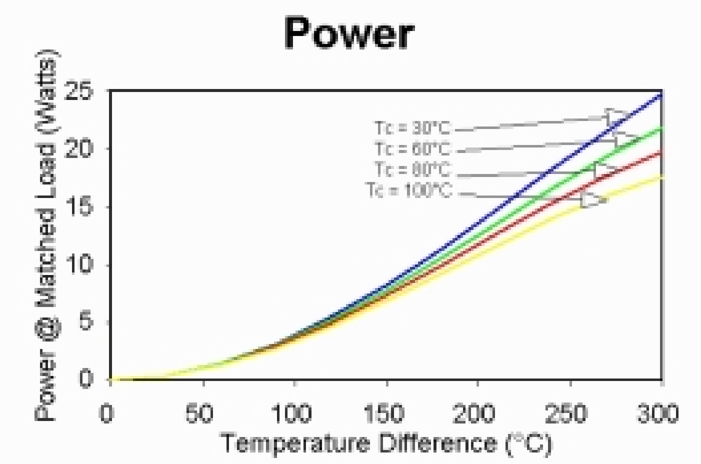
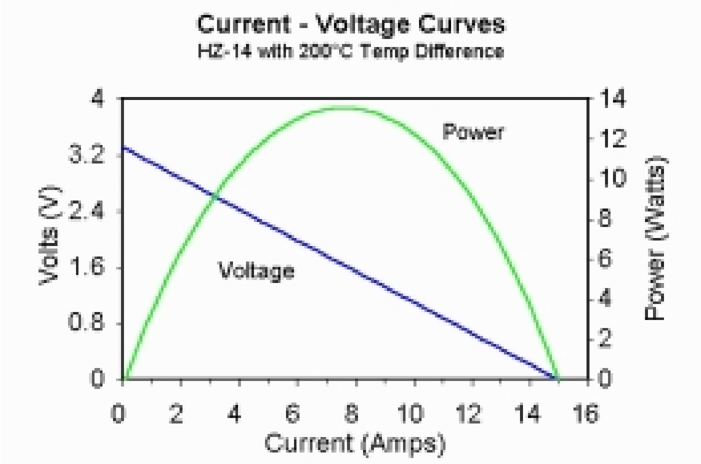
Solar Thermoelectric Technology: Part 2:
Thermoelectric Conversion Devices
by Dennis L Feucht

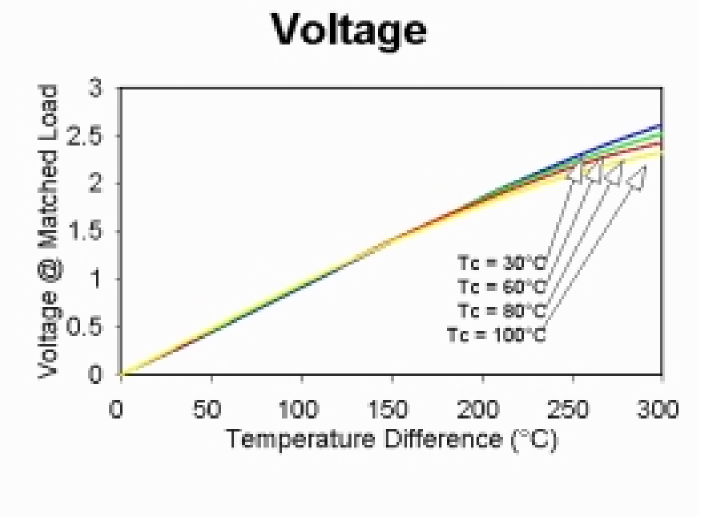
In Part 1 http://www.analogZONE.com/col_0305.htm solar thermoelectric system (STES) feasibility was examined and found to be favorable in cost compared to solar PV. The critical component of the system is the thermoelectric conversion device which was assumed to be the existing, still emerging, technology of thermoelectric modules (TEMs), based on thermocouples. In this part, emerging TE converters are surveyed in more detail.

