A SELF-POWERED FIELD FEEDING SYSTEM

Don Pickard* and Frank DiLeo,
US Army Natick Soldier Center
Natick, MA 01760-5011

Aleksandr Kushch, Markvard Hauerbach and Lawrence LeVine,
Hi-Z Technology, Inc.
San Diego, CA 92126-4210

ABSTRACT

Thermoelectric technology has been used to reduce the logistics of field feeding. A conventional Tray Ration Heater (TRH) powered by the HMMWV, was redesigned to include a thermoelectric generator, a low power consumption DC burner, and a newly designed Power Management System (POMS). Two STRHs were fabricated and tested, and demonstrated the capability of heating rations for field feeding independent of external power generation equipment. In addition, the STRH produces surplus electricity that can be used for various needs, such as lighting, battery charging, powering radios, communication devices, etc. Most importantly, the independent operation of the STRH provides the operational flexibility to drop the field feeding system should there be a requirement for the HMMWV to accomplish another mission. Compared to powering the TRH with a 2 kW diesel generator, the integral thermoelectric generator reduces the field feeding system weight, cost, and fuel consumption, while significantly increasing system reliability

1. INTRODUCTION

The Army Quartermaster has drafted an Objective Force field-feeding concept titled *Total Army Field Feeding-2010 (TAFF-2010)* which includes "pit stops" when soldiers are moving rapidly during operations. An Assault Kitchen (AK) (Fig. 1) is being developed for the pit stop, based on the US Marine Corps' Tray Ration Heater System (TRHS). The TRHS is basically a water heater that boils water to heat standard 6 pound polymeric tray-packs of food that are packaged as the Unitized Group Ration - Heat & Serve. One of the limitations of the Assault Kitchen is the need for electric power which must come from an idling HMMWV or 2kW generator. The TRHS is an ideal application for thermoelectric power generation. Although thermoelectric technology is less than 5% efficient for power generation, when used in Combined Heat and Power applications, overall system efficiency can be as high as 85%. More importantly, the solid state thermoelectric modules can provide the same function as the HMMWV engine or 2kW generator at a fraction of the weight, fuel consumption, and noise.

Figure 1. Assault Kitchen

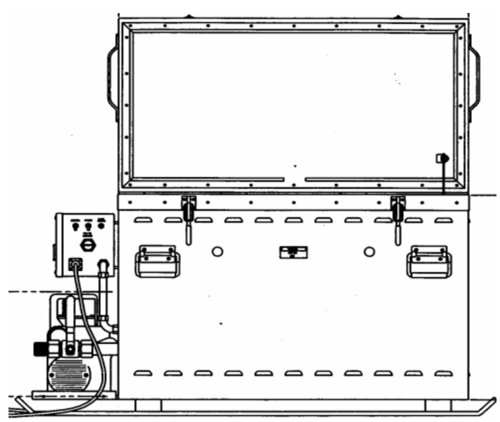

Figure 2. Current Tray Ration Heater

2. PRESENT SYSTEM

The TRHS (Fig. 2) was developed at the Natick Soldier Center 20 years ago. It is the primary expeditionary field feeding system used by the Maine Corps, and is also used by Air Force. It is a rectangular box filled with 20 gallons of water that is brought to a boil by a commercial residential oil burner configured to burn JP8. Eighteen standard six pound tray packs of shelf-stable food are placed in the boiling water for 45 minutes to heat them to a serving temperature of 160^{O}F. The AC powered burner is connected to an inverter that is connected to the HMMWV utility outlet or Diesel generator.

3. THERMOELECTRIC TECHNOLOGY

Thermoelectric technology is solid-state and directly converts heat to electricity. The thermo electric modules (TEM) are rugged devices, capable of withstanding high mechanical impacts (Hi-Z space modules can withstand about 1000 G without degradation). A waste heat recovery system, for heavy duty Diesel trucks that Hi-Z fabricated and tested for DOE, was installed on Kenworth truck for durability test. The TEG went through 543,000 equivalent miles during the durability test at Paccar technical facility without TEG degradation.

