packages

Film wrappers that must be cut or torn to gain access

Blister or bubble strip packs (visible evidence of backing material separated from blister, each compartment must be broken, cut or torn to gain access)

Heat-sealed bands or wrappers placed over a cap or lid and shrunk by heat. A perforated strip enhances tamper evidence (must be cut or torn to gain access)

Pouches (must be cut or torn to gain access)

Inner seals – induction seals are better than adhesive seals (must be cut or torn to gain access)

Breakable caps – the cap or part of it is broken to gain access to the container and cannot be replaced

Sealed metal or plastic tubes with both ends sealed. (The mouth has to be punctured to gain access and crimped ends cannot be unfolded without leaving evidence)

Aerosols are inherently tamper resistant

Cans and composite containers in which the top and bottom are joined to the walls so that they cannot be pulled apart

Child resistant closures (clic-lok, squeeze-lok, ringuard, pop-lok, etc.). However, these are not normally used for foods

From Paine (1991).

- roll-on pilfer-proof (ROPP) caps for bottles or jars (during rolling, a tamper-evident ring in the cap locks onto a special bead in the neck to produce a seal which breaks on opening and drops slightly)
- a safety button in press-on twist off closures for heat sterilised jars (a concave section, formed in the lid by the head space vacuum, becomes convex when opened). This may also be combined with a breakable plastic strip that together give both a visual and audible signal that a jar has not been previously opened.

25.6 Labelling

The label is the primary point of contact between a processor and a customer and is therefore an integral part of the marketing strategy for a product. The label is the main method of persuading a purchaser to buy a product without having sampled it, rather than a competing brand on a retail shelf. Details of the factors to be taken into account in the design of labels, legislative requirements and the information required on a label are beyond the scope of this book, and details are given by Blanchfield (2000).

Labels are made from paper, plastic film, foil or laminated materials, pre-printed by either lithographic or rotogravure techniques (Chapter 24). Cans and glass bottles are usually labelled using a hot-melt adhesive at 500 or more containers per minute. A wide variety of label combinations are possible to produce a distinctive brand image for the product. The main types of label are as follows:

- *Glued on labels* – the adhesive is applied at the time of labelling or the label is pre-glued and wetted for application.
- *Thermosensitive labels* – heat is applied at time of application (e.g. biscuit and bread wrappers). These are more expensive but they can also be used as a closure.
- *Pressure sensitive labels* – these self-adhesive labels are pre-coated with adhesive, mounted on a roll of release paper and removed before application.
- *Insert labels* – are inserted into transparent packs.
- *Heat transfer labels* – the design is printed onto paper or polyester substrate and transferred to the package by application of heat.
- *In-mould labels* – this involves thermoforming the container and labelling at the same time. A printed paper label that has a heat-activated coating on the reverse side is placed into the thermoforming mould before the parison is inserted (Chapter 24, Section 24.2.5). When air is injected to blow the package shape, the heat activates the coating. A combination of heat, air pressure and the cold surface of the mould secures the label to the pack and sets the adhesive. The label also contributes to the strength of the pack and reduces polymer use by 10–15%.
- *Shrink sleeve decoration* – used for glass and plastic containers. An axially oriented PVC or PP sleeve is made larger than the container and heat-shrunk to fit it. Alternatively, an LDPE sleeve is made smaller than the container and stretched to fit it. In both methods, the sleeve is held in place by the elasticity of the film, and no heat or adhesives are used. When shrunk over the necks of containers sleeves also provide a tamper-evident closure.
- *Stretchable inks* – that are applied before or during bottle manufacture for labelling plastic bottles.

25.7 Checkweighing

Checkweighers are incorporated in all production lines to ensure compliance with fill-weight legislation (average weight or minimum weight legislation) and to minimise product give-away. They are pre-set to the required weight for individual packs and any that are below this weight are automatically removed from the production line. They are microprocessor controlled and are able to weigh up to 450 packs min^{-1} and automatically calculate the standard deviation of pack weights and the total amount of product that is given away. This data is collated by computers and prepared into reports for use in process management and control procedures (Chapter 2). Checkweighers can also be linked by feedback controls to filling machines, which automatically adjusts the fill-weight to increase filling accuracy and reduce product give-away.

25.8 Metal detection

Details of contaminants in foods and methods of removing them before processing are described in Chapter 3. Contamination with metal fragments can also occur during processing as a result of wear or damage to equipment, and metal detection is therefore an important component of HACCP systems in all food processing plants as well as a requirement to prove due diligence (Chapter 1). The basic components of a metal detection system are:

- a detection head that is correctly matched to the product and set to its optimum sensitivity
- a handling system that conveys the product under the detection head
- a reject system that is capable of rejecting all contaminated product into a locked container
- an automatic fail-safe system if any faults arise
- staff training in procedures to carry out and record quality assurance tests (Greaves, 1997).

Excluding X-ray detectors (Chapter 3), there are two types of metal detectors: the ferrous-only type, used for products in aluminium containers which is based on alteration of a magnetic field; and detectors that are based on the 'balanced coil system'. These latter detectors are made from a coil of wire that conducts a high voltage to produce an electrical field, and two receiver coils placed either side. The voltages induced in the receiver coils are adjusted to exactly cancel each other out. When an electrical conductor (for example a ferrous or non-ferrous metal contaminant or metal-impregnated grease) passes through the detector, it changes the amplitude and/or the phase of the electrical signal induced in the coils, depending on the type of metal (Graves *et al.*, 1998). This change is detected by the electronic circuitry, which activates an alarm and a mechanism to reject the pack (Mayo, 1984). The detector is adjusted for each particular product to take account of differences in electrical conductivity of different foods. Various reject systems are available, including air-blast, conveyor stop, pusher arms for items up to 50 kg and a retracting section of conveyor that allows the product to fall into a collection bin underneath. Details of the operation of metal detectors are given by Anon. (1991). Recent developments include microprocessor control, which enables the characteristics of up to 100 products to be stored in the detector memory, automatic set-up to compensate for

product effects, automatic fault identification and production of printed records to show the number of detections and when they were found.

25.9 Acknowledgements

Grateful acknowledgement is made for information supplied by: ICI Petrochemicals and Plastics Division, Stockton on Tees, Cleveland TS18 3RD, UK; Ampack Ammann GmbH and Co. KG, D-8901 Konigsbrunn, Germany; Rose Forgrove Ltd, Seacroft, Leeds LS14 2AN, UK; Engelmann and Buckharn Machinery Ltd, Alton, Hampshire, UK; Ben Nevis Packaging Ltd, Trowbridge, Wiltshire BA14 8AB, UK; Ilapak Ltd, Hayes, Middlesex UB3 3BN, UK; Peter Holland Machinery Ltd, Stamford, Lincolnshire, UK; Bowater PKL Ltd, Houghton-le-Spring, Tyne and Wear DH4 6JN, UK; Loma Engineering Ltd, Farnborough, Hampshire GU14 0NY, UK; Siamatic Ltd, Soi 52, Bangkok 10110, Thailand; Johnsen & Jorgensen (Plastics) Ltd, London SE8 5AB, UK; Adelphi Manufacturing Co. Ltd, Haywards Heath, W. Sussex RH16 1XQ, UK; Flex Industries Ltd, Ghaziabad, UP 201301, India; Purdy Machinery Company Ltd, London E1, UK; Lumonics Ltd, Kanata, Ontario, Canada.

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Materials handling, storage and distribution

Correct handling of foods, ingredients and packaging materials from suppliers, through the production process, and during distribution to the consumer is essential to optimise product quality and to minimise costs. Improvements in materials handling have led to substantial increases in production efficiencies, and are used at all stages in a manufacturing process, including:

- harvest and transportation to raw material stores
- preparation procedures (Chapter 3) and movement of food within the factory or through a process
- collection and disposal of process wastes
- packaging, collation of packaged foods and movement to finished product warehouses
- distribution to wholesalers and retailers
- presentation of products for sale.

Until recently, materials handling has received relatively little attention, compared with optimisation of process design, packaging developments, marketing, etc., but advances in computer software which optimise the use of warehouse space and vehicle loads, together with developments in bulk handling systems and increasing energy costs, have led to substantial improvements to the efficiency of handling during the last decade. Other examples in which computer programs are used to optimise purchasing and processing choices to reduce costs are described in Chapter 2.

Waste materials are produced by most food processing operations and their handling and disposal are a significantly increasing cost to manufacturers. Legislative requirements for control of food quality, especially for 'high risk' foods, have also increased the costs of storage and distribution. At each production stage, it is therefore necessary to optimise the methods used to handle both foods and wastes to reduce costs. In this chapter, an outline of handling methods that are used to handle solid and liquid materials is given, together with recent advances in storage and distribution of foods, and waste management and disposal.

26.1 Materials handling

Efficient materials handling is ‘the organised movement of materials in the correct quantities, to and from the correct place, accomplished with a minimum of time, labour, wastage and expenditure, and with maximum safety’. Some advantages of correct materials handling are summarised in Table 26.1.

The important techniques identified in Table 26.1 are:

- a systems approach to planning a handling scheme
- the use of unit loads and bulk handling
- continuous methods of handling
- automation (described in Chapter 2).

