

# Small Thermoelectric Generators

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## Abstract

Thermoelectric generators with combustion heat sources are being developed for the U. S. Army, TACOM-ARDEC, by Hi-Z Technology, Inc., for battery replacement in the field and for powering lightweight portable battery chargers. These small generators range in output power from 0.3 watts to 20 watts. The main thrust of the development work is to demonstrate utilization of diesel or other military logistics fuel as the heat source. The thermoelectric generating modules being used operate at relatively low hot side temperatures and with modest power conversion efficiencies. Nevertheless, the concept shows potential advantage over batteries in watts per pound and watt-hours per pound, thus addressing the "battery problem" and the need for lightening the soldier's battery burden, and doing so at reasonable costs. The thermoelectric material used in this application is current state-of-the-art. However, Hi-Z is also developing advanced thermoelectric materials and devices that promise significantly improved performance in the near future.

## Background & Introduction

Thermoelectric conversion of heat to electricity has been used in various applications since the advent of semiconductor materials science enabled practical devices to be made. The widest use of the technology has been in applications to take advantage of the reliability and ruggedness that come from a high degree of solid state function, for example in comparison to rotating machinery for electric generation. The most successful applications have been in terrestrial remote locations and in outer planet space missions, generally with radioisotope fuel.

The U. S. Army has in the past looked to thermoelectric technology for its advantages of reliable, silent operation with multi-fuel capability, and several systems have been built, tested and deployed [1].

The work reported here is recent exploratory development of small thermoelectric generators that would serve as compact power sources. These would allow self-powering of certain weapons. The thermoelectric generator could compete on specific power and specific energy with batteries or could be used to recharge batteries in the field. Additional benefits to the Army could be greater personnel safety, lower cost, longer shelf life, and reduced disposal burden.

A recognized disadvantage of thermoelectric generation are limits on the efficiency of power conversion. This factor has

restricted wider applications of the technology to date. However, recent DARPA/ONR and DOE programs have generated a breakthrough in thermoelectric efficiency that may increase efficiency by a factor of two or three to levels that appear competitive with other means of production of electric power in the field.

## Initial Investigation

The initial objective of the work was to develop the design of a safe, small thermoelectric electric power source which has a very long service life and a wide operational temperature range suitable to provide electric power needed to illuminate armament fire controls.

There were three approaches used:

- a thermoelectric power supply with tritium heat source
- a thermoelectric power supply with flame heat source
- a thermoelectric power supply with molten salt energy storage

Conceptual design work and performance analysis was done, and the most promising of these was the power supply with flame heat source, especially if the fuel can be diesel (or other military logistics fuel).

## Progress and Discussion

The work is now at the beginning of the second year of a two year contract. We are carrying-out several tasks to build and test a series of thermoelectric generators. Each uses bismuth-telluride alloy thermoelectric module technology. The generators vary according to heat source and the size of Hi-Z module that is incorporated.

We designed, built and demonstrated a generator that makes use of a butane cartridge fuel supply. The scale of 300 milliwatt output was adopted for this generator based upon the Army's needs for fire control illumination. Such a generator would power LEDs that provided light either directly or through fiber optic light guides.

We also began work on a logistics-fueled generator with subcontractor Altex Technologies Corporation. Altex have been developer of a pocket-sized diesel-fueled personal stove for the Soldier Systems Center, Army Soldier and Biological Chemical Command. The stove utilizes a unique porous surface element wick. Altex has collaborated in the present work on a 1-2 W diesel generator we have called STEG (Small Thermoelectric Generator). As perceived at this stage of development, STEG

would be an alternative to batteries for illumination or fire control electronics.

A final task is a “large” diesel-fueled generator, similar to and possibly a scale-up of the STEG, which is tentatively sized at 15 to 20 W electric output. A useful Army application for this generator would be battery charging. Substantial work on this task has been scheduled in the second year.

We also began work on a 300 milliwatt thermoelectric generator that uses for its heat source a molten salt energy store. The design was detailed, and testing was begun on several energy storage media to validate the designed performance.

**Milliwatt Butane Generator**

The Milliwatt Generator was designed around a commercially available burner that runs on a butane cartridge that holds 12 g of fuel. A custom-made low power, high voltage thermoelectric module was used. The unit is shown in Figure 1 on test with 10 LEDs, each “rated” at 0.02 A at 2.0 V in 2 x 5 array and using a current controlling DC-DC converter to step up to 0.04 A at 8 V. Maximum light output was approximately 10 lumens.



**Figure 1: Milliwatt Butane-Heated Generator**

A summary of the generator performance is as follows. A task ahead is to lighten the mass of the system, and we calculate that with a fuel supply on the order of 1 kg the specific power would be 100 W-hr/kg, which is competitive with chemical batteries.

design (custom module), mW	300
actual output power, mW	360
generator output voltage, V	5.0
T <sub>H</sub> , T <sub>C</sub> “rated”, /C	250, 30
T <sub>H</sub> , T <sub>C</sub> actual, /C	260, 70
fuel consumption, mg/min	40
input heat @ 13.8 W-hr/g, W	33
conversion efficiency	1.2 %
ref. module efficiency	4 %
est. burner efficiency	30 %