The advantages of the durability and long-lifetime that comes from the solid-state nature of thermoelectric converters are demonstrated by Pioneer 10, which was equipped with a radioisotope-heated thermoelectric generator (RTG). Pioneer 10 was launched in 1972 and continued communication with Earth until January 2003 (almost 31 years). The distance from Earth in 2003 was about 7.6 billion miles.

A single thermoelectric couple is shown in Figure 3. A couple consists of two legs (N and P type) that are fabricated from semiconductor materials. The composition and doping of the leg materials determine the properties of the individual leg as well as the entire couple. Bismuth telluride (that is used in the current generator), lead telluride and silicon germanium are typical materials used in thermoelectric devices.

When heat is applied to the couple junction, DC electric power is generated and supplied to the external load. Temperature differential between hot and cold sides (?T) of the couple defines electric power generated by the device. Typically, electric power produced by the couple is proportional to $?T^2$.

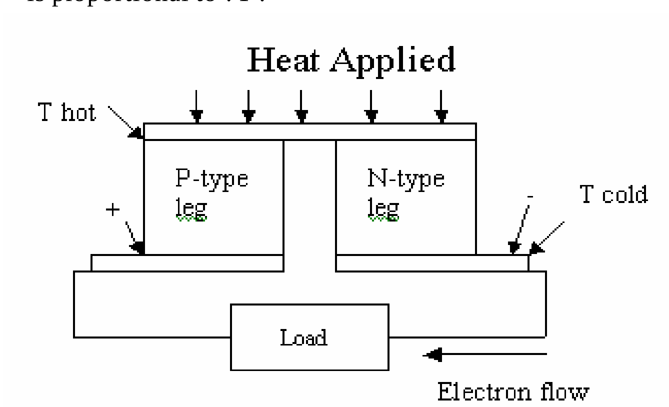

Figure 3. Thermoelectric Couple

The thermoelectric module consists of multiple thermoelectric couples that are interconnected electrically in series and thermally in parallel as shown in Figure 4.

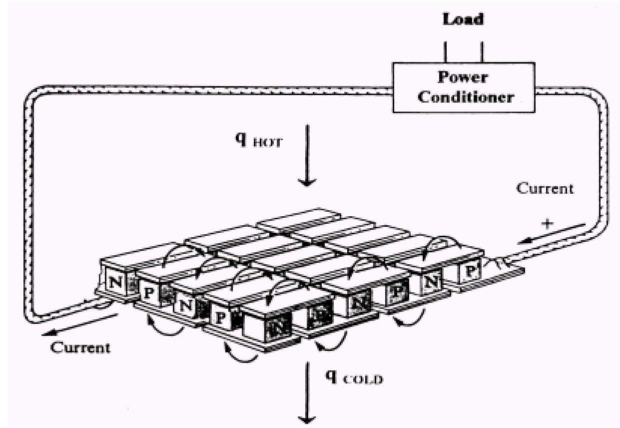

Figure 4. Thermoelectric module

The thermoelectric module hot side can be heated by different heat sources, including a fossil fuel burner, mobile or stationary engine exhaust, sunlight, geothermal heat, isotopes, *etc.* The solid state TEM does not have moving parts; it is a quiet and maintenance-free device.

Usually, the thermoelectric modules are manufactured for an electric power output of from 1W to 20W at about 1.5 to 3.5V. Output voltage is proportional to the number of couples in the module. Presently modules cost around $7 to $10 per watt in small quantities, but large scale production projections are for prices near $1 per watt.

Typically, the TEM is not very efficient because the rejected heat is normally wasted. The overall system efficiency is usually less than 2% because parasitic power is required for the burner and heat rejection system, typically a fan. The Self-powered Tray Ration Heater (STRH) cools the cold side of the TEM with hot water eliminating the parasitic loss of a fan. But, more importantly, all of the heat energy normally lost in a generator application is used in the STRH application providing an exceptionally good technology application

For the current project HZ-20 thermoelectric modules were used for the TEG integration, as shown in Figures 5 and 6.

