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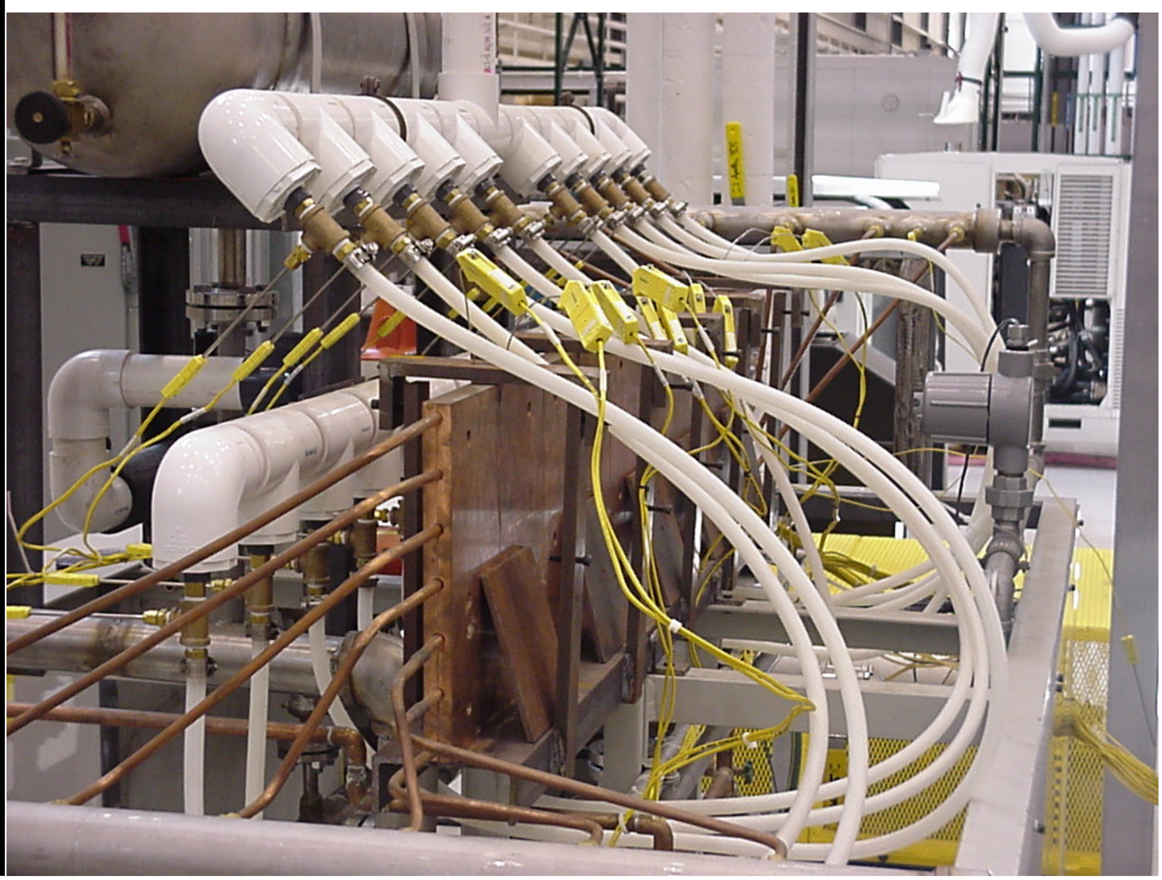
Application of Thermoelectric Devices to Fuel Cell Power Generation

Demonstration and Evaluation

John Huston, Chris Wyatt, Chris Nichols,
Michael J. Binder, and Franklin H. Holcomb

September 2004



Construction Engineering Research Laboratory

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Application of Thermoelectric Devices to Fuel Cell Power Generation: Demonstration and Evaluation

Michael J. Binder and Franklin H. Holcomb

Construction Engineering Research Laboratory
PO Box 9005
Champaign, IL 61826-9005