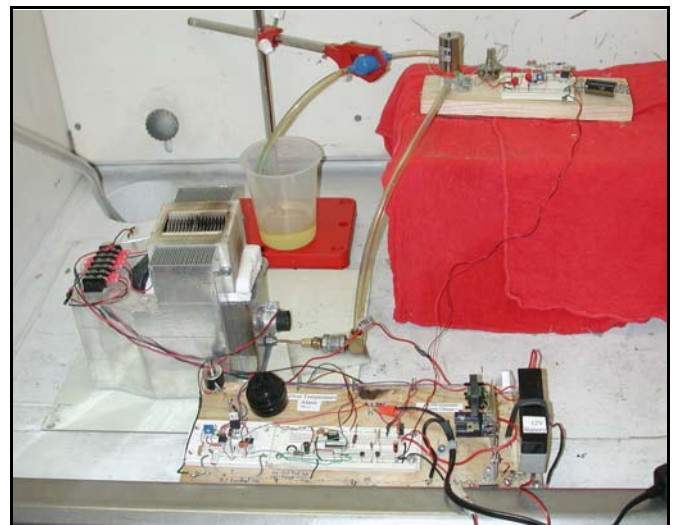
**STEG**

The STEG (Small Thermoelectric Generator) is to be both demonstrated and delivered in prototype form for testing by the Army. This is the main effort of the contract work. The unit is built around the Altex logistics fuel burner. In Figure 2 the insulated burner subassembly is shown in the center of the figure, and the burner is shown in the foreground. The generator subassembly is to the left.



**Figure 2: STEG Assembly**

The generator subassembly consists of two HZ-2 thermoelectric modules that are each “sandwiched” between finned heat exchanger blocks. Heat from the burner flows up across the hot side heat exchangers, and a fan at the left end in Figure 2 blows air to and upward across two cold side heat exchangers that are at the forward and back extremes of the subassembly in the figure. Figure 3 shows the generator on test along with the breadboard electronics for fuel flow control and output power conditioning.



**Figure 3: STEG on Test**

The STEG on test produced a net of 1/3 more power than the design intended. Summary of test results is as follows. At the rate of fuel consumption this generator would operate for 12 hours on 350 ml of diesel, which is the volume of a 12-ounce soft drink can.

Power output, gross, W	4.5
cooling fan, W	1.2
combustion fan, W	0.06
fuel pump, W	0.10
DC-DC converter loss at 85% efficiency	0.47
power output, net, W	2.7
output voltage, V	4.0 - 7.0
$T_H, T_C$ "rated", /C	250, 30
$T_H, T_C$ actual, /C	260, 60
fuel consumption, ml/min	0.50
input heat, W	250
fuel conversion efficiency, gross	1.8 %
fuel conversion efficiency, net	1.1 %
reference module efficiency	4 %
fuel energy delivered to module	45 %

### Scaled-Up STEG for Battery Charging

The final portion of the effort will address the demonstration of the STEG scaled-up to an electrical output of 15 to 20 W. At that power level a generator could interface with a portable battery charger. For example, at 18 W the BB-2590 Li-ion battery can be fully charged in 8 hours, or 10 Ni-Cd or 6 Ni-MH "D" cells could be charged in 4 hours.

### Recent Developments in Higher Efficiency Thermoelectric Devices

A new class of thermoelectric materials and devices have resulted from recent research and development in the field. These are categorized as "low-dimensional" thermoelectrics and they have the potential to greatly increase power conversion efficiencies.

One promising area is superlattice thin-films, also called "quantum wells". These are structures built up of layers of alternating semiconductor materials only several atomic layers thick. This structure allows for decoupling of the thermal and electrical conductivities of the material, and further tailoring of the layer materials can yield a higher value of the overall material thermoelectric figure of merit,  $ZT$ , where  $Z$  is the square of the Seebeck coefficient divided by the electrical resistivity and thermal conductivity. Figure 4 shows the progress of the increase in  $ZT$  since the beginning of recent DARPA/ONR and DOE programs on this technology [2]. Values between 3 and 4 are now considered possible.

Hi-Z has conducted an active program in quantum well thermoelectrics over the past eight years [3, 4]. Materials developed are multilayers of  $B_4C/B_5C$  and of  $Si/Si_{0.8}Ge_{0.2}$  formed by sputtering techniques. Laboratory-scale devices are operating from which efficiencies over 20% are extrapolated [4].

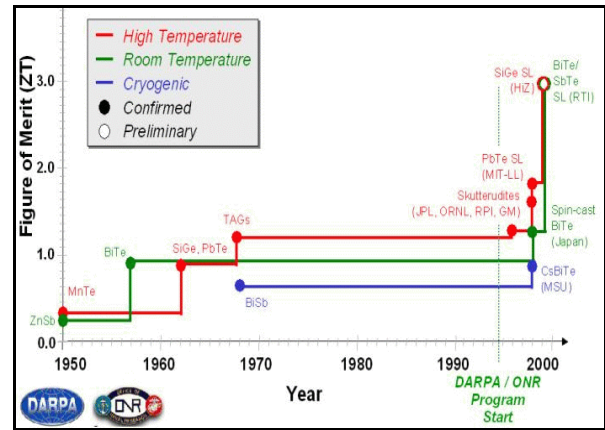


Figure 4: History of the Thermoelectric Figure of Merit,  $ZT$ , from Dubois [2]

Hi-Z's quantum well material exhibits this performance in the direction parallel to the thin-film layers. Another development shows good thermoelectric performance in the perpendicular direction for layers of  $Bi_2Te_3/Sb_2Te_3$  formed by molecular beam epitaxy [5]. A third program is investigating "quantum dots" [6], and performance improvement is seen from these results as well.

### Conclusion

The need for lightening the battery burden in present and future military systems can be met by some substitution of small-scale logistic fuel-heated thermoelectric generators. The feasibility of this alternative is being demonstrated. Recent advances in higher efficiency thermoelectrics indicate even better performance materials are becoming available.

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