When establishing methods for materials handling, a systems approach that covers raw materials and ingredients, in-process stock and distribution of finished products to consumers is needed. This creates optimum flows of materials, in the correct sequence throughout the production process, and avoids bottlenecks or shortages. This area is known as *production planning* and detailed descriptions are beyond the scope of this book. Further details are given by Eilon (1970), Magee and Boodman (1967), Tersine (1994) and Shafer and Meredith (1998). In summary, correct production planning should ensure that:

- raw materials, ingredients and packaging materials are scheduled to arrive at the factory at the correct time, in the correct quantities and in the required condition
- storage facilities are sufficient for the anticipated stocks of materials and are suitable to maintain the quality of materials for the required time
- handling equipment has sufficient capacity to move materials in the required amounts
- staff levels are adequate to handle the required amounts of materials
- processing and packaging equipment is selected to provide the required production throughput

Table 26.1 Advantages of correct materials handling techniques and methods of achieving greater efficiency in materials handling

Advantages	Methods of achieving efficiency
<ul style="list-style-type: none"> • Savings in storage and operating space • Better stock control • Improved working conditions • Improved product quality • Lower risk of accidents • Reduced processing time • Lower costs of production • Less wastage of materials and operator time 	<ul style="list-style-type: none"> • Only move materials when necessary and minimise all movements by placing related activities close together • Handle materials in bulk • Package or group materials for easier handling • Use continuous handling techniques and minimise manual handling • Automate where possible • Combine operations to eliminate handling between them • Use a systems approach to optimise material flows and make paths as direct as possible • Use all layers of a building’s height • Use handling equipment that can be adapted to different applications • Use gravity wherever possible

- finished product warehousing is sufficient to accommodate stock levels, taking into account both production and sales volumes
- distribution vehicles are sufficient in number and capacity, and journeys are scheduled to optimise fuel consumption and drivers' time, particularly minimising journeys with empty vehicles.

Aspects of production planning that relate to materials handling are discussed in more detail below and storage facilities, finished product warehousing and distribution are described in Section 26.3. Important questions to be asked when designing a materials handling system are listed by Farrall (1979) for different areas of a food factory and detailed information on materials handling is given by Ingram (1979) and Brennan *et al.* (1990). Sidebottom (1985) describes advances in the control of materials handling in processing and warehousing.

26.1.1 Handling equipment for raw materials and ingredients

The bulk movement of particulate, powdered and liquid food ingredients by road or rail tanker, and storage in large silos, has been common practice in large plants for many years. More recent advances in microelectronics are now applied to monitoring and control of storage silos (fill-level, humidity and temperature) and multi-ingredient batch weighing and metering systems, using PLC based logic controllers (Chapter 2). Additionally, within the last few years increasing use has been made of large (1 tonne or more) intermediate bulk containers (IBCs) for movement of foods. Examples include 'Combi' bins and woven polypropylene bags which are used to both ship ingredients and to move food within a production line. Large bulk packaging made from eight-layer corrugated outer card and an inner food grade membrane are increasingly replacing metal drums as shipping containers (details are given in Chapter 24).

Mechanised handling systems for fresh crops and other raw materials for processing have developed from, for example, the pea viners and combine harvesters that have been in common use for several decades. Mobile crop washing, destoning and grading equipment, gentle-flow box tippers that transport and unload crops with minimal damage, and automatic cascade fillers for large boxes and 'jumbo' bags are now routinely used to produce washed and graded crops for processors and retailers. Further details of raw material preparation are given in Chapter 3.

Batch weighing and metering systems are an integral part of ingredient or raw materials handling and there are a number of different systems: for example, sensors can be used to detect the loss in weight from a storage tank or silo as it is emptied and calculate the weight of ingredient used. Alternatively sensors on a mixing vessel can detect the increase in weight as different ingredients are added. The information from sensors is used by PLCs to control pumps, create pre-programmed recipe formulations and record data for production costing and stock control. Further details are given in Chapters 2 and 25.

26.1.2 Handling equipment for processing

The pattern of movement of materials during processing should be as simple as possible to avoid the risk of contamination of processed foods by raw foods and to attain the other benefits described in Table 26.1. Cross-contamination is a major concern for all food processors, but especially for those that produce 'high-risk' foods. Further details of

special procedures for these foods are described in Chapters 19 and 20. There is no single 'model' layout for plant and equipment, but five patterns are commonly used:

1. *straight line* – for relatively simple processes containing few pieces of equipment
2. *serpentine* (or 'zig-zag') – where the production line is increased for a given floor area by 'bending back' on itself
3. *U-shaped* – used when a process is required to place the finished product in the same general area as the starting point
4. *circular* – used when a part-processed or finished product is required in exactly the same place where it started
5. *odd-angle* – where there is no recognisable pattern, but where short flow lines are needed between a group of related operations, where handling is mechanised or where space limitations will not permit another layout.

Examples of factory layouts that are correctly and incorrectly designed for materials handling are shown in Figs 26.1(a) and (b).

It is important that all equipment which is used to handle foods is designed to be easily cleaned, to reduce the risk of product contamination. Hygienic design of equipment is described by Holm (1980) and Romney (1988). The principles of sanitary equipment design are incorporated into good practice guides (for example Anon., 1967). These can be summarised as follows:

- equipment surfaces that are in contact with food should be inert to the food being processed and must not migrate to, or be absorbed by, the food
- surfaces should be smooth and non-porous to prevent accumulations of food and bacteria
- surfaces should either be accessible for cleaning and inspection, or able to be easily disassembled for manual cleaning and inspection. If cleaned without disassembly, it should be demonstrated that results are similar to manual cleaning

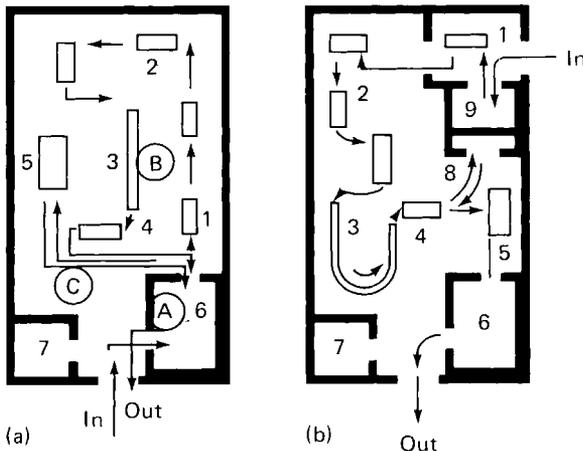


Fig. 26.1 Examples of factory layouts for materials handling: (a) correctly designed and (b) incorrectly designed: 1, cleaning; 2, peeling and preparation; 3, inspection; 4, packaging; 5, freezing; 6, cold store; 7, office; 8, overflow cold store; 9, raw material cold store. Note the following faults in design (a): A, raw material, partly processed product and finished product in same cold store; B, adjacent inspection of prepared food and washing of raw material; C, confused and excessive materials handling.

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- equipment should be self-draining and have a minimum number of internal crevices or 'dead spaces' where food or micro-organisms could collect
- equipment should protect food from external contamination.

Continuous handling equipment is an essential component of continuous processes and it also improves the efficiency of batch processing. The most important types of materials handling equipment used in food processing are

- conveyors and elevators
- pumps.

Other types of equipment, including chutes, cranes and trucks are described by Brennan *et al.* (1990) and are summarised in Table 26.2.

Conveyors and elevators

Conveyors are widely used in all food processing industries for the movement of solid materials, both within unit operations, between operations and for inspection of foods

Table 26.2 Applications of materials-handling equipment

	Conveyors	Elevators	Cranes and hoists	Trucks	Pneumatic equipment	Water flumes
Direction						
Vertical up		*	*		*	
Vertical down		*	*		*	
Incline up	*	*			*	
Incline down	*	*			*	*
Horizontal	*			*	*	
Frequency						
Continuous	*	*			*	*
Intermittent			*	*		
Location served						
Point	*	*			*	*
Path	*				*	*
Limited area			*			
Unlimited area				*		
Height						
Overhead	*	*	*		*	
Working height	*			*	*	*
Floor level	*		*	*		*
Underfloor	*				*	*
Materials						
Packed	*	*	*	*		
Bulk	*	*	*	*	*	
Solid	*	*	*	*	*	*
Liquid				*	*	*
Service						
Permanent	*	*	*		*	*
Temporary			*	*		

From Brennan *et al.* (1990).

(Table 26.2). There are a large number of conveyor designs, produced to meet specific applications, but all types can only cover a fixed path of operation. Their operation, and the development of 'intelligent' conveyors, is reviewed by Perera and Rahman (1997). Common types include *belt conveyors* – an endless belt which is held under tension between two rollers, one of which is driven. The belts may be stainless steel mesh or wire, synthetic rubber, or a composite material made of canvass, steel and polyurethane or polyester. They are described in detail by Brown (1983). Flat belts are used to carry packed foods, and trough-shaped belts are used for loose materials. Flat belts may be inclined up to 45° , if they are fitted with cross slats or raised chevrons to prevent the product from slipping.

Roller conveyors and *skate wheel conveyors* are usually unpowered, but roller conveyors may also be powered. The rollers or wheels are either horizontal, to allow packed foods to be pushed along, or slightly inclined (e.g. a fall of 10 cm in a length of 3 m) to allow packs to roll under gravity. Rollers are stronger than wheels and therefore able to carry heavier loads, but their greater inertia means that they are more difficult to start and stop, and they are more difficult to use around corners. Additionally, the build up of materials on the rollers and bearings causes increased friction, which increases power consumption and maintenance costs. 'Air-cushioned' conveyors overcome these problems by carrying materials on a film of air blown into tubular trough sections by a small fan.