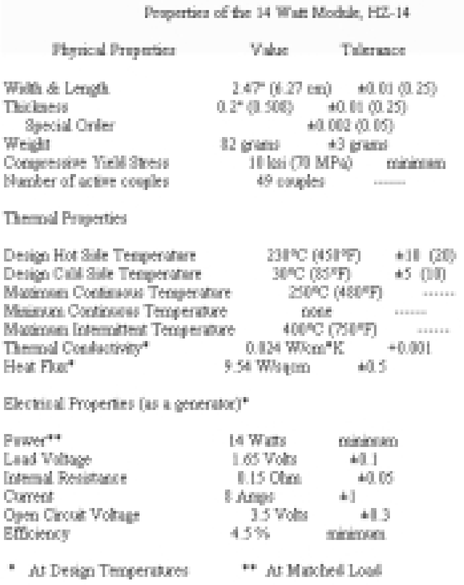
Thermoelectric Modules

TEMs are commercially available, though those optimized for electric generation are new and undergoing significant improvement. An assembly of seventy-two 14 W TEMs (HZ-14) in series provide about 1 kW of electric output power. Each assembly provides 8 A at 118.8 V, operating at maximum power conversion, with an efficiency of about 4.5%. This low efficiency relative to PV modules (which are typically around 15%) is more than compensated by the low cost and simplicity of thermal energy storage. A relatively large amount of thermal energy can be stored in a relatively small tank (see Part 1). A fluid with the heat capacity (4187 J/kg·°K) and density (1 kg/l) of water stores sensible heat of 4.187 kJ/l for each °C above ambient temperature, or 4.187 MJ/m^3. For a $\Delta T = 250$°C, the available heat stored per cubic meter is 1.047 GJ.







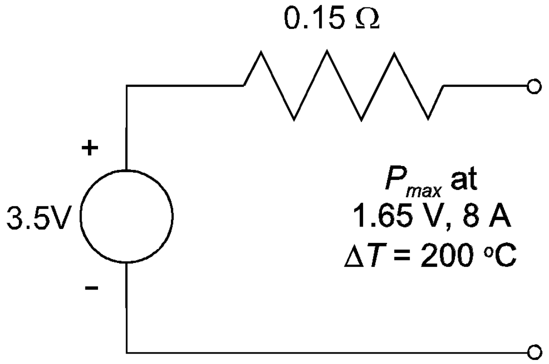


Properties of the 14 Watt Module, HZ-14

Physical Properties	Value	Tolerance
Width & Length	2.47" (6.27 cm)	±0.01 (0.25)
Thickness	0.2" (0.508)	±0.01 (0.25)
Special Order		±0.002 (0.05)
Weight	82 grams	±3 grams
Compressive Yield Stress	10 ksi (70 MPa)	minimum
Number of active couples	49 couples	------
Thermal Properties		
Design Hot Side Temperature	230°C (450°F)	±10 (20)
Design Cold Side Temperature	30°C (85°F)	±5 (10)
Maximum Continuous Temperature	250°C (480°F)	......
Minimum Continuous Temperature	none	......
Maximum Intermittent Temperature	400°C (750°F)	......
Thermal Conductivity*	0.024 W/cm°K	±0.001
Heat Flux*	9.54 W/sqcm	±0.5
Electrical Properties (as a generator)*		
Power**	14 Watts	minimum
Load Voltage	1.65 Volts	±0.1
Internal Resistance	0.15 Ohm	±0.05
Current	8 Amps	±1
Open Circuit Voltage	3.5 Volts	±0.3
Efficiency	4.5 %	minimum

* At Design Temperatures ** At Matched Load

The Thévenin equivalent circuit model of the HZ-14 is a 3.5 V source in series with a 0.15 Ω resistance:



The thermal voltage is related to the ΔT across the TEM by the *Seebeck coefficient*, α, in V/K:

$$v_\theta = \alpha \cdot \Delta T$$

The TEM output voltage is:

$$v_o = v_\theta - i \cdot R = \alpha \cdot \Delta T - i \cdot R$$

Electric output power:

$$p_o = v_o \cdot i = \alpha \cdot \Delta T \cdot i - i^2 \cdot R$$

The thermal input power:

$$p_i = \dot{Q}_i = G_\theta \cdot \Delta T$$

where, G_θ is the TE thermal conductance:

