Thermoelectric generators can enhance military medicine

A micro thermoelectric generator can produce small, though usable power from temperature differences as low as 5 K, introducing the capability to power devices from body heat. Medical systems, such as wireless patient monitoring, nerve stimulation implants or cochlear hearing replacements, as well as unique systems for military medicine, can harness these capabilities.

By Ingo Stark

The miniaturization and reduced power consumption of modern electronics draws attention to emerging energy-harvesting technologies that provide power solutions for completely autonomous self-powered sensors and microsystems. Primary batteries can have excessive weight and size and limit the lifespan and autonomy of electronic devices because of the need of replacement. This makes them unsuitable in systems with limited accessibility and cost prohibitive in wireless microsensor networks with a high quantity of powered devices[1, 2]. A long lifespan and small dimensions of the power source are particularly important and advantageous for wearable electronics and systems with limited accessibility, such as structure-embedded wireless microsensors or biomedical implants, where it is impractical or impossible to deliver power through wires. A cardiac pacemaker, for example, occupies about 20 ml of space, approximately half of which is consumed by the internal battery[3]. These facts have stimulated worldwide research in the field of energy-harvesting devices. One approach uses the thermoelectric principle, in which energy can be recovered that is typically lost as heat dissipated to the environment.

Thermoelectric generators based on compact polycrystalline or sintered materials are state of the art and well-established products[4]. However, they are relatively large and heavy, and have a limited number of thermocouples, leading to small output voltages at small temperature differences. Recently, several investigations were carried out with the goal to design and develop miniaturized thermoelectric generators following various approaches[5-7].

Figure 1.Thermo Life in comparison with a penny.

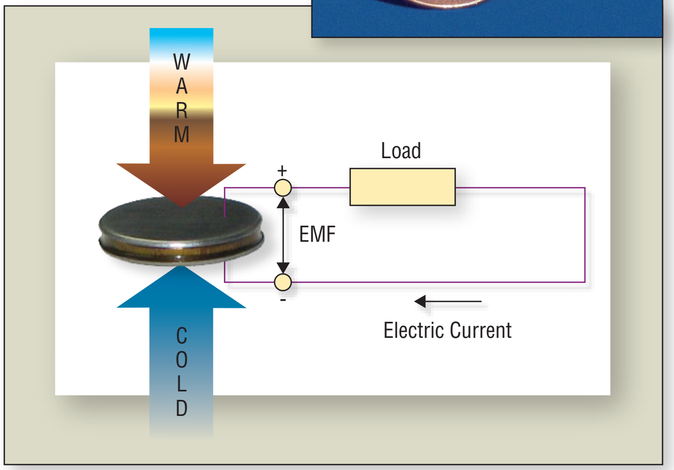

Figure 2. Working principle of thermoelectric generator Thermo Life.

The Thermo Life thermoelectric generator

The Thermo Life thermoelectric converter shown in Figure 1 is a compact energy source for sensors and microelectronics driven by a small temperature difference (Figure 1). This thermal energy harvester is capable of producing an output power of a few hundred microwatts and voltages on the order of a few volts from small temperature differences of a few degrees Kelvin. The latest developed prototypes achieve a performance of 120 µW at 3 V and a ΔT of 5 K. These devices can be electrically connected in parallel or series to increase the output current or voltage, respectively.

The Thermo Life uses the Seebeck effect to convert heat energy directly into electrical energy using more than 5000 thermocouples that are electrically in series and thermally in parallel. When the heat coupling plates are thermally connected with a heat source and a heat sink, heat flows through the thermopile and generates an electromotive force (EMF). This yields useful power across a

Geometrical Parameter	Unit	Value
Total height of device	mm	0.8
Outer diameter of device	mm	9.6
Volume of device	mm3	58
Mass of device	mg	185
Number of thermocouples		5200
Thermal Parameter		
Total thermal resistance	K/W	14
Electrical Parameters (ΔT=5 k)		
Open circuit voltage	V	5.8
Short-circuit current	µA	85
Resistance	kW	68
Voltage @ matched load	V	2.9
Current @ matched load	µA	42.5
Power @ matched load	µW	123

Table 1. Main parameters of the advanced Thermo Life prototype shown in Figure 1.