John Huston, Chris Wyatt, and Chris Nichols

Concurrent Technologies Corporation (CTC)
100 CTC Drive
Johnstown, PA 15904-1935

Final Report

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Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under Work Unit No. 007KEA

ABSTRACT: The Department of Defense (DOD) is concerned with reliable and cost-effective power generation of on-site power generators as well as minimizing the environmental impact of these generators. Thermoelectric (TE) devices offer the opportunity to generate power without additional fuels, without moving parts, and with negligible environmental impact. An electrical energy conversion efficiency of approximately 15 percent would be required to obtain an acceptable return on investment for TE devices. A feasibility study to was performed to determine how, assuming a 16 percent efficiency, TE devices could impact the DOD's power generation capabilities.

Based on research indicating energy conversion efficiencies of 20 percent, TE devices were built and tested. Of 27 TE devices supplied, only 8 were functional; each device produced only 1 Watt of power. Current manufacturing processes and design parameters were assessed and recommendations made. Three locations were prepared as demonstration sites for TE devices, site evaluation criteria were outlined, and process results given. Control and Data Acquisition (CDAQ) Systems for single and multiple test stands were developed to gather all necessary data variables during the demonstrations, and a portable technology system was developed to enable personnel to demonstrate the technology in any location.

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Conversion Factors

Non-SI* units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(5/9) x (°F – 32)	degrees Celsius
degrees Fahrenheit	(5/9) x (°F – 32) + 273.15.	kelvins
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 ft-lb force per second)	745.6999	watts
inches	0.0254	meters
kips per square foot	47.88026	kilopascals
kips per square inch	6.894757	megapascals
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square miles	2,589,998	square meters
tons (force)	8,896.443	Newtons
tons (2,000 pounds, mass)	907.1847	kilograms
Yards	0.9144	Meters

* *Système International d'Unités* ("International System of Measurement"), commonly known as the "metric system."

Preface

This study was conducted under RDTE project, "Thermoelectric Power Generation," Work Unit 007KEA, PROMIS CFE-B151. The Technical Monitor was Bob Boyd, Office of the Director, Defense, Research and Engineering (ODDR&E).

The work was performed by the Energy Branch (CF-E) of the Facilities Division (CF). The CERL Principal Investigators were Dr. Mike Binder and Franklin H. Holcomb. Part of this work was done by Concurrent Technologies Corporation (CTC) Johnstown PA, and by Leonardo Technologies Inc. Murrysville PA, under General Services Administration (GSA) Task Order 5TS5701C256. Dr. Thomas Hartranft is Chief, CEERD-CF-E, and L. Michael Golish is Chief, CEERD-CF. The associated Technical Director was Gary W. Schanche, CEERD-CVT. The technical editor was William J. Wolfe, Information Technology Laboratory.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL James R. Rowan, and the Director of ERDC is Dr. James R. Houston.

1 Introduction

Background

The supply of reliable, cost-effective electric power with minimal environmental impact is a constant concern for Department of Defense (DOD) installations and systems energy personnel. Electricity purchased from utilities is expensive. Consumed electricity represents only about 30 percent of the original energy output at the generating station due to generation and distribution inefficiencies. Master metering and large air-conditioning loads can cause the demand portion of an installation's electric bill to account for more than 50 percent of its total energy bill.

While electric utilities in the United States have an excellent record of reliability, there is significant potential for improving the security of electrical power supplied by using on-site power generation. On-site, distributed power generation can reduce potential power outages due to weather, terrorist activities, or lack of utility generating capacity. Also, as increased emphasis is placed on environmental concerns such as global warming, acid rain, and air pollution in general, the development of clean, highly efficient power producing technologies is not only desirable, but also mandatory. In addition, most central heat plants on U.S. Military installations are nearing the end of their useful life. This circumstance creates immediate opportunities to replace outdated equipment with modern technologies.

One mission of the U.S. Army Engineering Research and Development Center, Construction Engineering Research Lab (ERDC-CERL) is to "increase the Army's ability to more efficiently construct, operate, and maintain its installations and ensure environmental quality and safety at a reduced life-cycle-cost." CERL researchers have investigated and demonstrated various fuel cell technologies to provide on-site power generation at a number of DOD installations.