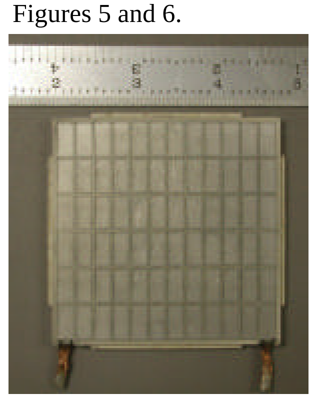

Figure 5. HZ-20 module

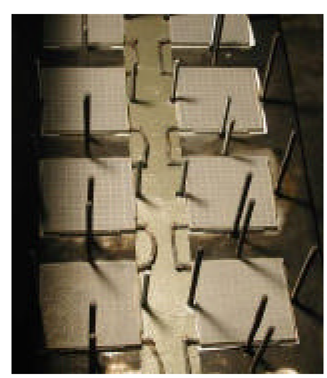

Figure 6. TEG for STRH

Table 1. HZ-20 thermoelectric module technical characteristics

Properties of the 19 Watt Module, HZ-20		
Physical Properties	**Value**	**Tolerance**
Width and Length	2.95 in. (7.5 cm)	±0.01 (0.025)
Thickness	0.2 in. (0.508 cm)	±0.01 (0.025)
Special Order		±0.002 (0.005)
Weight	115 grams	±3 grams
Compressive Yield Stress	10 ksi (70 MPa)	Minimum
Number of active couples	71 couples	-
Thermal Properties		
Design Hot Side Temperature	230EC (450EF)	±10 (20)
Design Cold Side Temperature	30EC (85EF)	±5 (10)
Minimum Continuous Temperature	None	-
Maximum Intermittent Temperature	400EC (750EF)	-
Thermal Conductivity[1]	0.024 W/cm*K	±0.0005
Heat Flux[1]	9.54 W/cm^2	±0.5
Electrical Properties (as a generator)[1]		
Power[2]	19 Watts	minimum
Load Voltage	2.38 Volts	±0.2
Internal Resistance	0.3 O	±0.05
Current	8 Amps	±1
Open Circuit Voltage	5.0 Volts	±0.3
Efficiency	4.5%	minimum

[1] At design temperatures
[2] At matched load, refer to the graphs for properties at various operating temperatures and conditions.

The properties of the HZ-20 thermoelectric module are presented in Table 1 and Figure 5

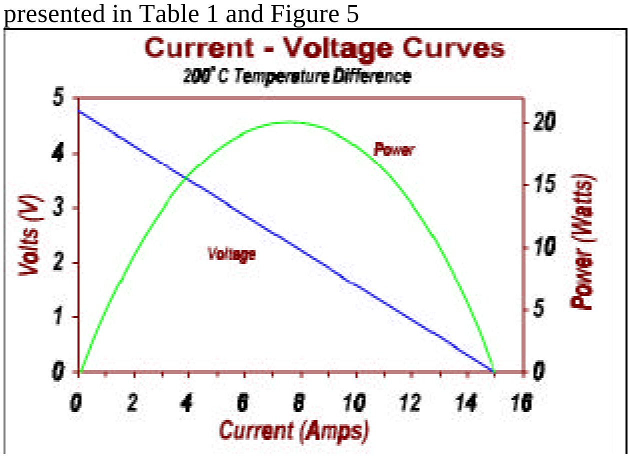

Figure 7. HZ-20 module current-voltage curves at 200^{O}C hot/cold delta T

4. STRH DEVELOPMENT

The STRH system, shown in Figure 8, was developed by integrating a thermoelectric generator with very low power consumption a DC logistic fueled burner (Fig. 9), and a power management system into a modified tray ration heater.

Cooling the cold side of the TEM with stagnant boiling water had never been done so there were several challenges that had to be overcome. The TEM hot side design temperature is 250°C. Higher temperatures cause degradation and lower temperatures result in a loss of power. A hot side heat exchanger (HSHE) was designed with mica plates (as thermal interface material between the thermoelectric module and the HSHE) with variable thickness to provide the proper temperature.