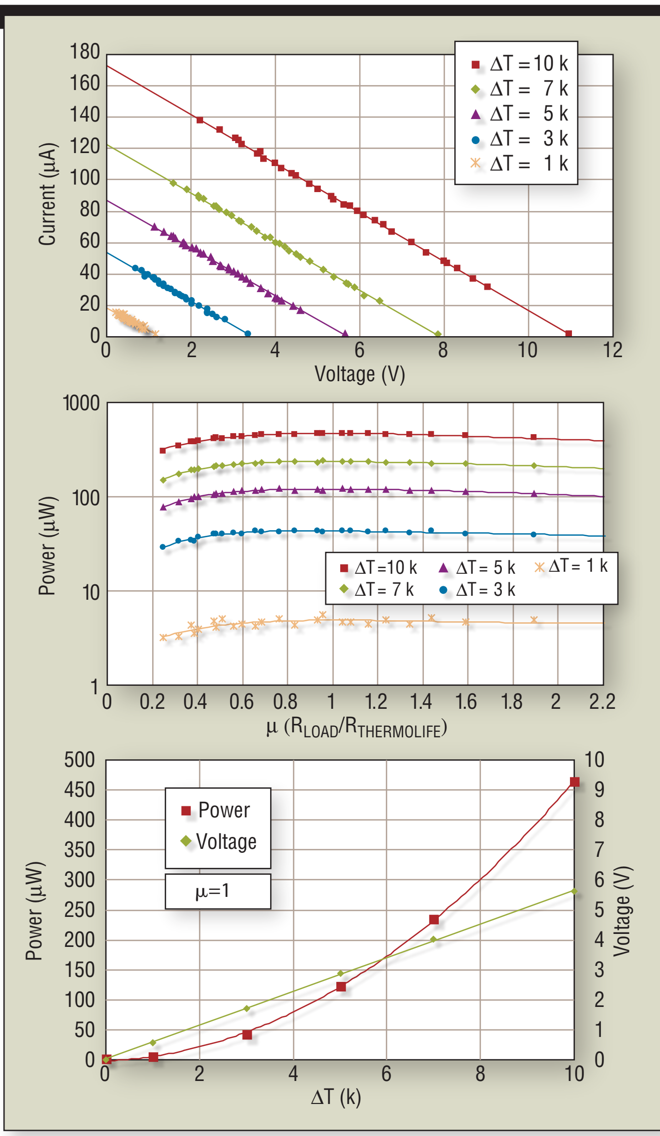

Figure 3. Technical data and performance of an advanced Thermo Life thermoelectric generator.

connected electrical load for as long as the heat source and sink maintain the applied temperature gradient, as illustrated in Figure 2.

Thermo Life generators are based on the development of a unique thin-film technology for the deposition of highly efficient thermoelectric materials of the Bi_2Te_3-type on thin Kapton foils. The Bi_2Te_3-type material used by the Thermo Life for energy conversion has the best thermoelectric properties in the range of room temperature. The physical, electrical and thermal parameters of Thermo Life are adjustable to customer-specific applications. The thin-film technology has the ability to scale up to mass production, which results in less-expensive devices comparable to batteries. Technological processing steps and fabrication equipment are similar to those used in the manufacture of microelectronics.

Technical data

The critical physical, thermal and electrical parameters of the advanced Thermo Life prototype developed at Thermo Life Energy shown in Figure 1 are presented in Table 1.

Figure 3 gives detailed information about the electrical performance of an advanced Thermo Life prototype as thermoelectric output voltage U, electrical current I and power P measured at a basic temperature of 30 °C.

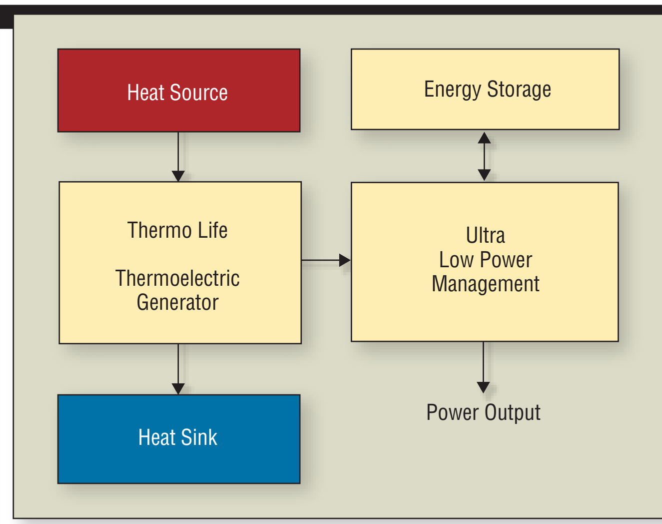

Figure 4. Micropower system with Thermo Life.