Fuel cells are electrochemical power generators that can attain very high electrical conversion efficiencies, that operate quietly, and that produce minimal polluting emissions. In addition, byproduct thermal energy generated in the fuel cell is available for cogeneration of hot water or steam, which can potentially raise the overall conversion efficiency of the system (electrical plus thermal) to about 85 percent.

The economic value of waste heat cogeneration depends on the value of the conventional energy it displaces. In many European countries where heat is supplied to buildings through district heating systems, the cost to the consumer of the purchased heat can equal that of purchased electricity. In such cases, a tremendous economic benefit derives from the use of cogeneration for space heating. In the United States, however, the cogeneration heat displaces heat from conventional natural furnaces or boilers, which may not even justify the cost of the cogeneration equipment. High temperature Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC) resolve this problem by using the waste heat in conjunction with a microturbine in a hybrid system. While this increases the overall electrical energy conversion efficiency, it adds a noisy high-speed rotating piece of equipment to a system whose primary attributes are quiet operation with virtually no moving parts. This hybrid concept is not an option for the low temperature Proton Exchange Membrane Fuel Cells (PEMFC) and Phosphoric Acid Fuel Cells (PAFC), which operate at lower temperatures.

Consequently, a device that could extract additional electric power from any type of fuel cell, quietly and without moving parts, would represent a quantum leap forward for fuel cell technology. Thermoelectric (TE) devices, which would use the systems typical waste heat to generate electrical energy during normal operation, could potentially fulfill this need. This work was undertaken to integrate Leonardo Technologies, Inc. (LTI) TE devices into existing fuel cell power plants and other sources of waste heat, such as boiler systems.

Objective

The objective of this work was to provide demonstrations and evaluations of the application of TE devices for supplemental electric power generation from fuel cells and other sources of waste heat, leading to increased electrical generation efficiency and reduced environmental impacts.

Approach

1. ERDC-CERL tasked Concurrent Technologies Corporation (CTC) to perform a broad study of potential Department of Defense (DOD) applications where waste

heat could be used to generate electrical energy using TE Devices. This included testing and evaluation of LTI TE Devices manufactured in both laboratory and real world application environments.
2. Site assessments were done and test stands were designed and fabricated to support the testing and evaluation of the LTI TE Devices.
3. The scope of the project was narrowed to evaluate the operation of a small subset of the TE Device, the N-type and P-type material pair.
4. Once operational, the equipment, production procedures, and material compositions were evaluated to validate LTI's approach and procedures.
5. Some N-type and P-type material pair were produced.
6. The material pair, in wafer form was evaluated by both CTC and LTI.

Mode of Technology Transfer

This report will be made accessible through the World Wide Web (WWW) at URL:

http://www.cecer.army.mil

2 Thermoelectric Device Technology

TE Devices

TE Devices use the Peltier Effect, the phenomenon whereby the passage of an electrical current through a junction consisting of two dissimilar metals creates a temperature differential. One side will cool and the opposite side will heat. As a result, TE Devices can be used for cooling, heating, or power generation. The use of TE Devices as coolers is widespread particularly in computer processor and laser diode applications. The use of TE Devices as power generators is significantly less common.

The Seebeck Effect is the phenomenon where electrical current will flow in a closed circuit made up of two dissimilar metals when the junctions of the metals are maintained at different temperatures. This phenomenon has been well documented; it is used for temperature measurement throughout industry and academia in thermocouple devices. N-type and P-type semiconductor materials are welded to form a basic thermocouple. Thermocouples used for temperature measurement have been developed for their repeatable millivolt output across a known temperature range. Many thermocouples exist with various temperature ranges depending on the materials used. The most common is a Type K thermocouple consisting of a junction of Nickel Chromium and Nickel Aluminum with a traceable operating range of –300 to +1250 °C.