Chain conveyors are used to move churns, barrels, crates and similar bulk containers by placing them directly over a driven chain, which has protruding lugs at floor level. *Monorail* conveyors are used for moving meat carcasses or boxed poultry carcasses on an overhead track. *Screw conveyors* comprise a rotating helical screw inside a metal trough. They are used to move bulk foods such as flour and sugar, or small-particulate foods including peas and grain. The main advantages are the uniform, easily controlled flowrate, the compact cross-section without a return conveyor and total enclosure to prevent contamination. They may be horizontal or inclined, but are generally limited to a maximum length of 6 m as above this, high friction forces result in excessive power consumption. *Vibratory conveyors* cause a small vertical movement to food to raise it a few millimetres off the conveyor, and forward movement to transport it along the conveyor (Fig. 26.2). The amplitude of vibration is adjusted to control the speed and direction of movement and this precise control makes vibratory conveyors useful as feed mechanisms for processing equipment.

Pneumatic conveyors consist of a system of pipes through which powders or small-particulate foods, such as salt, flour, peas, sugar, milk powder, coffee beans, etc., are suspended in recirculated air and transported at up to $20\text{--}35\text{ m s}^{-1}$. The air velocity is

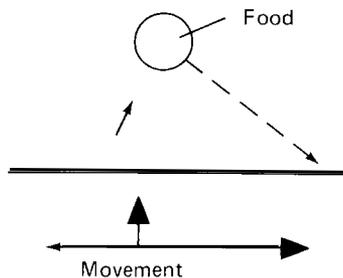


Fig. 26.2 Action of a vibratory conveyor.

INTRODUCTION

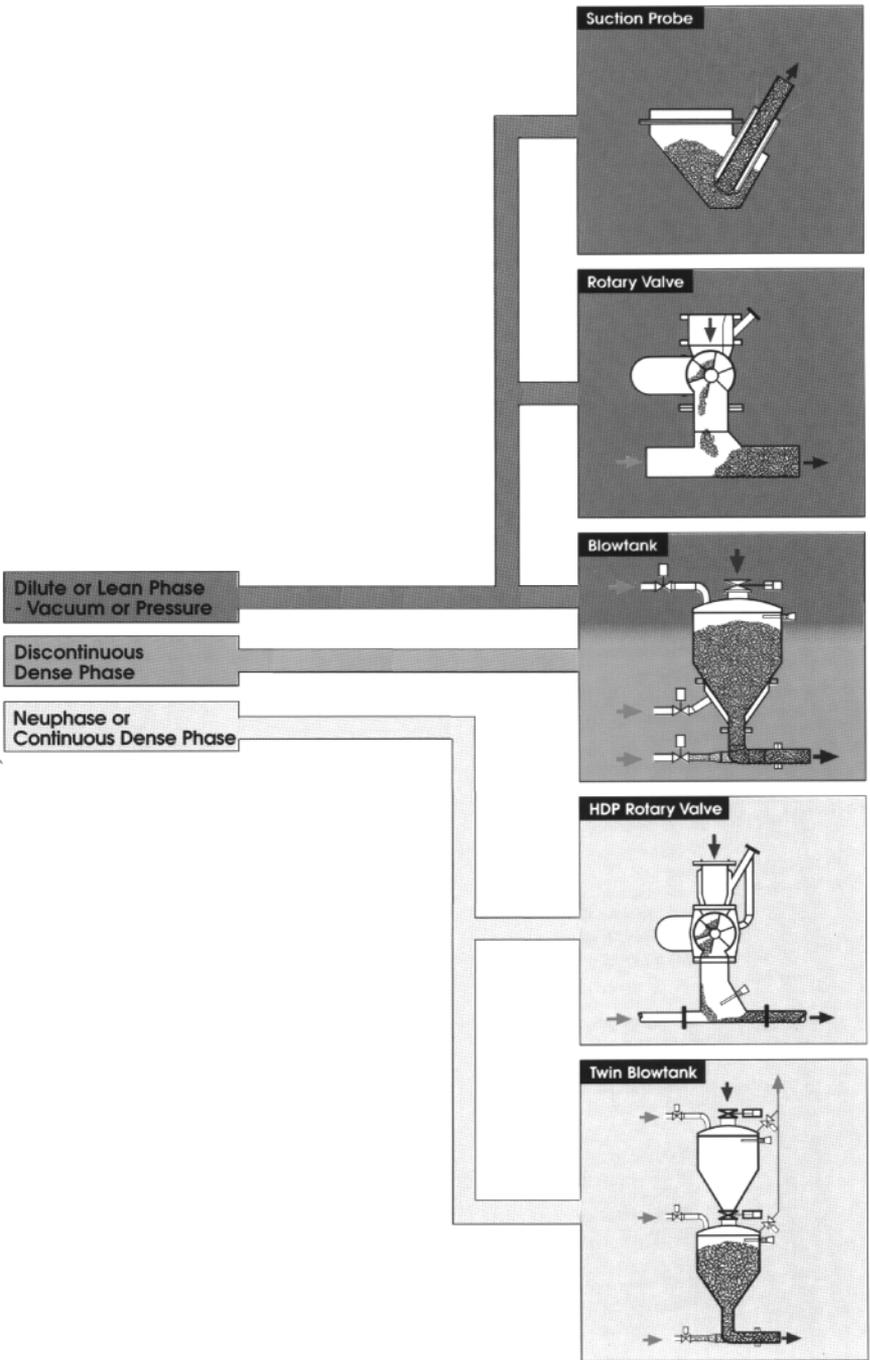


Fig. 26.3 Different types of pneumatic conveying.
(Courtesy of NEU Ltd.)

DISCHARGE



Dilute or Lean Phase - Vacuum

Suction created so that pipeline operates below atmospheric pressure. Product cannot escape into environment. Dust free product introduction. Pick up from single or multi-sources simplified.

Dilute or Lean Phase - Pressure

Material carried by aerodynamic force with comparatively high air velocities (20 - 35 m/s), but low pressures (max approx 1 bar). Simplest, most economical blowing system. Ideal for conveying free-flowing product from source to one or especially more than one destination.

Discontinuous Dense Phase

Product is conveyed in an airborne mass at pressures usually in the region of 2 - 6 bar. Velocities are in the range of 15 - 20 m/s and high product to air ratios are achieved. Material feed is normally on a batch basis from a pressure vessel or twin blowtank arrangement. Low pressure loss results in minimum power consumption and air requirement, leading to smaller pipes and receiving equipment. Ideal for cohesive, damp, dense or granular products, but other bulk particulates can also be handled.

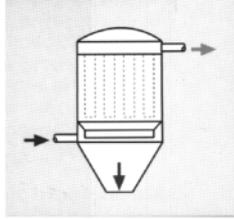
Neuphase or Continuous Dense Phase

Product is transferred very slowly at a fraction of the speed of other systems. Velocities are restricted to 4 - 6 m/s along the whole route. Very high product/air ratios (kg/kg) in excess of 150:1 can be obtained, resulting in low air consumption. Ideal means of conveying fragile or abrasive products. Twin blowtanks are the traditional method of product introduction, but the Neu HDP Rotary Valve is a highly efficient alternative. Advantages include continuous operation, compact size and product conservation.

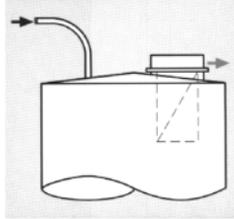
Conveying Velocity
Minimum conveying velocity means minimum product damage and system wear, especially important with fragile or abrasive products. Achieved by selecting correct velocity and most applicable conveying technique for each product.

Stepped Pipelines
Applicable to all systems. As the pressure along a constant diameter conveying pipe gradually decreases so the velocity increases. To maintain a velocity within $\pm 10\%$ of design, the pipeline is progressively expanded in steps, reducing pipeline wear, product damage and energy consumption.

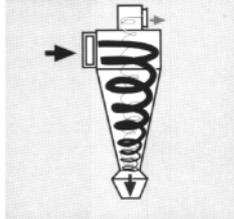
Filter Receiver



Insertable Filter



Cyclone



critical; if it is too low, the solids settle out and block the pipe, whereas if it is too high, there is a risk of abrasion damage to the internal pipe surfaces. The calculation of air velocity needed to suspend foods is described in Chapter 1. Different types of pneumatic conveying are described in Fig. 26.3, together with various methods of introducing materials into the pneumatic conveyor and removing them after conveying. Similar equipment is used to classify foods (Chapter 3), and when heated air is used, to dry foods (Chapter 15). Generation of static electricity by movement of foods is a potential problem that could result in a dust explosion when conveying powders, and is prevented by earthing the equipment, venting, or explosion containment and suppression techniques. Pneumatic conveyors cannot be overloaded, have few moving parts, low maintenance costs and require only a vacuum pump or a supply of compressed air at around 700×10^3 Pa. Details of new developments in conveying are given by Sharp (1998).

Conveying foods in water using shallow inclined troughs (or *flumes*) and pipes finds application for the simultaneous washing and transporting of small particulate foods, such as peas, sweetcorn, etc. The main advantage is reduced power consumption as water flows under gravity, especially at factory sites located on hillsides. Water is recirculated to reduce costs and is filtered and chlorinated to prevent a build up of micro-organisms.