Low power management

The energy extracted from Thermo Life needs to be stored in a rechargeable battery or supercapacitor. Such an energy scavenging/collecting system can be considered as a ‘river-reservoir’ concept, where the Thermo Life acts as the river and the energy storage element represents the reservoir. The storage system has to be chosen by the infrequency and amount of scavenged energy, which is necessary to maintain operation of the electronic load when no temperature difference is available. Since the harvested energy depends on the temperature gradient, the energy can manifest itself as an irregular, random, and discontinuous energy flow, requiring an efficient, electronic ultralow-power management function to provide stable power for a final electronic application. This can include the following functions depending on the specific application:

- stabilization of the output voltage;
- protection of the powered device against high and low voltage;
- rectifying and transfering energy from the thermoelectric generator to the energy storage; and
- minimization of self-discharging within the energy storage device.

Figure 4 demonstrates the principal arrangement of such a thermoelectric micropower aystem and the energy flow.

Potential medical applications

The harvesting of thermal energy from small temperature gradients using Thermo Life thermoelectric generators can deliver useful amounts of power, as presented in the technical data in Table 1 and Figure 3. The relatively high output voltage due to more than 5000 thermocouples in series and the relatively high thermal resistance make this device ideal for energy scavenging from body and waste heat; the smaller the usable temperature gradient, the larger the number of potential applications. The exploitation of body heat as a thermal energy source makes Thermo Life particularly attractive for attached medical devices and biomedical implants.

In the special situation of body heat energy conversion, several constraints must be taken into consideration. For example, the Carnot efficiency $((T_H - T_C)/ T_H)$ limits the percentage of usable energy that can be extracted from heat flowing between two different temperatures. At room temperature, the Carnot efficiency is only 1.6% when the temperature gradient is 5 K, and the best thermoelectric materials achieve maximum efficiency values up to about 17% of the Carnot efficiency for small temperature gradients[4], leading to overall conversion efficiencies for standard thermoelectric materials in the range from 0.2% to 0.8% for temperature differences from 5 K to 20 K[8].

Another consideration is that the efficiency of a thermoelectric

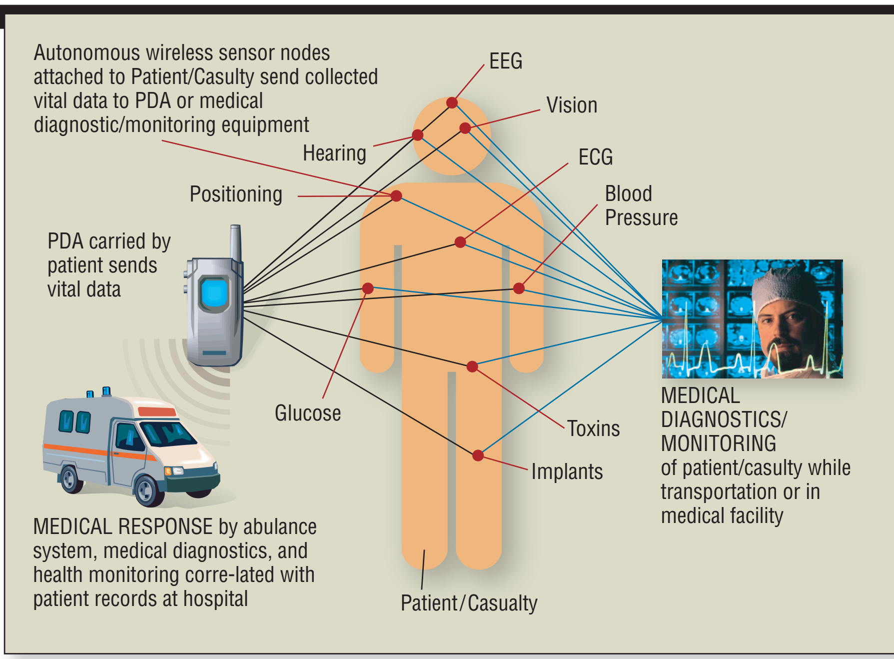

Figure 5. Possibilities of medical care based on a wireless sensor network with autonomous body-attached sensor nodes.

generator depends to a certain extent on how the external load is matched to the resistance of the generator. Because the maximum power transfer is obtained if the electrical resistance of the load is equal to the electrical resistance of the generator, the efficiency can never exceed 50% of the Carnot efficiency.