$$G_\theta = \frac{k_\theta \cdot A}{l}$$

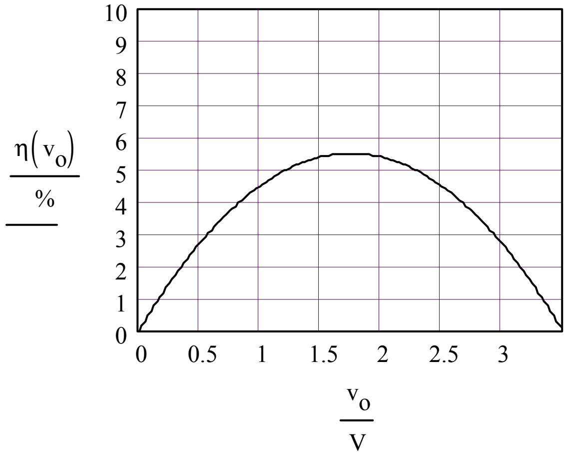
where, k_θ = TE thermal conductivity, A = TEM heat-flux cross-sectional area, and l = TEM thickness. Then the power conversion efficiency is:

$$\eta = \frac{p_o}{p_i} = \frac{\alpha}{G_\theta} \cdot i \cdot \left(1 - \frac{i}{I_0}\right)$$

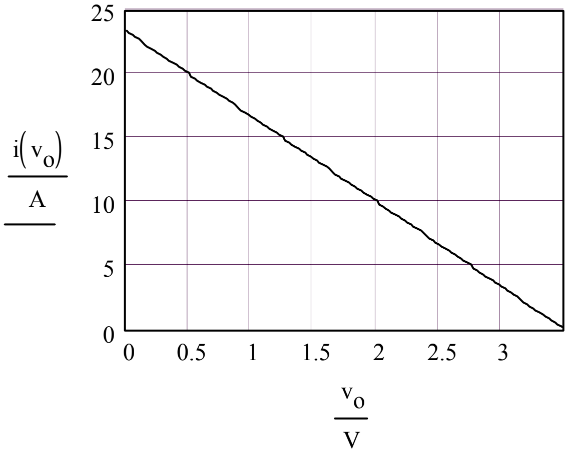
where:

$$I_0 = \frac{v_\theta}{R} = \alpha \cdot \frac{\Delta T}{R}$$

η is maximum at $v_\theta/2$, as shown below:



Output power is also maximum at $I_0/2$ and $v_\theta/2$:



At this point, the efficiency coefficient becomes a figure of merit, Z:

$$Z \cdot \Delta T = \frac{\alpha}{G_\theta} \cdot I_0 = \left(\frac{\alpha^2}{G_\theta \cdot R}\right) \cdot \Delta T$$

The geometric expressions for both thermal and electrical conductance have the form:

$$G = \frac{k \cdot A}{l}$$

where, A and l are the cross-sectional TEM area and thickness for both thermal and electrical G.

For electrical G ($= 1/R$), $k = \sigma$, and for thermal G, $k = k_\theta$.

Substituting and solving for Z:

$$Z = \frac{\alpha^2 \cdot \sigma}{k_\theta}$$

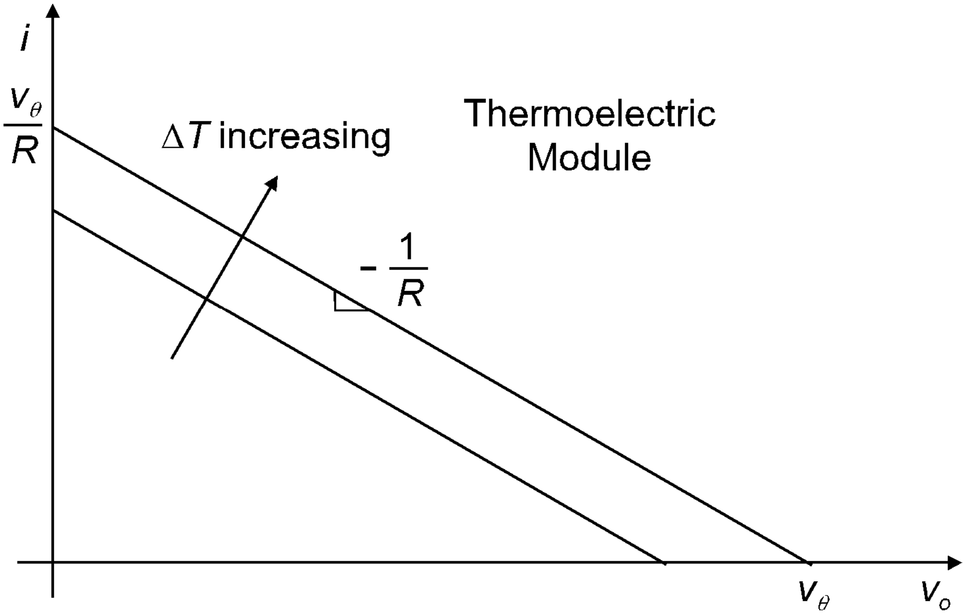
The quest for more efficient TE materials is to increase Z. The search is well beyond elemental metals because their electrical and thermal conductivities track.

