Small Thermoelectric Generators

by G. Jeffrey Snyder

Thermoelectric generators are all solid-state devices that convert heat into electricity. Unlike traditional dynamic heat engines, thermoelectric generators contain no moving parts and are completely silent. Such generators have been used reliably for over 30 years of maintenance-free operation in deep space probes such as the Voyager missions of NASA.[1] Compared to large, traditional heat engines, thermoelectric generators have lower efficiency. But for small applications, thermoelectrics can become competitive because they are compact, simple (inexpensive) and scaleable. Thermoelectric systems can be easily designed to operate with small heat sources and small temperature differences. Such small generators could be mass produced for use in automotive waste heat recovery or home co-generation of heat and electricity. Thermoelectrics have even been miniaturized to harvest body heat for powering a wristwatch.

Thermoelectric Power

A thermoelectric produces electrical power from heat flow across a temperature gradient.[2] As the heat flows from hot to cold, free charge carriers (electrons or holes) in the material are also driven to the cold end (Fig. 1). The resulting voltage (*V*) is proportional to the temperature difference (ΔT) via the Seebeck coefficient, α, ($V = \alpha\Delta T$). By connecting an electron conducting (n-type) and hole conducting (p-type) material in series, a net voltage is produced that can be driven through a load. A good thermoelectric material has a Seebeck coefficient between 100 µV/K and 300 µV/K; thus, in order to achieve a few volts at the load, many thermoelectric couples need to be connected in series to make the thermoelectric device (Fig. 1).

A thermoelectric generator converts heat (*Q*) into electrical power (*P*) with efficiency η.

$$P = \eta Q \qquad (1)$$

The amount of heat, *Q*, that can be directed though the thermoelectric materials frequently depends on the size of the heat exchangers used to harvest the heat on the hot side and reject it on the cold side. As the heat exchangers are typically much larger than the thermoelectric generators themselves, when size is a constraint (or high *P/V* is desired) the design for maximum power
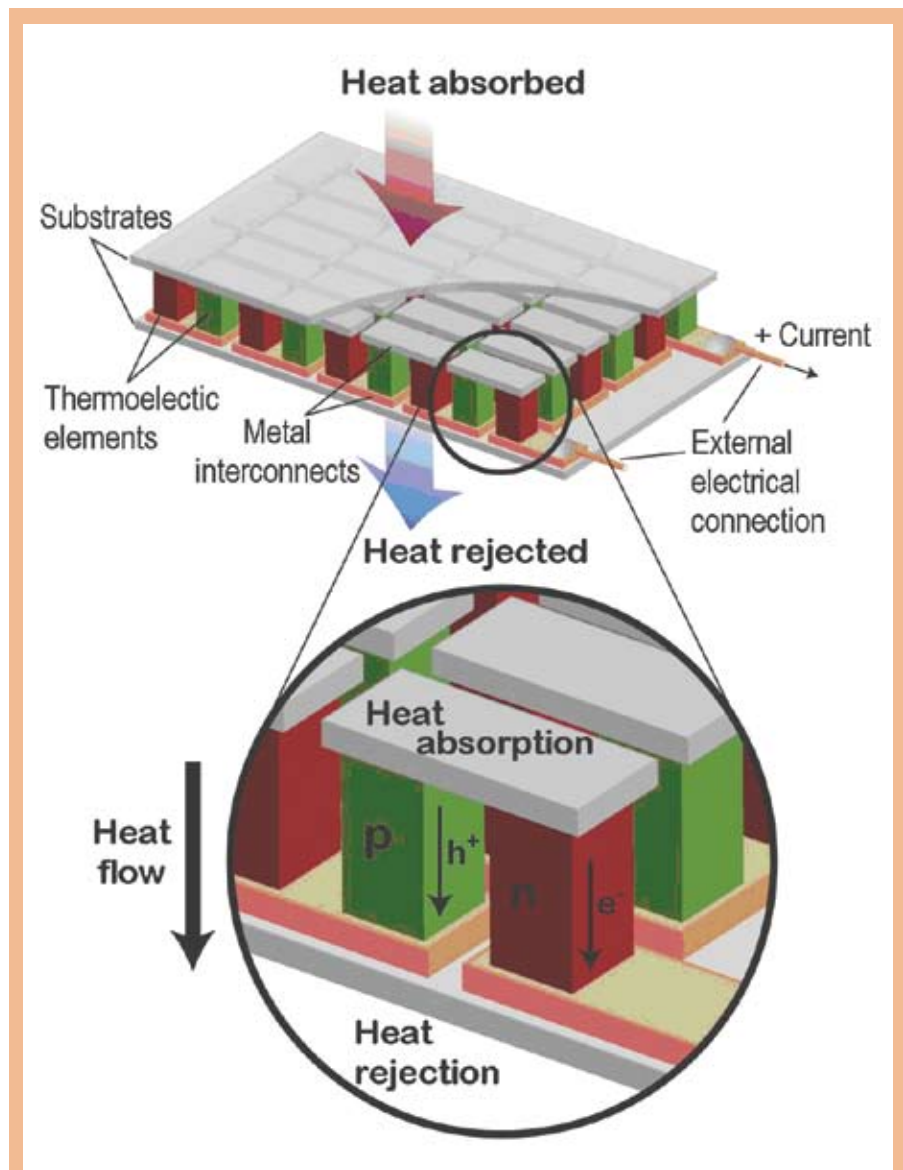