Many metal and semiconductor materials' thermoelectric properties have been researched and quantified by the product of the materials' electrical conductivity and Seebeck coefficient. The Seebeck coefficient is expressed in volts per degree, or microvolts per degree, and provides a reference of a materials' thermoelectric properties. Optimal thermoelectric materials should possess large Seebeck coefficients with low thermal conductivity. These desirable properties are embodied in a so-called figure-of-merit (z). This figure of merit may vary at a given temperature (T) so a nondimensional figure of merit (zT) is used.

Although the principals of thermoelectricity were developed in the early 1800s, TE Devices did not receive much attention until the 1930s when better thermoelectric materials were developed. It is quite clear that insulators are not viable materials due to their low electrical conductivity. Many metals also prove to be poor for thermoelectrics, because it is difficult to increase the electrical conductivity without increasing the thermal conductivity as well. However, with the advent of semiconducting materials came the rise of thermoelectrics. Semiconductors, which are essentially insulators in their pure state, can become good conductors by doping, or adding impurities. This doping allows the materials to either give up or accept electrons to the conducting band. Highly doped P-type and N-type semiconductors allow for increases in conductivity, with a minimal change in the thermal conductivity.

The particular materials in use, BiTe, are sensitive to temperature differentials and produce comparatively large voltage potentials when exposed to relatively low temperature differentials (below 250 °C) when compared to non-thermoelectric materials. The use of TE Devices as alternative energy sources has been investigated with limited success. Manufacturing costs and limited power generation efficiency (on the order of 2 to 4 percent) have previously prohibited the economical, large-scale production and use of the TE Devices as a viable alternative energy source. To obtain an acceptable return on investment, any TE Device used would need to operate at a thermal to electrical energy conversion efficiency of approximately 15 percent or greater. Recently, however, Leonardo Technologies Inc. (LTI) has addressed these issues and developed a more economical TE Device that has previously demonstrated an order of magnitude increase in power generation efficiency in preliminary laboratory investigations. The LTI device is therefore potentially suitable for supplemental electric power generation from fuel cells and other sources of waste heat.

Leonardo Technologies, Inc.

LTI was incorporated as a response to the thermoelectric power generation research by Dr. Andre Rossi. Dr. Rossi indicated that his devices would produce 20 percent efficiencies, a vast increase from the current science of 4 percent conversion of waste heat to electrical power. Dr. Rossi believed that he could increase the physical size of the TE Devices and maintain superior power generation. In furtherance of his research, in early 2000, LTI had tests conducted at the University of New Hampshire (UNH), Durham, NH, using a small scale LTI TE Device. Over a period of 7 days, the UNH power plant staff recorded voltage and amperage readings every 1/2 hr. The TE Device produced approximately 100 volts and 1 ampere of current, providing 100 watts of power. After this initial success, and a fire that destroyed his Manchester, NH location, Dr. Rossi returned to Italy to continue the manufacture of the TE Devices. In Italy, Dr. Rossi believed that LTI could manufacture more cost-effective TE generating devices with lower labor and assembly costs. Accordingly, Dr. Rossi engaged a subcontractor to fulfill the requirements of manufacturing and assembly.

Unfortunately, the Italian subcontractor was unable to provide second-generation TE Devices with satisfactory power generation. Nineteen of 27 TE Devices shipped to *CTC*, Johnstown, PA, were incapable of generating electricity for a variety of reasons, from mechanical failure to poor workmanship. The remaining eight produced less than 1 watt of power each, significantly less than the expected 800–1000 watts each. Appendix C documents TE Device testing.

In an effort to determine, and possibly correct the reasons for TE Device failures, LTI personnel traveled to the Italian laboratory. The common theme that began to emerge was the inability to upgrade from small-scale TE modules to large-scale multiple module TE Devices with large footprints. The most fundamental reason for the LTI second-generation TE Devices' failure was the complex thermal expansion interplay among the various components. Contributing to the TE Device failure were the large number of soldered electrical connections (over 80), the inability to match the thermal expansion rates of the mono-block cooling tanks to the circuit boards and to the semiconductor materials, all within the clamp pressure or the retaining hardware in the grip of high temperature adhesives.