There are many designs of *elevator*, but two common types are bucket and magnetic elevators: *bucket elevators* consist of metal or plastic buckets fixed between two endless chains. They have a high capacity for moving free-flowing powders and particulate foods. The shape and spacing of the buckets and the speed of the conveyor ($15\text{--}100$ m min^{-1}) control the flow rate of materials. *Magnetic elevators* are used for conveying cans within canneries (Chapter 12). They have a positive action to hold the cans in place, and are thus able to invert empty cans for washing, and they produce minimal noise.

In general, conveyors and elevators are best suited to high-volume movement, where the direction of flow of materials is fixed and relatively constant. They can also be used as a reservoir of work-in-progress.

Pumps and valves

Pumps, valves and associated pipework are the usual method of handling liquid foods, cleaning fluids, etc., and there is a very wide range of designs that are available, often for specific applications. Centrifugal pumps are widely used in food processing and the selection of a particular pump is based on the following requirements:

- type of product, particularly its viscosity
- product flowrate, pressure and temperature
- type of impeller
- motor size (determined by the required flowrate and impeller diameter) and speed
- type of seal on motor shaft and pump body
- type of pipework couplings and other fittings (e.g. motor shroud, number of legs, lifting handle and mounting brackets).

In some applications, high pressure piston pumps, positive displacement pumps, vacuum pumps, or rotary pumps for gentle product handling or special hygiene conditions may be required. Further details are given by Hogholt (1998).

There are a large number of different types of valves that are used in food processing pipelines, each of which is suitable for easy cleaning-in-place (CIP) to prevent contamination of the product and can be operated either manually or, more commonly, automatically using compressed air and/or electricity.

- *Butterfly valves* contain a pivoting disc that can be closed against a food grade seal. They are suitable for pressures up to 1 MPa.
- *Single and double seat valves* contain a stainless steel ball that is moved into a corresponding seat using an actuator. They are suitable for process pressures of up to 0.5 MPa. The double seat type enables two fluid streams to pass through the valve without mixing and thus finds application in CIP (Fig. 26.4).
- *Diaphragm valves* consist of a elastomer membrane or stainless steel bellows that prevent the product from having contact with the valve shaft. They are used for sterile applications up to product pressures of 0.4 MPa.

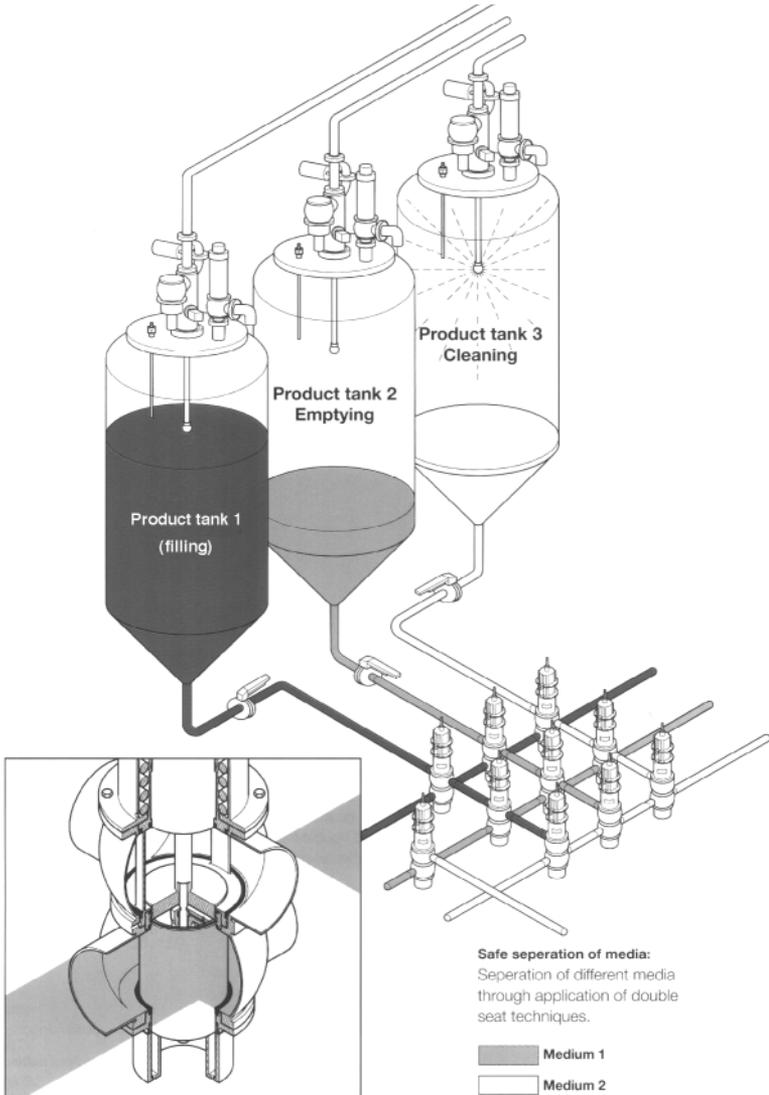


Fig. 26.4 Double seat type valve in an application for cleaning in place (CIP).
(Courtesy of APV Fluid Handling Ltd.)

Other types of valve include:

- *safety valves* to prevent excess pressure in pressure vessels
- *vacuum valves* to protect vessels or tanks from collapse under unwanted vacuums
- *modulating valves* to permit the exact control of product throughputs
- *non-return (or 'check') valves*, and *sampling valves* to allow bacteriologically safe samples to be taken from a production line without the risk of contaminating the product.

All valves can be fitted with proximity switches to detect and transmit their position, and pneumatic or electro-pneumatic actuators to position the valve accurately. Further details of the use of valves in process control are given in Chapter 2.

26.2 Waste management and disposal

With the exception of a few processes (for example baking or grain milling), solid wastes and liquid effluents are produced in large quantities by food processing (Table 26.3). They arise due to cleaning and preparation of raw materials (Chapter 3), spillages and cleaning of equipment and floors, and change-overs to different products.

Adequate cleaning routines in food plants are part of good manufacturing practice (GMP) (Anon., 1998a) and form an integral part of management systems needed to implement quality assurance and HACCP programmes (Chapter 1). Software to assist managers to devise adequate cleaning schedules to meet HACCP requirements is described by Dillon and Griffith (1999). Detailed information on plant cleaning is also available in a number of texts including Quartly-Watson (1998), Marriott (1989), Tamplin (1980), Guthrie (1988) and Dillon and Griffith (1999).

The nature of wastes varies according to the type of food being processed: fruit and vegetable processing, for example, produces effluents that have high concentrations of sugars, starch and solid matter such as peelings, whereas meat and dairy processing effluents contain a higher proportion of fats and proteins. Nearly all processors also produce dilute waste water from washing equipment, and solid wastes from discarded packaging materials, office paper, etc. Sources of production of effluents and their

Table 26.3 Volumes and composition of wastes from selected food processing operations

Commodity	Volume (litres per unit)	BOD (mg/l)	Suspended solids (mg/l)
Fruit products ¹	90–450	1 000–5 000	100–2 000
Meat packing ²	9 000–36 300	600–1 600	400–720
Milk processing ³	12–23	20–650	30–360
Mushrooms ²	30 000	80–850	50–240
Potato chips ²	18 000	730–1 800	800–2 000
Poultry packing ⁴	6.8	725–1 150	770–1 750
Sauerkraut	14–80	1 400–6 300	60–630
Vegetable products ⁵	90–1 260	500–11 000	30–4 000

¹ Per case of product (data from apples, apricots, citrus, pumpkin and tomatoes).

² Per ton of product.

³ Per litre of milk.

⁴ Per chicken.

⁵ Per case of product (data from beans, carrots, corn, peas, peppers, spinach).

Data adapted from Guthrie (1988), Potter (1986) and Dalzell (1994).

treatment methods are described by Tebbutt (1992) and Brennan *et al.* (1990). Wheatley (1994) describes the composition of typical food industry wastes and methods that can be used to minimise waste production. Anon. (1996) describe methods for auditing wastes and reducing their costs.

In large processing plants or those located in unpopulated areas, effluent treatment can be carried out on-site in purpose-built facilities, but the effluent from most food factories is treated by municipal authorities or private water utilities. The cost of effluent treatment is based on a combination of the volume of effluent and its polluting potential, as measured by both chemical oxidation demand (COD)¹ and the amount of suspended solids (in mg l⁻¹). High concentrations of sugars, starches and oils have very high polluting potential (CODs from 500–4000 mg l⁻¹ compared to domestic sewage at 200–500 mg l⁻¹) because as micro-organisms utilise these materials, they remove dissolved oxygen from water, which may kill fish and aquatic plants. Charges are therefore considerably higher for treatment of these effluents. The cost of effluent treatment in the UK is calculated using the Mogden formula (Anon., 1998b):

$$C = R + (V \text{ or } VB \text{ or } VM \text{ or } M) + B(O_t/O_s) + S(S_t/S_s) \quad \boxed{26.1}$$

where C = total charge per m³ of trade effluent, R = reception and transport charge per m³, V = volumetric and primary treatment charge per m³ in effluent treatment works that do not have biological treatment, VB = volumetric and primary treatment charge per m³ in effluent treatment works that have biological treatment, VM = treatment and disposal charge per m³ at non-designated sea outfalls, M = treatment and disposal charge per m³ at designated sea outfalls, O_t = COD (mg l⁻¹) of trade effluent after 1 h settlement, B = biological oxidation charge per m³ of settled sewage, S_t = total suspended solids (mg l⁻¹), S = treatment and disposal charge per m³ of primary sludge, O_s = mean strength (COD) of settled sewage at treatment works (currently 453 mg l⁻¹), S_s = mean suspended solids at treatment works (currently 395 mg l⁻¹) (Anon., 1998b).