Fig. 1. *Schematic of a thermoelectric generator. Many thermoelectric couples (top) of n-type and p-type thermoelectric semiconductors are connected electrically in series and thermally in parallel to make a thermoelectric generator. The flow of heat drives the free electrons (e⁻) and holes (h⁺) producing electrical power from heat. (Copyright Nature Publishing Group,[2] reprinted with permission.)*

may take precedence over maximum efficiency. In this case the temperature difference (and therefore thermoelectric efficiency as described below) may be only half that between the heat source and sink.[3]

The efficiency of a thermoelectric converter depends heavily on the temperature difference $\Delta T = T_h - T_c$ across the device. This is because the thermoelectric generator, like all heat engines, cannot have an efficiency greater than that of a Carnot cycle ($\Delta T/T_h$). The efficiency of a thermoelectric generator is typically defined as

$$\eta = \frac{\Delta T}{T_h} \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + T_c/T_h} \qquad (2)$$

Where the first term is the Carnot efficiency and *ZT* is the figure of merit for the device. While the calculation of

a thermoelectric generator efficiency can be complex,[4] use of the average material figure of merit, zT, can provide an approximation for ZT.

$$zT = \frac{\alpha^2 T}{\rho \kappa} \qquad (3)$$

Here, Seebeck coefficient (α), electrical resistivity (ρ), and thermal conductivity (κ) are temperature (T) dependent materials properties.

Recently, the field of thermoelectric materials is rapidly growing with the discovery of complex, high-efficiency materials. A diverse array of new approaches, from complexity within the unit cell to nanostructured bulk, nanowire and thin film materials, have all lead to high efficiency materials.[2]

Heat to Electricity

For large electrical power generation applications traditional dynamic thermal to electric generators (*e.g.* Rankine, Brayton, or Stirling engine) have several times the efficiency of a thermoelectric system. However, such dynamic systems are expensive and do not scale easily for small applications. When high quality combustible fuel is available, internal combustion engines are cost effective and reasonably efficient in the 100 W to 100 kW range but tend to be noisy. For applications requiring less than 100W, the scalability of thermoelectrics gives them a clear advantage.

Power from Waste Heat

Efforts are already underway to demonstrate waste heat recovery in automobiles (Fig. 2).[5] In this ~1 kW range, even relatively inefficient thermoelectrics can be competitive for use with such waste heat sources (*e.g.* automobile exhaust) when design, fabrication, and maintenance cost are factored in. The thermoelectric generator will extract waste heat from the exhaust that will deliver DC electrical power to recharge the battery. By reducing or even eliminating the need for the alternator, the load on the engine is reduced thereby improving fuel efficiency by as much as 10%.