After a month of research and observation at the Italian laboratory, it was determined that the best way to proceed would be to develop an independent laboratory in New Hampshire so that two development facilities could work at the problems from two separate locations and viewpoints. During this period of time, the Italian laboratory continued to deliver TE materials, but none that exceed the current science of TE power generation.

LTI Develops New Hampshire Laboratory

Beginning in mid-2002, the LTI-NH laboratory was designed with the technical assistance of *CTC* personnel. By September, TE materials were being manufactured. The final piece of equipment, the Directional Fusion Machine, was installed by December of 2002, at which time ingot manufacture was possible. As in Italy, the New Hampshire laboratory encountered manufacturing challenges.

Outside experts were engaged and were able to assist laboratory personnel in working through the roadblocks. The New Hampshire laboratory equipment was designed to allow for adjustments of almost every parameter in the TE manufacturing process, including, but not limited to:

- various metals and their proportional blends
- times and depths of both the vacuum and backfilling with inert gases
- times, temperatures, and oscillation speeds for melting, compounding, and recompounding
- size of P- and N-type semiconductors, varying both diameters and thickness of the wafers
- size of TE Devices based on semiconductor geometry.

3 Summary of Accomplishments

This report documents the work performed by *CTC* and LTI during the 2-year duration of this project. It summarizes information previously reported in monthly and quarterly progress reports. This report fulfills the final deliverable in the Contract Data Requirements List of the latest Statement of Work, Section 3.5. Documenting the tasks completed as defined in Section 3.2, Specific Requirements of the Statement of Work.

Task 1 Application Study

Overview

A brief overview study was conducted to evaluate the potential range of applicability, energy efficiency, clean production and economic advantages of thermoelectric technology application in fuel cell, traditional and potential power generation units. The complete application study report can be found in Appendix A. The following is a brief summary of that report.

Related applications discovered through the interview and literature search process of this study have also been noted. For the purposes of this study, applications were divided into applications at fixed defense facilities and applications at non-facility locations such as weapons systems, vehicles, and sensors. To determine the potential benefits of the installation of TE Devices at the facility level, case studies of facilities from each of the Armed Services were performed. Also, the findings of previous studies performed for the Department of Energy's (DOE's) Office of Fossil Energy (FE) and Office of Industrial Technologies (OIT) were leveraged for this report. The potential benefits of TE Devices extend into the U.S. utility/non-utility power generation and Industries of the Future sectors in addition to the DOD. Table 1 summarizes the findings of the reports for FE and OIT as well as this report for the DOD.

Table 1. Potential Annual Benefits of TE Device Application

Sector	Electricity Generation (MWh)	Generation Capacity (MWe)	Cost Avoidance ($1M)	Oil Equivalent Saved (1000 x barrels)	Carbon Emissions Savings (metric ktons)	No. of Potential Applications
Defense	464,000	53	34.5	268	21	43
Utility/non-utility power generation (*CTC* & LTI 2001b)	603,000,000	68,000	45,000	355,000	41,200	57
U.S. Industries of the Future (*CTC* & LTI 2001a)	74,000,000	8,400	5,500	43,000	5,000	101

The results of the study will assist the development of future demonstrations of LTI's TE technology at a DOD facility. The report documents the findings that are germane to facility and non-facility applications within the DOD:

- TE Devices have the potential to generate 464,000 MWh of electricity each year when applied to low-grade waste heat (LGH) generated from military applications. This equates to:
  - 53 MWe of generation capacity
  - $34.5 million cost avoidance for the production of electricity
  - 1.5 billion BTUs of energy production from normally discarded LGH
  - 268,000 barrels of oil equivalent saved annually
  - 21,000 metric tons per year savings in carbon emissions.
- Potential savings are in the area of $250,000 per year from a typical facility's utility bill.
- Over 40 specific applications were identified and ranked within these sectors.
- The TE Device is environmentally benign and requires no fuel for the production of electricity.