This formula is important for calculating the cost of effluent treatment as, together with water purchase, this is steadily increasing and now comprises a major cost to food businesses. In many processes it is possible to reduce treatment costs by separating concentrated waste streams from more dilute ones (for example, washings from boiling pans in confectionery or jam production can be isolated from general factory wash-water). Effluents that contain a relatively high percentage of sugars, starch or pectic materials have been used in some instances as growth media for yeasts or moulds (Fellows and Worgan, 1987a and 1987b) to produce saleable animal feeds and thus reduce the costs of treatment (Forge, 1978; Hang, 1980 and Jarl, 1969). Other means of reducing both polluting potential and waste treatment charges include:

- recycling water
- recovering fats and oils by aeration flotation for sale as by-products
- storing concentrated effluents and blending them over a period of time with dilute wastes to produce a consistent moderately dilute effluent
- removing solids using screens and discharging them as solid waste to commercial waste disposal companies or for composting

1. COD is a measure of chemical oxidation using boiling potassium dichromate and concentrated sulphuric acid. BOD (biological oxidation demand) is a measure of the oxygen requirement by micro-organisms when breaking down organic matter, but is no longer used to calculate effluent treatment charges.

- flocculating suspended solids using a chemical coagulant (for example lime or ferrous sulphate) or removing suspended solids directly by sedimentation, filtration or centrifugation (Chapter 6) and disposing of them as solid waste
- treating effluents using a biological method such as a trickling filter, activated sludge processes, lagoons, pond, oxidation ditches, spray irrigation or anaerobic digesters
- fermenting waste materials to produce more valuable products (e.g. organic acids, vitamins, etc.).

Descriptions of the methods used to treat effluents and details of the advantages and limitations of these treatment methods are given by Tebbutt (1992) and Brennan *et al.* (1990).

Solid wastes, packaging and office waste materials are collected in some countries by municipal authorities and in others by private waste management and recycling companies. They are usually disposed of in landfill sites, but increasing shortages of suitable sites and steadily increasing costs of collection have stimulated incentives and opportunities for recycling and re-use, especially for paper, metals and some types of plastics. These developments are described in Chapter 24.

26.3 Storage

Storage of raw materials, ingredients and products can take place under ambient conditions or under controlled conditions of temperature, humidity or atmospheric composition. Storage of chilled and frozen foods is described in Chapters 19 and 21 respectively and controlled or modified atmosphere storage is described in Chapter 20. Storage of packaging materials is discussed in Chapter 24. In this section, storage under ambient conditions is described for a range of representative foods.

In general, manufacturers reduce the amount of stored ingredients and products to a minimum for the following reasons:

- financial – money is tied up in materials that have been paid for, or in final products that have incurred the costs of production. Large amounts of stored materials may adversely affect the cashflow of a company.
- loss of quality – chemical or biochemical changes to foods and deterioration of some types of packaging materials may occur during storage which reduce their quality and value, or render them unusable.
- risk of pilferage for some high value products
- high cost of warehousing and storage space.

However, because of the seasonality of supply for some raw materials and, for some products a seasonal demand, it is necessary for processors to maintain stocks of ingredients, packaging materials and final products. The ‘just-in-time’ methodologies of materials supply that are found in some other industries (Johnson *et al.*, 1997) are less common in the food processing sector. Stored goods (or *inventory*) may be classified into raw materials, work-in-progress and finished goods. However, they can be categorised more usefully by their role in the production system (Johnson *et al.*, 1997) as follows:

- buffer (or safety) inventory, to compensate for uncertainties in supply or demand
- cycle inventory – this occurs because a processor chooses to produce in batches that are greater than the immediate demand

- anticipation inventory – this is created where seasonal demand or supply fluctuations are significant but predictable. It is used especially for supply of seasonal fruits and vegetables, or for products that have a specific seasonal demand (for example Easter eggs and Christmas cakes)
- pipeline (or in-transit) inventory, for materials that are in the process of being moved from a point of supply to a point of demand.

Decisions on the size of stocks of different materials that are held in storage depend on the balance between two sets of costs: the cost of buying and the cost of storage. For example one strategy is to hold a small stock and only buy materials as they are needed. This has little effect on the cashflow of a business but may be more expensive in having to make frequent orders and not obtaining discounts from bulk purchases. Conversely, ordering large amounts of materials infrequently may benefit a company by achieving a discounted price and reduced administration, but incurs higher storage costs. One way of controlling inventory costs is to rank individual materials by their *usage value* (their rate of usage multiplied by their individual value) into three classes (Johnson *et al.*, 1997):

1. Class A – the 20% of high value materials that account for 80% of the total usage value
2. Class B – the next 30% of medium value materials which account for 10% of the usage value
3. Class C – the lowest value materials that are stocked, comprising 50% of the total, which account for 10% of the usage value.

Class A products are then given inventory preference over Class B and in turn over Class C.

The physical conditions of storage are an important aspect that may be given less attention than other areas of processing and as a result, causes problems of contamination and financial losses. It is important that there is a similar level of control over hygiene and storage conditions in warehouses and distribution vehicles to that given to processing operations. The main causes of spoilage of stored foods and ingredients are as follows:

- contamination by rodents, birds, insects and micro-organisms
- contamination by dust or foreign bodies
- respiratory activity of fresh foods, or enzyme activity leading to development of rancidity or browning
- losses from spillage, bursting of containers, etc.
- incorrect storage conditions such as exposure to sunlight, heat and moisture.

Correct storage and prevention of spoilage are particularly important for finished products, because the expenditure that has already been made during processing makes losses at this stage very damaging financially.

Storerooms, warehouses and distribution vehicles should therefore be constructed to prevent access by rodents, insects and birds, and carefully inspected on a regular basis to ensure that preventative measures are effective. Details of materials used for construction of storerooms are given by Brennan *et al.* (1990). Windows are screened against insects, drainage channels and power cable ducting are fitted with devices to prevent entry by rodents, the structure of the roof and walls is designed to prevent insects, rodents and birds from gaining entry. Doors are fitted with screens or air curtains and rooms are equipped with insect electrocutors. Floors are covered with vinyl based coatings to prevent cracks that could harbour insects and micro-organisms.

For ambient temperature storage, the store-room should be cool with good ventilation to maintain a flow of air. Fresh foods are only stored for short periods, but the storeroom temperature should be low and humidity sufficiently high to prevent wilting or drying out (see Chapter 20). Ingredients such as sugar, salt and powdered flavourings or colourants can pick up moisture from the atmosphere. Where this is likely to result in loss of quality or function, the humidity in a storeroom should be controlled to equal the equilibrium relative humidity (ERH) (see Chapters 1 and 15) of the stored product. For example, white sugar which has an ERH of 60% will form a cake if it picks up moisture, and it is therefore stored below 60% humidity. Fats and oils are particularly susceptible to odour pickup, and spices are likely to contaminate other ingredients with their odour. Both types of ingredient are therefore stored separately from other foods.

Most foods are packaged for protection and convenience of handling. Packages which are grouped into larger (or 'unitised') loads require less handling when they are moved through storage and distribution networks. Wooden pallets are commonly used to move unitised loads of cases or sacks by fork-lift or stacker trucks. A development of this method uses fibreboard slipsheets to reduce the volume occupied by pallets in vehicles and warehouses (Spren and Ellis, 1983). Products are secured onto the pallet or slipsheet by shrink-film or stretch-film (Chapters 24 and 25).

Working procedures in storerooms and warehouses ensure that sacks or cartons of food are stored on pallets or racks to keep them off the floor, with space to clean behind the stack. They should be carefully stacked to the recommended height to prevent crushing or collapse and injury to operators. Lighting should be as bright as possible and at a high level to reduce shadowing caused by stacked pallets. Warehouse management systems are increasingly computer controlled (Chapter 2) and are used to monitor material movements into and out of the stores, check stock levels, stock rotation, the use of materials in the process and the destinations for delivery of products. Daily cleaning routines are used as part of a HACCP plan (Chapter 1) to prevent dust or spilled food accumulating which would encourage insects or rodents.

Large warehouses use computerised truck-routing systems, which store information on stock levels, their location in a warehouse and warehouse layout. Computers that control automated guided vehicles (AGVs) have been used for a number of years. The AGVs follow fixed routes guided either by wires buried in the warehouse floor or coloured lines painted onto the floor. These are now being replaced by 'free-path' AGVs in which the computer assigns an optimum route for each vehicle. Packaged goods are palletised and each pack and pallet is coded with a bar code that is read by a microprocessor. The coded stock is allocated a storage location by the computer, which compiles both a map of the warehouse and current stock levels in its memory. The progress of each AGV in retrieving or replacing stock is monitored and controlled using information transmitted by an odometer in the vehicle and by bar-code directions that are displayed throughout the warehouse, which are read by a laser mounted on the truck. Developments in robotic handling and picking in warehouses and other areas of food processing are described by Murphy (1997a, 1997b).