Instead of recovering waste heat, Co-generation recovers some of the useful work wasted on heat. Often a high energy content fuel with a high flame temperature (such as natural gas) is used for low ΔT heating (*e.g.* home heating or hot water). In electricity–heat cogeneration, electricity is produced with nearly 100% efficiency (as opposed to ~40% for power plants) because the remaining energy is used for heating instead of being wasted. In applications such as home co-generation, the desire for silent, vibration, and maintenance free operation will favor thermo-electrics. Residential co-generation and automotive waste heat recovery are two examples where "small" systems could have an impact on the global energy consumption if implemented on a large scale.

Portable Power

For small portable applications, power sources that are smaller and lighter than conventional batteries are of great commercial interest. The energy density of a combustible fuel is 10 to 100 times that of a battery. Thus in principle, even for low thermal-to-electric conversion efficiencies (*e.g.* a few percent), a small combustor supplying heat to a thermoelectric generator could provide greater energy density than a battery. However, a 10% efficient generator can require at least 500°C. In addition, to ensure that the heat is directed through the thermoelectric and not lost in the exhaust, the heat exchangers must be carefully designed. One such design is that of a "Swiss roll" combustor where catalytic combustion is localized to a small region to maintain a high source temperature while the exhaust is directed through a counter flow heat exchanger to preheat the incoming gasses (Fig. 3).[6] The thermal efficiency of such combustors can be 80-95%. Perhaps the best way to achieve high efficiency with such a device is to include a fuel cell just before the catalytic combustion. A single chamber fuel cell[7] produces electricity when placed in a hot fuel-air mixture. The unreacted fuel could then be combusted by the catalyst for use by the thermoelectric.

Harvesting MicroPower

The ability to fabricate exceedingly small semiconducting thermoele-ments has enabled the possibility of harvesting very small amounts of heat for low power applications such as wireless sensor networks, mobile devices, and even medical applications.[8] Various thin film techniques have been utilized to produce small thermoelectric devices including electrochemical MEMS,[9] CVD[10] and sputtering[11,12] with at least three companies (Micropelt, Nextreme, ThermoLife) recently established to produce devices (Fig. 4). Devices utilizing the thermoelectric material in a direction parallel to the deposition plane[12] lose some efficiency due to the thermal shorting of the substrate, but gain from the density and length
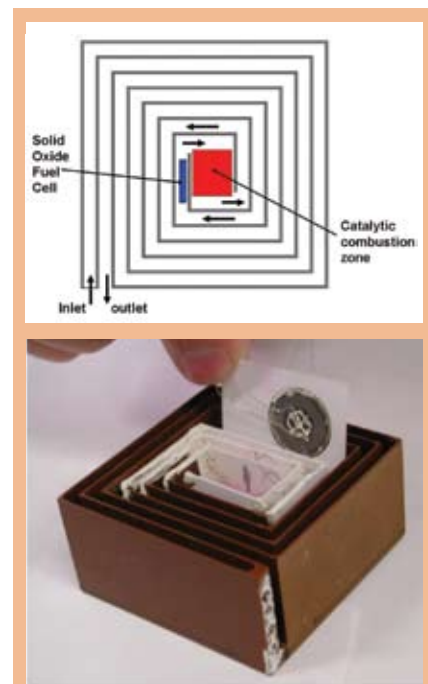

Fig. 3. *Single-chamber solid-oxide fuel cell with Swiss roll combustor.[6] The high power density fuel cell produces electricity from a mixture of fuel and air. The unreacted mixture is then catalytically combusted at the center of the Swiss roll heat exchanger that could be placed between two thermoelectric generators for additional electrical power.*