Based on the results of this study, it is recommended that further work be conducted to identify and evaluate the potential of TE Devices through field-scale demonstrations at defense facilities. This work would lead to refined estimates of cost for TE Device application and allow the specific determination of financial cost/benefit and return on investment.

Ranking

This study identified discrete processes, within the DOD, that are potential applications for thermoelectric technology. More than 40 specific applications were identified. For each application there were many potential locations for consideration. These applications were then ranked based on the quality and quantity of low-grade heat available, effects on process performance, equipment issues, and potential electric generation.

Due to National Security issues surrounding defense and other government activities, many documents normally available through literature and Internet searches were restricted from public availability. These documents included detailed layouts of facilities, reports on energy consumption and specifications of equipment. Therefore, many of the assumptions in this report were made without the benefit of detailed information available before 11 September 2001. Table 2 provides a summary of ranking results for processes for the DOD applications. Detailed ranking results are contained in Appendix A.

Task 2 Site Assessment

Efforts under Task 2 were to perform an assessment of potential demonstration site(s). The primary goals were to determine sources of waste heat and the installation requirements for demonstration. Facility requirements such as facility chilled water flow or power requirements for the air-cooled heat exchanger were also determined during site visits. Each potential site requires unique mounting fixtures and methods of transferring the thermal energy to the TE Device(s) as well as methods of cooling the TE Devices. These presented design challenges and costs that are documented in the following sections.

Table 2. Criteria scoring for facility and non-facility applications.

Criteria-based Ranking	Average Score	Area of Application	Potential Electricity Generation/yr (MWh)	Number of Applications
1	70.5	Non-facility, Ships	17,000	4
2	64.2	Facilities, Industrial Processes	79,400	6
3	61.2	Facilities, Electricity Generation	183,865	20
4	61.1	Facilities, HVAC	163,436	2
5	58.0	Non-facility, other	N/A	2
6	49.8	Non-facility, vehicles	18,000	3
7	44.7	Non-facility, support equipment	3,000	6
Total			464,701	43

Assessment Criteria

Each test site was evaluated using the following criteria to determine the viability of constructing a test stand to demonstrate the TE Devices:

1. Minimum surface temperature of 120 °C (248 °F).
2. Thermal capacity to support a TE Device, and quantity of TE Devices the site is capable of supporting. Determine if the site can supply 34,200 BTU/hr, minimum, for each TE Device.
3. The surface characteristics of the site and level of difficulty to interface the TE Device(s) to the site.
4. The level of cost necessary to interface the TE Device(s) to the selected site.
5. Availability of needed utilities such as power, chilled water, and dedicated phone line.
6. The level of cost necessary for alternative utility resources, if the required utilities are not available.
7. Identification of site environmental concerns – e.g., extreme ambient temperatures, extreme vibration, personal safety issues (radiation, gasses, other).
8. Availability of space for support equipment.
9. Secondary site for support equipment if a closer site is not available or suitable.
10. Site need for DC power produced by the TE Device(s). If not, an appropriately sized DC load bank will be used.

Portsmouth Naval Shipyard Site Assessment

Portsmouth Naval Shipyard (PNSY) in Portsmouth, NH provides industrial and engineering support for nuclear submarine maintenance and inter-service regional maintenance. PNSY was designated as a potential site where TE Devices could be integrated into existing systems. A site assessment was conducted to evaluate the best location to install a test platform. The staff of the PNSY Technology Transfer Office selected several potential locations prior to the assessment. With their guidance, each of the locations were evaluated following the previously listed criteria.