26.4 Distribution

The link between harvesting and production of a processed food and purchase by the customer is known as the *distribution chain* (for example Fig. 26.5) and the different

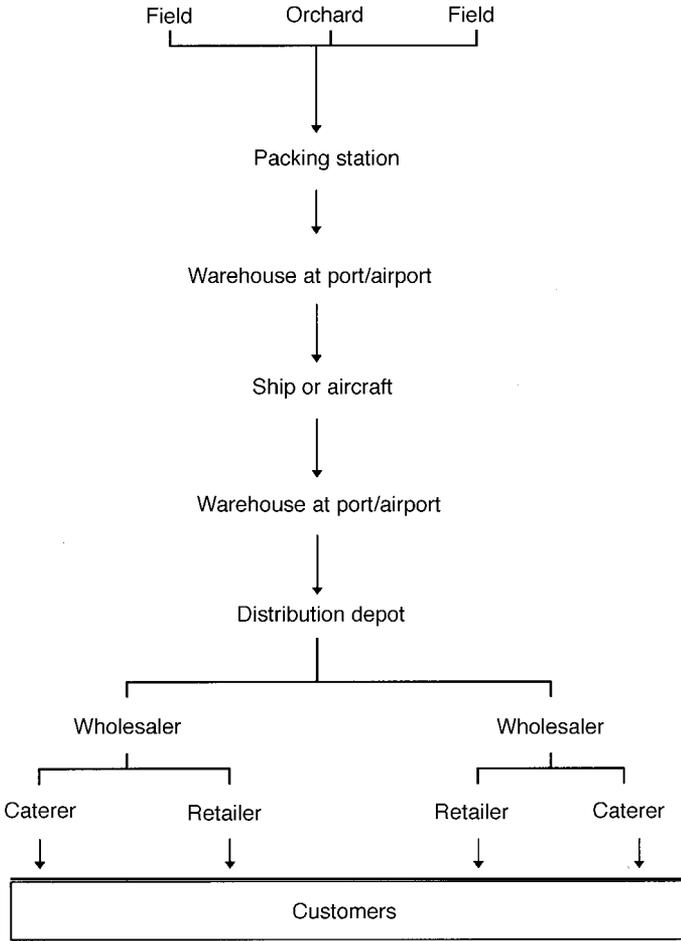


Fig. 26.5 Simplified distribution chain for fresh fruit and vegetables.
(→ transport by road or rail)

systems involved in distribution are termed ‘logistics’. The main factors that are involved in an efficient distribution chain are:

- providing the consumer with products at the right place, at the right time and in the right amount
- reducing the cost to a minimum (distribution is an expense but does not add value to a product)
- maintaining the product quality throughout the distribution chain.

Further details are given by Rushton and Oxley (1989) and a case study that describes the handling and distribution of peas from harvest to sale of frozen product is described by Chambers and Helander (1997).

Within the last decade, consumers have demanded foods having better quality, freshness, availability, and a greater variety. This consumer pressure has resulted in a substantial increase in the volume and range of foods that are handled by the major food retailers, together with higher standards for temperature control of some foods (Chapter 19). This in turn has caused retailers to change their methods of storage and distribution,

and these companies now dominate food distribution. Previously, products from a food manufacturer were transported to a relatively large number of small distribution depots that each handled a single product. Delivery volumes were low and it was not economic to deliver every day. In addition, foods that required temperature-controlled transport had to be carried on separate vehicles, some of which were owned by contractors who operated their own distribution policies and delivery schedules. Each of these aspects increased the cost of distribution and reduced both quality and efficiency.

These problems caused retailers to change their strategy for food distribution, and use mathematical models and simulations to improve the logistics of food supply to reduce costs and distribution times as a result of:

- combining distribution streams of various suppliers
- combining transport of fresh food, frozen food and dry foods
- changing the method and frequency of ordering
- redesigning and reorganising warehouses

Koster (undated).

These developments resulted in a smaller number of large ‘composite’ distribution depots that can handle a wide range of products. Each composite depot, which may cover 23 000 square metres (250 000 square feet), can typically handle more than 30 million cases of food per year and serve up to 50 retail outlets. The depot is divided into five temperature zones (ambient, semi-ambient (+10°C), chill (+5°C), chilled (0°C) and frozen (−25°C)) to handle the range of short- and long-shelf life products found in most large stores (Harrison, 1997). Delivery vehicles use insulated trailers that are fitted with movable bulkheads and refrigeration units to create three different temperature zones. Short shelf life products are received into distribution depots during the afternoon and evening, and are delivered to retail stores before trading starts the next day (termed the ‘first wave’ delivery). Longer shelf life and ambient products are taken from stock and formed into orders for each retail store over a 24-hour period, and are delivered in a ‘second wave’ between 8 am and 8 pm at scheduled times that are agreed with each store. Many larger retailers now use electronic data interchange (EDI) to automatically order replacement products, directly in response to consumer purchases (also Chapter 24, Section 24.3.1). This results in more frequent deliveries of smaller amounts of product, in order to minimise stock levels in stores. Further details are given by Krcmar *et al.* (1995) and O’Callaghan and Turner (1995). However, these developments have caused a dramatic increase in distribution and handling costs for processors. Many smaller- and medium-scale processors now co-operate in logistics, to gain cost savings and more efficient distribution from the larger volumes that are handled. In addition, co-operation and sharing of costs enables these processors to invest in automatic order picking systems that would be unaffordable for individual companies (Koster, undated).

Managers in processing factories use forecasts of demand for foods and actual orders to inform computer-based systems, known as material requirement planning (MRPI) systems which co-ordinate decisions on ordering, stock levels, work-in-progress, storage and distribution of finished products. This enables them to calculate the amounts of materials that are needed at a particular time to manufacture products to meet customer demand. The software is also used to generate customer orders and sales forecasts, the physical distribution routes for products, records of available stocks and inventory. The information can then be used to produce purchase orders for raw materials, work orders and material plans (Johnson *et al.*, 1997).

The concept of MRPI has expanded during the last 20 years to integrate other parts of the business and has become Manufacturing Resource Planning (MRPII). This is a single integrated system, containing a database that can be accessed by all parts of the company, including engineering departments, sales and marketing departments, finance and accounting departments as well as production managers. Information from sales can therefore be used directly in, for example, production scheduling, buying and plant maintenance. Details of computerised systems for management and process control are described in Chapter 2 and further information is given by Orlicky (1975) and Tersine (1994).

26.5 Acknowledgements

Grateful acknowledgement is made for information supplied by: Mettler Instrument Corporation, Hightstown, New Jersey 08520, USA; CAP Industry Ltd, Reading, UK; Ferranti Computer Systems, Simonsway, Wythenshawe, Manchester M22 5LA, UK; APV International Ltd, PO Box 4, Crawley, West Sussex RH10 2QB, UK; Baker Perkins Ltd, Peterborough PE3 6TA, UK; Alfa Laval Ltd, Brentford, Middlesex TW8 9BT, UK; Anglia Water Services Ltd, Huntingdon, Cambs. PE18 6XQ, UK; Peal Engineering Ltd, Horcastle, Lincs. LN9 6JW, UK; Euro-pak, B-1150 Brussel-Bruxelles, Belgium; NEU Engineering Ltd, Woking, Surrey GU22 7RL, UK; APV Fluid Handling, Ternevej 61-63, DK-8700 Horsens, Denmark.

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Appendix A

Vitamins in foods

Vitamin	Nature and properties
Vitamin A	Present in animal foods as retinol, and in plant foods mostly as all- <i>trans</i> β -carotenes. The chemical structure includes double bonds which were susceptible to oxidation. Attacked by peroxides and free radicals formed from lipid oxidation. Losses promoted by traces of copper and iron which catalyse the oxidation. Negligible losses due to leaching. Heat converts part of the <i>trans</i> isomer to neo- β -carotene-U which has lower potency
Thiamin (Vitamin B ₁)	Present in animal and plant tissues either as free thiamin or bound to pyrophosphate or protein. Destroyed by sulphur dioxide (in sulphited fruits and vegetables), potassium bromate flour improver and thiaminase. Polyphenoloxidase catalyses thiamin destruction by phenols in plant tissues. Substantial losses due to leaching (Chapter 10) and drip losses (Chapters 16 and 21)
Riboflavin (Vitamin B ₂)	Occurs as free form in milk but mostly bound with phosphate in other foods. Destroyed by alkaline conditions, light and excessive heat. Stable to air and acids
Niacin	Occurs as nicotinamide (as nicotinamide adenine dinucleotide and nicotinamide adenine dinucleotide phosphate) and as nicotinic acid. Bound to polysaccharides and peptides and therefore not available in many cereals unless liberated by heat or alkaline conditions (for example by baking powder (Chapter 16)). The amino acid tryptophan is converted to niacin in the body (niacin equivalent is free niacin plus one sixtieth of the tryptophan). Generally stable
Folic acid	Occurs in various forms, expressed as pteroylglutamic equivalents, with various numbers of glutamate residues and methyl or

formyl groupings. Richest sources are dark green leaves, liver and kidney. More difficult to assay than other vitamins. Possibly one of the few causes of deficiency disease in industrialised countries, especially in pregnant women, pre-term infants and the elderly