The human body can be used as steady energy source, and the amount of energy released by the metabolism mainly depends on the amount of muscular activity. The metabolism can range from 46 W/m² while sleeping up to about 550 W/m² during sports activities such as running. A metabolic rate commonly used is 70 W/m², corresponding to normal work when sitting in an office leading to a person's power dissipation of about 119 W (a normal adult has a surface area in average of 1.7 m²), burning about 10.3 MJ per day. These fundamental limits are also important design factors.

In order to maintain an available temperature gradient at a thermoelectric generator, the device must have a high thermal resistance to minimize the drain of thermal energy from the heat source. Also, the respective thermal couplings between the thermoelectric generator and the heat source and heat sink determine the temperature gradient across the device. Therefore, an optimized thermal design will use heat transfer materials with high thermal conductivity, as well as heat exchangers that increase the effective surface area of the coupling plates of the thermoelectric generator.

Energy harvesting from body heat is not limited to devices applied to the skin, which develops a temperature difference of about 15 K between the skin and ambient air. Active implantable devices can also be located under the skin for applications such as cardiac pacemakers, muscle stimulators, neurological stimulators or Cochlear implants. Battery capacity usually determines the lifetime of these devices, and device replacement due to battery depletion requires surgical procedures, and accounts for up to one-third of all pacemakers sold. Attempts to eliminate batteries by providing unlimited energy using radio transmission or nuclear energy have not gained clinical acceptance[9].

Thermoelectric generators powered by body heat can improve medical diagnostics and monitoring of patients. In a critical care situation, a number of vital signs need to be checked and monitored, such as blood pressure, ECG and EEG. During emergency transportation in an ambulance or even by the Air Force Critical Care Air Transport Team (CCATT), attention must be paid to cables connected to the patient-attached sensors that provide this data. The right side of Figure 5 illustrates a wireless sensor network where autonomous wireless sensor nodes (each comprising a sensor or sensor array, a micropower system and a wireless communication module) are able to collect and send vital data directly to the diagnostic/monitoring equipment.

A modified wireless sensor network configuration for proactive patient monitoring is shown on the left side of Figure 5. In this system, the autonomous wireless sensor nodes transmit the collected vital data to a cellular phone, which communicates via a wireless local area network (WLAN) or a cellular phone network with a medical center and triggers different medical services. For example, in an emergency, an ambulance can be dispatched (see also[10, 11]).

A variation of this system could serve the war fighter. A wearable mesh of wired sensors could be tied to a tactical data radio that maintains radio silence. The radio would only begin transmitting data in the event of some pre-defined condition, such as the detection of chemical agents. The connecting wiring might be further refined into a mesh to detect and specify locations of where it has been pierced by a bullet. The entire system could be powered by a battery or capacitor that has been charged by an array of thermoelectric generators embedded in the same garment.

At present, some of the considered standard medical sensors still need more power than a single Thermo Life thermoelectric generator can produce from body heat in order to operate continuously. A detailed consideration of the power requirements of each sensor type is necessary to determine which sensors can be made completely autonomous through the use of the Thermo Life, and which sensors need to engineered for lower power consumption to match the power available from thermoelectric body heat conversion. **DE**

ABOUT THE AUTHOR

Ingo Stark received a bachelor degree in physics and Ph. D. degree in Physics from the Martin-Luther University Halle-Wittenberg, Germany, in 1989 and 1994, respectively. From 1994 to 1995, he was an R&D collaborator at Teccom (Germany) and he was involved in the research and development of thermoelectric materials and the manufacturing of thermoelectric products. Prior to joining Thermo Life Energy, he was a co-founder and senior R&D manager of the German startup D.T.S. from 1995 to 2002, which dealt with using thermoelectric thin films and succeeded in developing a low-power thermoelectric generator as a unique power source for micro and sensor systems. After Applied Digital acquired D.T.S. in 2003, he moved the entire laboratory to California, where he now serves as senior engineer. Since 2005 he has been the chief technology officer of Thermo Life Energy, responsible for development of prototypes of thermoelectric thin film generators for customer-specific applications. Having more than 19 years of experience in the field of thermoelectric materials and physical-vapor deposition (PVD) processes for thin film deposition, he has published in several scientific journals and presented at international conferences. Stark can be contacted at istark@adsx.com.

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