At present, manufactured TEMs are dominated by semiconductor materials such as bismuth telluride. What is needed to significantly increase Z is a material that is highly electrically conductive but thermally insulative, with a large α.

The plot of i versus v_o with ΔT as the parameter is shown on the next page, following from:

$$i = \frac{v_\theta}{R} \cdot \left(1 - \frac{v_o}{v_\theta}\right)$$

As ΔT increases, the maximum power and current increases linearly by increasing v_θ.



The operating ΔT for the HZ-14 TEMs is chosen to be from 150°C to 250°C. Consequently, the available thermal energy from the tank is over this temperature range of 100°C. The useable stored energy is consequently 418.6 kJ/l·°K ≡ 418.6 MJ/m^3·°K. For a 500 gallon (1.893 m^3) tank, the useable stored energy is 792 MJ, or 220 kW·h.

Under full input ΔT, and unloaded, the TEM assembly of 72 HZ-14 TEMs connected electrically in series has an open-circuit voltage of 252 V. Inverters or converters must be rated for this open-circuit voltage. The full 72-TEM stack also has a total internal resistance at P_{max} of 10.8 Ω.

Thermionic And Thermotunneling Devices

Another kind of thermal-to-electric conversion transfers heat by *thermionic* emission. The heat and charge transfer mechanism is not electron diffusion, as it is for thermocouples, but is ballistic. Electrons take a ballistic path through an electric field, as in vacuum tubes (or more descriptively, thermionic valves, as the British call them) in which the emitting surface must be heated. The energy required for electrons to leave a surface is related to the work function of the material. Metals have too high of a work function for ambient thermionic conversion, but semiconductors are feasible. Electrons flow from hot to cold electrode. An external load reduces voltage across electrodes to less than the open-circuit voltage that opposes electron flow, and power is converted. One research group expects a doubling of efficiency over thermocouples. While for thermoelectric devices figure of merit, Z, is at best little more than one, for thermionic devices it is in the range of 2 to 5. Ballistic transport carries more heat than diffusion. (See *Multilayer Thermionic Refrigerator and Generator*, G D Mahan, *et. al.*, University of Tennessee, Knoxville, and Solid State Division, ORNL, Oak Ridge, TN, January 27, 2003.)

There is yet another promising device in the works. *Thermotunneling* devices are based on a third heat and charge transfer mechanism, the quantum effect of tunneling, as occurs in tunnel diodes. Conceptually, this kind of device seems almost too good to be true: separate two flat metal plates 10 nm apart, and coat the emitting plate with a low work-function material, to enhance tunneling. At that spacing electrons tunnel from one plate to the other, carrying heat with them. The problem in practice is the close spacing. (Thermionic transport occurs at an optimal spacing of ten times as much, around 100 nm.) Semiconductor processes are used to create two surfaces with matching non-uniformities over the tunneling surface. The close spacing relative to the dimensions of plate area results in localized shorts which decrease efficiency. Prototypes are claimed by http://www.powerchips.gi/technology/index.shtml to have shown 15% efficiency, three to four times that of TEMs. (Also, see the parent company at http://www.borealis.com.)

A problem shared by thermionic and thermotunneling devices is that the narrow barrier causes thermal conductivity to be high, resulting in large heat flow for a given current. The problem is being addressed for semiconductor thermionics by the University of Tennessee-ORNL effort by using multiple barriers in series, causing thermal resistance to add.

Closure

Thermal-electric conversion should be very interesting this decade, as revolutionary new devices become commercially available. At the projected efficiencies, not only will solar thermal electric generation be competitive with existing power generation technologies, vapor-compression refrigeration and the internal combustion engine might also be heading for replacement. The current state of development for thermionic and thermotunneling devices has gone sufficiently far to establish their basic feasibility. What remains is plenty of engineering refinement and then novel applications for these new devices.

Other major power-conversion technologies under development are thermophotovoltaics (TPV), which greatly increases PV efficiency by making use of infrared energy through an optical processing layer, and the re-emergence of efficient and low-ΔT Stirling engines.

If you are an entrepreneur or investor and have a serious interest in commercializing STES products, please contact me, at dennis@innovatia.com.

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