The Boiler Site was on the top most catwalk of the facility power plant, where the Super Heater for Boiler 5 is located. Temperatures on the manifold of the Super Heater were measured and recorded between 355 °C and 366 °C. These temperatures are the closest of the three sites to the maximum operating temperature of the TE Devices. The length of the 13-in. diameter manifold is 13 ft, which is long enough to satisfy the physical requirements of 10 TE Devices. To locate the TE Devices on this manifold, a mounting plate will have to be designed in such a manner as to not be affected by the irregularities of the surface of the manifold. Temperatures were measured using a handheld infrared thermometer at multiple positions on each potential site. The temperatures were manually recorded on notebooks. Dimensions were measured using a simple tape measure and recorded in the notebooks as well. The Steam Boiler Site was on the surface of the boiler housing on the ground floor. The temperatures here ranged from 50 °C to 60 °C. It was unanimously decided by involved *CTC* Engineers that these temperatures would be too low to complete the required tests.

The last potential site was the exhaust ductwork of a Micro-Turbine. From discussions with the PNSY staff it was determined that the ductwork was of a double walled, insulated construction. Due to the type of construction of the ductwork, the temperatures on the surface were very uneven. The temperatures measured on the ductwork on the most accessible side ranged from 96 °C to 190 °C. The temperatures on the bottom of the ductwork ranged from 80 °C to 170 °C. The least accessible and least visible side of the ductwork had temperature ranges of 85 °C to 200 °C. It was also discussed that the TE Device may cool off the surface and not generate large amounts of power because of the ductwork insulating properties. However, it was decided that this is a potentially good site for a single unit, short-term demonstration, due to it being physically easier to access, cleaner, and a more spacious work area.

The superheater manifold of Boiler 5 was selected as the best site to install a TE Device demonstration/test stand. A fixture assembly was designed to conduct the thermal energy to the TE Device surface from the manifold. The fixture was designed as several pieces to support 10 TE Devices. To locate the TE Devices on this manifold, a mounting plate or "saddle" was designed to couple the thermal energy to the TE Devices (see Figure 1). To support 10 TE Devices, 20 saddles were required. Two saddles were fabricated from a block of 6061 Aluminum, to test them and ensure the proper fit on the superheater prior to expending a large amount of labor to fabricate all 20 saddles. Since the two saddles were fabricated, no functional TE Devices have been received to perform the testing. Table 3 provides approximate cost to fabricate the TE Devices heat exchanger and cooling manifolds into the PNSY Boiler site. This site was not able to provide a source of chilled water so a closed loop cooling system was specified. Future demonstration activities will require a new site assessment and design of heat exchanger system at PNSY. PNSY has decommissioned Boiler No. 5 due to facility energy efficiency upgrades. The lack of functional TE Device prevented the test while the boiler was in operation.

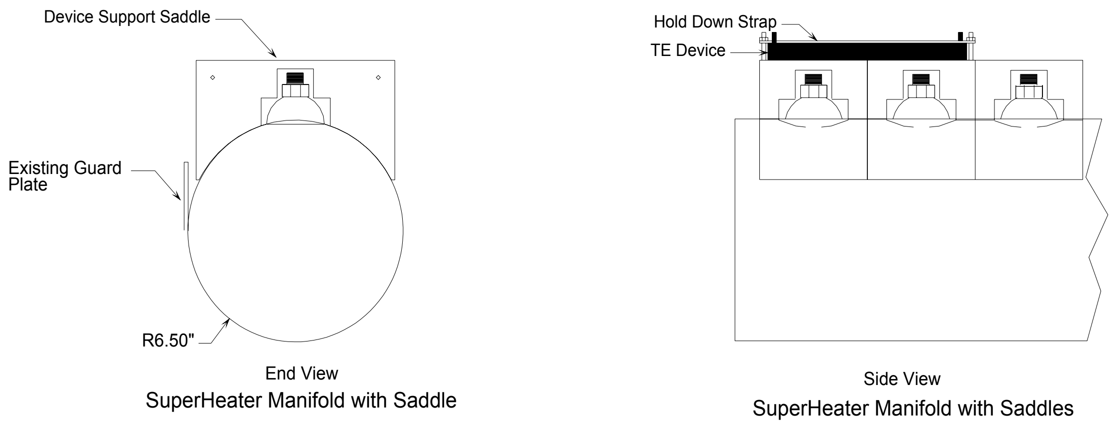

Figure 1. PNSY Boiler No. 5 superheater manifold with TE device saddle sketch.