Fig. 2. *Conceptual design of thermoelectric generator producing electricity from waste heat in the engine exhaust. Copyright BMW, reprinted by permission.*
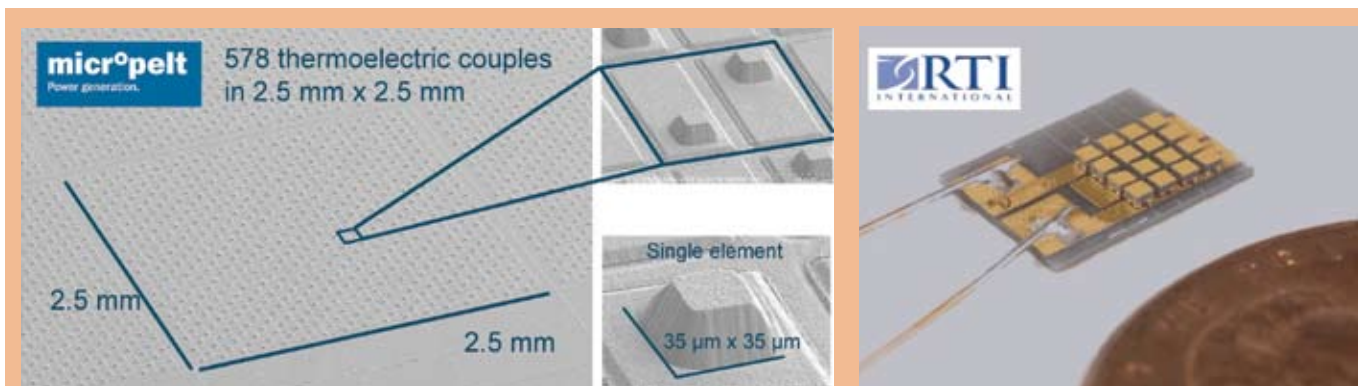
FIG. 4. *Microfabricated thermoelectric elements (Copyright Micropelt). Completed device (RTI) next to a penny (USA 1 cent.) (Copyright RTI.)*

of the thermoelectric elements such that 5V can be produced with a 10K temperature drop (ThermoLife).

At the same time, manufacturers of bulk thermoelectric devices, which typically have thermoelectric elements of 1-2 mm in length, can now reduce the size of the thermoelectric elements[13] even to 100μm.[14]

A good example of thermoelectric energy harvesting is the thermoelectric wristwatch, which utilizes thin bulk thermoelectric devices (Fig. 5). The watch is driven by body heat converted into the electrical power by the thermoelectric. At least two models have been built, one by Seiko and another by Citizen. The Seiko watch[14] (Fig. 5) under normal operation produces 22 μW of electrical power. With only a 1.5K temperature drop across the intricately-machined thermoelectric modules, the open circuit voltage is 300 mV, and thermal to electric efficiency is about 0.1%.

Although no longer in production, the thermoelectric wristwatch demonstrates the viability of utilizing thermoelectric in small power sources. As the cost of producing these devices drops with mass production and the increasing need for remote power sources, viable applications will undoubtedly arise. In addition, with the ever increasing economic and social cost of energy production, small thermal to electric power sources for cogeneration and waste heat recovery may someday play a significant role, however small.

Acknowledgments

About the Author

G. JEFFREY SNYDER is a faculty associate at the California Institute of Technology (Caltech) in Pasadena, California. His interest is focused on thermoelectric engineering and advanced materials development such as complex Zintl phase and nanostructured bulk thermoelectric materials (http://thermoelectrics.caltech.edu/). He may be reached at jsnyder@caltech.edu.

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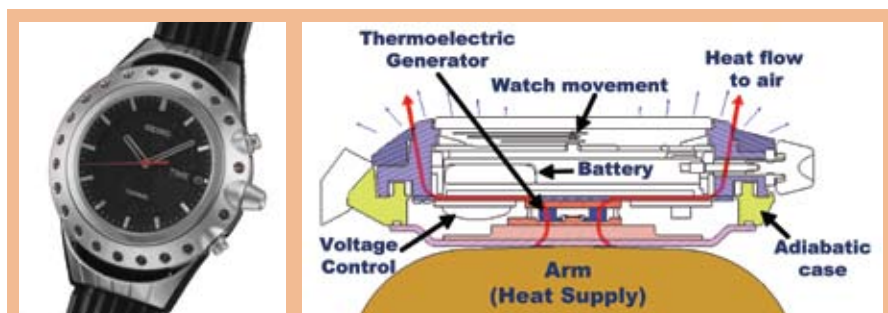
FIG. 5. *Seiko Thermic, a wristwatch powered by body heat using a thermoelectric generator; (a) the watch, (b) cross-sectional diagram.[14] (Copyright by Seiko Instruments Incorporated, reproduced with permission.)*