Figure 8. Self-powered tray ration heater

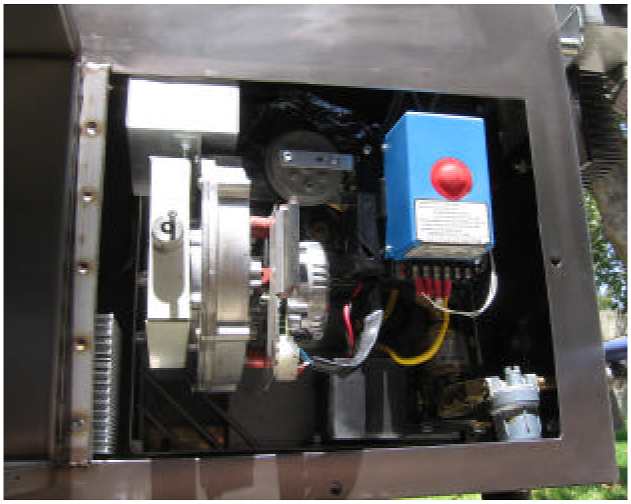

Figure 9. DC low power consumption logistic fueled burner installed on STRH

Figure 10 illustrates the TEG hot side temperature distribution for uniform mica thickness and final TEG configuration with variable mica thickness. An aluminized surface treatment of the HSHE enabled the use of inexpensive carbon steel in the corrosive combustion chamber. The TEM cold side heat transfer was improved by using alumina wafers as the thermal interface material between the TEMs and water tank. The TEG of the STRH includes 16 HZ-20 TEMs that are commercially produced by Hi-Z Technology, Inc. The TEMs were sandwiched between the cold plate (embedded in the bottom of the water tank) and the HSHEs and compressed to about 200 PSI to ensure good heat transfer. The TEMs were interconnected in series in order to maximize the TEM output voltage. The novel Power Management System (POMS) that is presented in Figures 11 and 12 was designed, fabricated and integrated into the STRH.

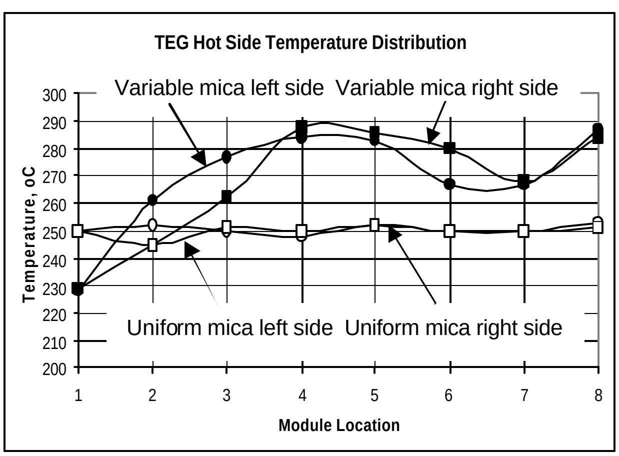

Figure 10. STRH #1 hot side temperature distribution before and after temperature adjustment