Pyridoxine (Vitamin B ₆)	Occurs in three forms: pyridoxine, pyridoxal and pyridoxamine. The first two are found in plants and the last two in animal tissues. Most is in a free form in milk but is otherwise bound. Difficult to assay and may be deficient in some diets. Lost by reaction with sulphhydryl groups of proteins and amino acids when heated or during storage
Cyanocobalamin (Vitamin B ₁₂)	Small losses due to interaction with vitamin C and sulphhydryl compounds in the presence of oxygen in milk. Generally stable
Ascorbic acid (Vitamin C)	Occurs as both ascorbic acid and dehydroascorbic acid. The latter is very heat labile, with or without the presence of oxygen. Very soluble and readily lost by leaching and in drip losses. Destroyed by a number of plant enzymes, including ascorbic acid oxidase, peroxidase, cytochrome oxidase and phenolase. Copper and iron catalyse oxidation in air, but sulphur dioxide protects against oxidation. Most labile of the vitamins and substantial losses in most food processing. Vitamin C retention sometimes used as an indicator of the severity of processing. Also used as an anti-oxidant and stabiliser (Table 12.6), as a flour improver and in cured meats
Vitamin D	Occurs in foods as cholecalciferol (D ₃) and produced in the skin under the influence of UV light. The synthetic type, ergocalciferol (D ₂) is added to some milk products, baby foods and margarine. The vitamin is stable under all normal processing and storage conditions
Vitamin E	Occurs as eight compounds: four tocopherols and four tocotrienols, each of which has a different potency. Activity usually expressed as α -tocopherol equivalents. Naturally occurring anti-oxidant but is lost relatively slowly. Generally stable during processing, except frying (Chapter 17) in which it is destroyed by peroxides

Appendix B

Nutritional and functional roles of minerals in foods

Mineral	Source	Function
Aluminium	Low and variable in foods	Possibly essential, evidence not conclusive. Deficiency unknown. Leavening agent: as sodium aluminum sulfate ($\text{Na}_2\text{SO}_4 \cdot \text{Al}_2(\text{SO}_4)_3$). Texture modifier.
Bromine	Brominated flour	Not known to be essential to humans. Dough improver: KBrO_3 improves baking quality of wheat flour.
Calcium	Dairy products, green leafy vegetables, tofu, fish bones	Essential nutrient: deficiency leads to osteoporosis in later life. Texture modifier: forms gels with negatively charged macromolecules such as alginates, low-methoxyl pectins, soy proteins, caseins, etc. Firms canned vegetables when added to canning brine.
Copper	Organ meats, seafood, nuts, seeds	Essential nutrient: deficiency rare. Catalyst: lipid peroxidation, ascorbic acid oxidation, non-enzymatic oxidative browning. Colour modifier: may cause black discoloration in canned, cured meats. Enzyme cofactor: polyphenoloxidase. Texture stabiliser: stabilises egg-white foams.
Iodine	Iodised salt, seafood, plants and meat from animals grown in areas where soil iodine is not depleted	Essential nutrient: deficiency produces goitre and cretinism. Dough improver: KIO_3 improves baking quality of wheat flour.

Iron	Cereals, legumes, meat, contamination from iron utensils and soil, enriched foods	Essential nutrient: deficiency leads to anaemia, impaired immune response, reduced productivity, impaired cognitive development in children. Excessive iron stores may increase risk of cancer and heart disease. Catalyst: Fe^{2+} and Fe^{3+} catalyse lipid peroxidation in foods. Colour modifier. Colour of fresh meat depends on valence of Fe in myoglobin and hemoglobin: Fe^{2+} is red, Fe^{3+} is brown. Forms green, blue or black complexes with polyphenolic compounds. Reacts with S^{2-} to form black FeS in canned foods. Enzyme cofactor: lipoxygenase, cytochromes, ribonucleotide reductase, etc.
Magnesium	Whole grains, nuts, legumes, green leafy vegetables	Essential nutrient: deficiency rare. Colour modifier: removal of Mg from chlorophyll changes colour from green to olive-brown.
Manganese	Whole grains, fruits, vegetables	Essential nutrient: deficiency extremely rare. Enzyme cofactor: pyruvate carboxylase, superoxide dismutase.
Nickel	Plant foods	Essential nutrient: deficiency in humans unknown. Catalyst: hydrogenation of vegetable oils – finely divided, elemental Ni is the most widely used catalyst for this process.
Phosphates	Ubiquitous	Essential nutrient: deficiency rare due to presence in virtually all foods. Acidulent: H_3PO_4 in soft drinks. Leavening acid: $\text{Ca}(\text{HPO}_4)_2$ is a fast-acting leavening acid. Moisture retention in meats: sodium tripolyphosphate improves moisture retention in cured meats. Emulsification aid: phosphates are used to aid emulsification in comminuted meats and in processed cheeses.
Potassium	Fruits, vegetables, meats	Essential nutrient: deficiency rare. Salt substitute: KCl may be used as a salt substitute. May cause bitter flavour. Leavening agent: potassium acid tartrate.
Selenium	Seafood, organ meats, cereals (depending on levels in soil)	Essential nutrient: Keshan disease (endemic cardiomyopathy in China) was associated with selenium deficiency. Low selenium status may be associated with increased risk for cancer and heart disease. Enzyme cofactor: glutathione peroxidase.
Sodium	Food additives, milk, low in most raw foods	Essential nutrient: deficiency is rare; excessive intakes may lead to hypertension. Flavour modifier: NaCl elicits the classic salty taste in foods. Preservative: NaCl may be used to lower water activity in foods. Leavening agents: many leavening agents are sodium salts, e.g. sodium bicarbonate, sodium aluminium sulphate, sodium acid pyrophosphate.
Sulphur	Widely distributed	Essential nutrient: a constituent of the essential amino acids methionine and cystine. Sulphur amino acids

may be limiting in some diets. Browning inhibitor: sulphur dioxide and sulphites inhibit both enzymatic and non-enzymatic browning. Widely used in dried fruits. Anti-microbial: prevents, controls microbial growth. Widely used in wine making.

Zinc	Meats, cereals	Essential nutrient: deficiency produces loss of appetite, growth retardation, skin changes. Marginal deficiency exists in US and Europe but extent is unknown. Pronounced deficiency was documented in populations in the Middle East. ZnO is used in the lining of cans for protein rich foods to lessen formation of black FeS during heating. Zn can be added to green beans to help stabilise the colour during canning.
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From Miller, D.R. (1996) 'Minerals'. In: O.R. Fennema (ed.) *Food Chemistry*. Marcel Dekker, pp. 617–47.

Appendix C

EEC permitted food additives

In the following tables the E numbers are generally recognised by the EEC as safe additives. Those without the prefix E are, at the time of writing, proposals and need not necessarily be adopted.

C.1 Permitted colours

Colour	Alternative name(s)	E number
Curcumin		E100
Riboflavin	Lactoflavin	E101
Riboflavin-5'-phosphate		101(a)
Tartrazine		E102
Quinoline yellow		E104
Yellow 2G		107
Sunsey yellow FCF	Orange yellow S	E110
Cochineal	Carminic acid	E120
Carmoisine	Azorubine	E122
Amaranth		E123
Ponceau 4R	Cochineal red A	E124
Erythrosine BS		E127
Red 2G		128
Patent blue V		E131
Indigo carmine	Indigotine	E132
Brilliant blue FCF		133
Chlorophyll		E140
Copper complexes of chlorophyll and chlorophyllins		E141
Green S	Acid brilliant green BS	E142

Caramel		E150
Black PN	Brilliant black PN	E151
Carbon black	Vegetable carbon	E153
Brown FK		154
Brown Ht	Chocolate brown HT	155
Carotene α , β or γ		E160(a)
Annatto, bixin, norbixin		E160(b)
Capsanthin	Capsorubin	E160(c)
Lycopene		E160(d)
β -apo-8'-carotenal (C ₃₀)		E160(e)
Ethyl ester of β -apo-8'-carotenoic acid (C ₃₀)		E160(f)
Flavoxanthin		E161(a)
Lutein		E161(b)
Cryptoxanthin		E161(c)
Rubixanthin		E161(d)
Violaxanthin		E161(e)
Rhodoxanthin		E161(f)
Canthaxanthin		E161(g)
Beetroot red	Betainin	E162
Anthocyanins		E163
Titanium dioxide		E171
Iron oxides and hydroxides		E172
Aluminium		E173
Silver		E174
Gold		E175
Pigment rubine	Lithol rubine BK	E180

C.2 Permitted stabilisers

Emulsifier-stabiliser	Alternative name	E number
Alginic acid		E400
Sodium alginate		E401
Potassium alginate		E402
Ammonium alginate		E403
Calcium alginate		E404
Propane-1,2-diol alginate	Propylene glycol alginate	E405
Agar		E406
Carrageenan		E407
Locust bean gum	Carob gum	E410
Guar gum		E412
Tragacanth		E413
Gum arabic	Acacia	E414
Xanthan gum		E415
Karaya gum		416
Sorbitol	Sorbitol syrup	E420

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Mannitol		E421
Glycerol		E422
Polyoxyethylene (8) stearate		430
Polyoxyethylene (40) stearate		431
Polyoxyethylene (20) sorbitan monolaurate	Polysorbate 20	432
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<i>Tetrasodium diphosphate</i>		
<i>Tetrapotassium diphosphate</i>	}	E450(b)
<i>Pentasodium triphosphate</i>		
<i>Pentapotassium triphosphate</i>	}	E450(c)
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C.3 Permitted acids, bases and salts