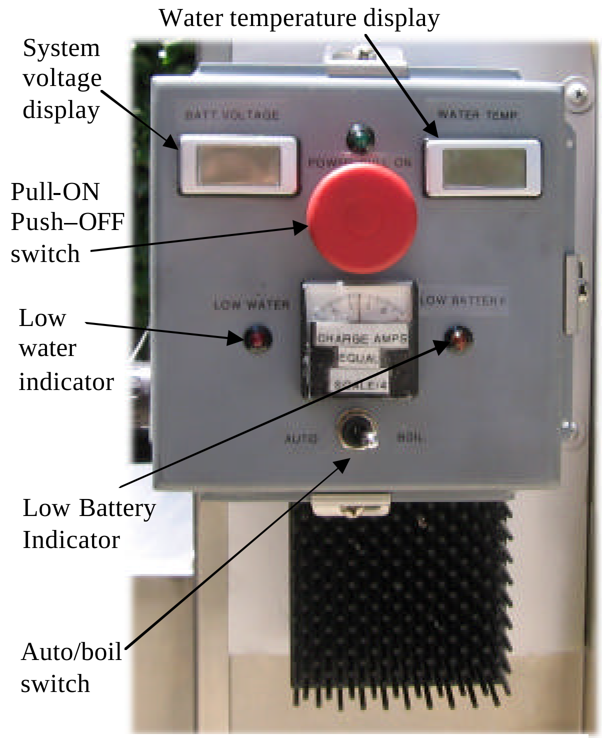

Figure 11. Power management system

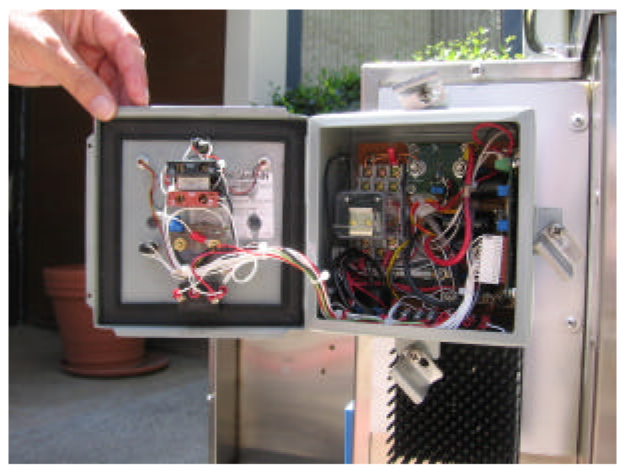

Figure 12. POMS circuits

The POMS acts as an interface between the TEG, the start-up battery and the DC burner. The POMS starts the STRH from the battery, which is located in a battery pack shown in Figure 13. When the burner starts, the temperature differential between the TEG hot and cold sides increases and the TEG starts producing electric power. When the TEG output voltage reaches the system voltage, it starts to "help" the battery to drive the system. When the TEMs generate sufficient power, the POMS allows the TEG to power the STRH, recharging the start-up battery, and providing battery overcharge protection. The POMS also enables the STRH to operate in auto and boiling modes, and ensures safety shut off at low water level, low battery state, and when the system is tilted.

Figure 13. STRH Battery Pack

The POMS also allows recharging the start-up battery from an external 28 V DC source (diesel generator or HMMWV) when the start-up battery is partially depleted. Surplus power is provided to a 24 V DC outlet.

5. STRH TESTING

Two STRH were fabricated and tested. The major objectives of these tests were to verify that the TEG is capable of generating a sufficient amount of electric power to drive the STRH and to recharge the start-up battery. The POMS functionality and the DC burner reliability were also tested. Figure 14 shows test results of the first STRH. When the system starts, all the power comes from the battery that is reflected by negative values of electric power. The TEG begins generating power and starts assisting the battery in less than 3 minutes and takes over burner operation from the battery in 9 minutes (electric power becomes positive). From this point the

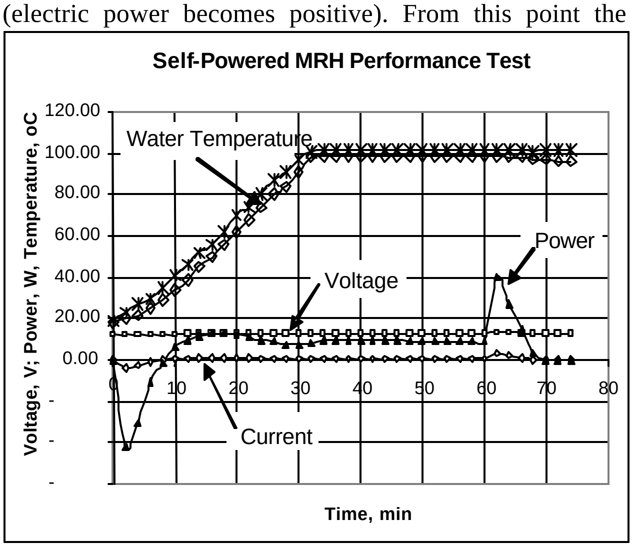

Figure 14. STRH Performance

TEG drives the complete system and charges the battery. The system performance test demonstrated that in steady state operation the TEG is capable of generating surplus electricity (about 10 W to 13 W) that can be used for lighting, charging batteries or other needs. At the end of operation, when the burner is turned off, the TEG will produce electricity until the hot/cold side temperature differential drops to a point where the TEG output voltage is higher or equal to the system voltage. So, when the system is shut down and the burner is turned off, all the electricity that is produced by the TEG is delivered to the start-up battery, charging it and ensuring the next successful start-up. The battery voltage before the test was 12.44 V, after the test 12.67 V which indicates that the battery was completely recharged after 60 minutes of the STRH operation.