	Alternative name(s)	E number
Sodium bicarbonate	Bicarbonate of soda	500
Potassium carbonate and potassium hydrogen carbonate		501
Ammonium carbonate and ammonium hydrogen carbonate		503
Magnesium carbonate		504
Hydrochloric acid		507
Potassium chloride		508
Calcium chloride		509
Ammonium chloride		510
Sulphuric acid		513
Sodium sulphate		514
Potassium sulphate		515
Calcium sulphate		516
Magnesium sulphate		518
Sodium hydroxide		524
Potassium hydroxide		525
Calcium hydroxide		526
Ammonium hydroxide		527
Magnesium hydroxide		528
Calcium oxide		529
Magnesium oxide		530
Sodium ferrocyanide	Sodium hexacyanoferrate (II)	535
Potassium ferrocyanide	Potassium hexacyanoferrate (II)	537
Dicalcium diphosphate		540
Sodium aluminium phosphate		541
Edible bone phosphate		542
Calcium polyphosphates		544
Ammonium polyphosphates		545
Silicon dioxide	Silica	551
Calcium silicate		552

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Magnesium silicate synthetic	Magnesium trisilicate	553(a)
Talc		553(b)
Aluminium sodium silicate		554
Aluminium calcium silicate		556
Bentonite		558
Kaolin		559
Stearic acid		570
Magnesium stearate		572
D-Glucono-1,5-lactone	Glucono δ -lactone	575
Sodium gluconate		576
Potassium gluconate		577
Calcium gluconate		578

C.4 Permitted flavour enhancers

	Alternative name(s)	E number
L-Glutamic acid		620
Sodium hydrogen L-glutamate	<i>MonoSodium glutamate (MSG)</i>	621
Potassium hydrogen L-glutamate	<i>MonoPotassium glutamate</i>	622
Calcium dihydrogen di-L-glutamate	Calcium glutamate	623
Guanosine 5'-(disodium phosphate)	Sodium guanylate	627
Inosine 5'-(disodium phosphate)	Sodium inosinate	631
Sodium 5'-ribonucleotide		635
Maltol		636
Ethyl maltol		637

C.5 Permitted processing aids

	Alternative name(s)	E number
Dimethylpolysiloxane		900
Beeswax		901
Carnauba wax		903
Shellac		904
Mineral hydrocarbons		905
Refined microcrystalline wax		907
L-Cysteine hydrochloride		920
Potassium bromate		924
Chlorine		925
Chlorine dioxide		926
Azodicarbonamide	Azoformamide	927

C.6 Selected permitted preservatives and antioxidants

Preservative	E number
Sorbic acid	E200
Sodium, potassium, calcium sorbate	E201–203
Benzoic acid	E210
Sodium, potassium benzoate	E212–213
Hydroxybenzoates	E214–219
Sulphur dioxide	E220
Sodium sulphite, bisulphite, metaspulphite	E221–223
Diphenyl	E230
Nisin	234
Potassium and sodium nitrite	E249–250
Sodium and potassium nitrate	E251–252
Acetic acid	E260
Potassium, sodium hydrogen, sodium, calcium acetate	E261–263
Lactic acid	E270
Propionic acid	E280
Sodium, calcium, potassium propionate	E281–283
Carbon dioxide	E290
Malic acid	E296
Antioxidant	E number
Ascorbic acid	E300
Sodium and calcium ascorbate	E301–302
α , γ -, δ -tocopherol	E307–309
Propyl-, octyl-, dodecyl gallate	E310–312
Butylated hydroxyanisole (BHA)	320
Butylated hydroxytoluene (BHT)	321
Lecithins	E322
Sodium, potassium, calcium lactate	E325–327
Citric acid	E330
Sodium, potassium, calcium citrate	E331–333
Tartaric acid	E334
Sodium, potassium, potassium sodium tartarate	E335–337
Phosphoric acid	E338
Sodium, potassium, calcium salts of phosphoric acid	E339–341
Sodium, potassium, calcium malate	350–352
Succinic acid	363
Nicotinic acid	375
Ammonium citrate, ammonium ferric citrate	380–381
Calcium disodium EBTA	385

Appendix D

Units and dimensions

All physical properties are measured by a quantitative numerical value and a qualitative definition in terms of its dimensions. For example, in Table 1.5, the thermal conductivity of frozed beef is $1.3 \text{ W m}^{-1} \text{ K}^{-1}$; 1.3 is the quantitative value and $\text{W m}^{-1} \text{ K}^{-1}$ is the qualitative definition. There are three main fundamental dimensions: mass (M), length (L) and time (T). Temperature (θ) is also accepted as a fourth dimension. Other properties are described by these four dimensions: for example density = mass/unit volume and has the dimensions ML^{-3} . Other examples are shown in Table D.1.

Table D.1 Units and dimensions

Quantity	Unit name	Unit	Dimension
Mass	Kilogram	kg	M
Length, diameter	Metre	m	L
Time	Second	s	T
Temperatue	Kelvin	K	θ
<i>Derived units with a special name</i>			
Force	Newton (N)	kg m s^{-2}	MLT^{-2}
Pressure	Pascal (Pa)	N m^{-2}	$\text{ML}^{-1}\text{T}^{-2}$
Energy	Joule (J)	N m	ML^2T^{-2}
Power	Watt (W)	J s^{-1}	ML^2T^{-3}
Frequency	Hertz (Hz)	Hz	T^{-1}
Absorbed dose of ionising radiation	Gray (Gy)	J kg^{-1}	L^2T^{-2}
<i>Derived units without a special name</i>			
Area		m^2	L^2
Volume		m^3	L^3
Density		kg m^{-3}	ML^{-3}
Specific gravity		none	none
Dynamic viscosity		N s m^{-2}	$\text{ML}^{-1}\text{T}^{-1}$
Kinematic viscosity		m^2s^{-1}	L^2T^{-1}
Enthalpy		J kg^{-1}	L^2T^{-2}
Specific heat		$\text{J kg}^{-1} \text{ K}^{-1}$ (or °C)	$\text{LT}^{-2}\theta^{-1}$

Quantity	Unit name	Unit	Dimension
Thermal conductivity		$\text{W m}^{-1} \text{K}^{-1}$ (or $\text{W m}^{-1} \text{°C}^{-1}$)	$\text{MLT}^{-3}\theta^{-1}$
Heat transfer coefficient		$\text{W m}^{-2} \text{K}^{-1}$ (or $\text{W m}^{-2} \text{°C}^{-1}$)	$\text{MT}^{-2}\theta^{-1}$
Velocity		m s^{-1}	LT^{-1}
Acceleration		m s^{-2}	LT^{-2}
Momentum		kg m s^{-1}	MLT^{-1}

Some combinations of physical properties produce ratios in which the dimensions cancel out. These are termed *dimensionless groups*. For example, the Reynolds number (Chapter 1) = (density \times velocity of a liquid \times diameter of the pipe)/viscosity of the liquid. From Table D.1 the dimensions are as follows:

$$\frac{\text{L} \times \text{LT}^{-1} \times \text{ML}^{-3}}{\text{ML}^{-1}\text{T}^{-1}}$$

The dimensions cancel and the Reynolds number is therefore dimensionless.

In the SI system, there are seven basic units of measurement:

1. length (metres (m))
2. mass (kilograms (kg))
3. time (seconds (s))
4. electric current (amperes (A))
5. thermodynamic temperature (kelvins (K))
6. luminous intensity (candela (Cd))
7. amount of substance (mole).

In practice, degrees Celsius (°C) is often used in food processing instead of degrees kelvin (K). Other units are derived from these. Some have a special name, but most are expressed in basic units, as shown in Table D.1. Multiples of these units use the prefixes given in Table D.2.

Table D.2 Prefixes in common use before units

Prefix	Symbol	Multiple	Prefix	Symbol	Multiple
atto	a	10^{-18}	decca	da	10^1
femto	f	10^{-15}	hecto	h	10^2
pico	p	10^{-12}	kilo	k	10^3
nano	n	10^{-9}	mega	M	10^6
micro	μ	10^{-6}	giga	G	10^9
milli	m	10^{-3}	tera	T	10^{12}
centi	c	10^{-2}	peta	P	10^{15}
deci	d	10^{-1}	exa	E	10^{18}

A selection of conversion factors from imperial units to SI units is shown in Table D.3.

Table D.3 Conversion factors

Quantity	British (Imperial) system	SI
Length	1 ft	0.3048 m
Time	1 h	3.6 ks
Area	1 ft ²	0.09290 m ²
Volume	1 ft ³	0.02832 m ³
Mass	1 lb	0.4536 kg
Density	1 lb ft ⁻³	16.019 kg m ⁻³
Force	1 lbf	4.4482 N
Energy	1 Btu	1055.1 J
	1 cal	4.1868 J
Pressure	1 lbf in ⁻²	6894.8 Pa
	1 atm	1.0133 × 10 ⁵ Pa
	1 torr	133.32 Pa
Power	1 Btu h ⁻¹	0.29307 W
	1 hp	745.70 W
Velocity	1 ft s ⁻¹	0.3048 m s ⁻¹
Dynamic viscosity	1 P (poise)	0.1 N s m ⁻²
Kinematic viscosity	1 St (stokes)	10 ⁻⁴ m ² s ⁻¹
Specific heat	1 Btu lb ⁻¹ °F ⁻¹	4.1868 kJ kg ⁻¹ K ⁻¹
Thermal conductivity	1 Btu h ⁻¹ ft ⁻¹ °F ⁻¹	1.7303 W m ⁻¹ K ⁻¹
Heat transfer coefficient	1 Btu h ⁻¹ ft ⁻² °F ⁻¹	5.6783 W m ⁻² K ⁻¹
Mass transfer coefficient	1 lb ft ⁻² s ⁻¹	1.3563 g m ⁻² s ⁻¹
Temperature	°F	$\frac{5}{9}$ °C

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