All the POMS features were repeatedly tested to verify operation. The second STRH was fabricated as a replica of the first unit except the hot/cold side temperature differential was improved compared to the STRH #1.

The test results of the STRH #2 in comparison with the STRH #1 are presented in Figures 15 and 16.

Figure 15 shows that STRH #2 generates more electric power than the first unit (because of improved hot/cold side temperature differential). The system voltage increases much faster and the battery voltage at the end of 60 minutes test is greater for STRH #2.

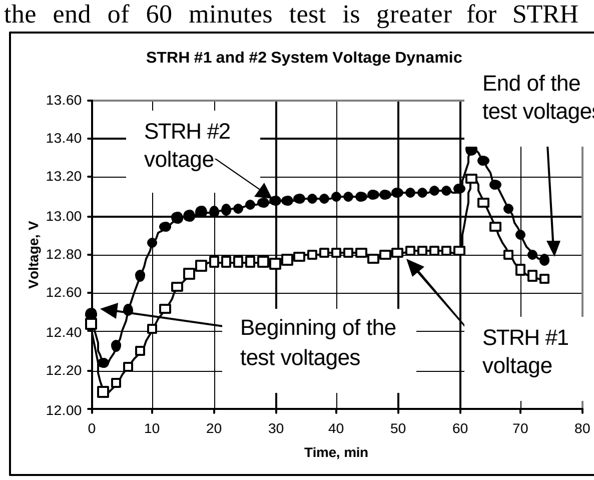

Figure 15. STRH #1 and #2 voltage behavior

STRH # 1 and 2 power balance, presented in Figure 16 shows that the second unit produced about twice as much surplus power (20 W to 24 W) compared to the first unit (10 W to 13 W). The second unit reaches the break even point (positive electric power values) faster (in about 5 minutes) and also STRH #2 recharges the start-up battery faster. This surplus electricity, if necessary, can power various additional electrical devices such as light sources, battery charger, communication devices, radio, etc. If there is no need to power additional devices, the TEG power production can be reduced (to the level of the first STRH or slightly lower) by reducing the number of the thermoelectric modules in the TEG. The current TEG

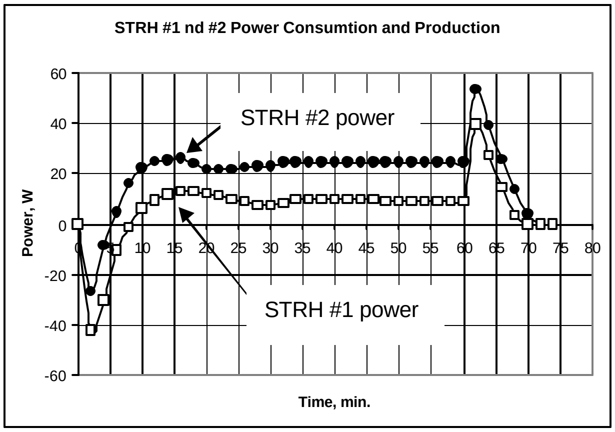

Figure 16. Electric power balance for STRH #1 & #2

consists of 16 thermoelectric modules. Based on the STRHS #2 test results it is anticipated that the number of TE modules can be reduced to 12 each with the associated TEG cost and weight reduction

6. FUTURE DEVELOPMENT AND CONCLUSIONS

The STRH will be demonstrated in the field in FY 07 and transitioned to the Army Product Manager Force Sustainment Systems (PM FSS) for Full Scale Engineering Development in FY 08. Future development efforts will focus on reducing costs primarily by reducing thermoelectric module and associated heat exchangers and fasteners. Manufacturability and producibility will also be examined. The final product will be a performance specification that will allow competitive procurement by the Army as well as the Navy, Air Force and Marines. The STRH is an exceptional application for thermoelectric technology that demonstrates systems do not necessarily have to be powered by engine driven generators. Thermoelectric generators can substantially reduce system weight, volume, fuel consumption, complexity, noise and improve the system reliability.