Table 3. Fabrication and installation costs for the PNS heat exchanger.

Activity/Item	Amount
Material	$3,416
Labor to fabricate 20 saddles	$66,660
Potential total to Integrate	$70,076

*Johnstown FC*Tec *Site Assessment*

The ERDC/CERL Fuel Cell Test and Evaluation Center (FC*Tec*) in Johnstown, PA was selected as another potential demonstration/test site. *CTC* operates this center and provides independent third party evaluation of fuel cell technologies.

The United Technologies Corporation (UTC) 200kW Phosphoric Acid Fuel Cell Power Plant (PC25C) currently undergoing testing at the FC*Tec* (Figure 2) was determined to be suitable for use as a test stand for the TE Device Demonstration. The location of the fuel cell at the FC*Tec* allows for an economical use of resources and close observation by *CTC* personnel. This fuel cell's reformer and stack assemblies generate surface temperatures ranging from 315 °C to 371 °C. Although these areas would be ideal as a heat source they cannot be used due to the operating characteristics of the fuel cell. The fuel cell is dependent on these temperatures for normal operation. Parasitic heat losses from adding the TE Devices in these areas would have a negative effect on the overall operating characteristics of the fuel cell. This fuel cell is still undergoing operating characteristic testing within the scope of the Fuel Cell Mod 2 Testing Project. Due to these testing requirements, any operating characteristic effected by non-normal conditions would have an unacceptable negative affect on the test results.

Figure 2. UTC 200kW phosphoric acid fuel cell.

The fuel cell generates a significant amount of waste heat under normal operating conditions. This heat is normally dissipated via a heat exchanger or other thermal load. The FC*Tec* currently has a thermal load bank attached to the fuel cell to monitor and characterize the fuel cell's high and low grade heat generation capacity. The load bank is capable of dissipating the full fuel cell's thermal output of 700,000 BTU/hr via a water-to-water heat exchanger system and can operate at temperatures of up to 149 °C. This temperature is relatively low but was found to be acceptable to demonstrate the TE Devices, which require a minimum temperature differential of 100 °C.

The *CTC* facility chilled water system is readily available to supply the necessary cooling water for the TE Device operation with minimal integration resources. The facility-chilled water system is a constant 12 °C; this would provide an optimum temperature differential of approximately 137 °C.

A custom heat exchanger was designed, constructed, and integrated to bypass the water-to-water heat exchanger, forcing the thermal energy through the TE Devices, then into the facility chilled water system (Figure 3). Table 4 lists approximate cost to fabricate and install the heat exchanger and cooling manifolds for the FC*Tec* Fuel Cell site.

Figure 3. FC*Tec* thermal load bank test stand.

Table 4. Fabrication and installation costs for the FC*Tec* heat exchanger.

Item	Amount
Material Costs	$1,920
Labor Costs	$4,388
Total	***$6,308***

Alaska Test Site

A third potential site is located at the Chena Hot Springs Resort, Fairbanks AK. In cooperation with the Institute of Northern Engineering Energy Center at the University of Alaska, Fairbanks, this site was located and recommended as a potential demonstration site for TE Device operation in an Arctic environment. LTI personnel visited this site but a detailed site assessment was not completed by *CTC* due to budget constraints. The Chena Hot Springs Resort is in a remote location and it receives its electrical power from three (3) - 200 kW diesel generators. The diesel generator's exhaust produces enough thermal energy to potentially operate TE Devices. The air temperatures in this geographical area regularly reach –37 °C. There is a strong potential for using these environmental conditions to generate the required temperature differentials. Future projects may use this platform on completion of a site assessment and design of mounting fixtures and heat exchanger(s).

Task 3 Installation and Initial Operation

The objective of Task 3 tasking was to prepare the sites selected under Task 2 for demonstration of the TE Devices. This includes the selection and acquisition of necessary instrumentation, control and data acquisition systems and design and fabrication of all necessary fixtures required to interface the TE Devices to the waste heat source of the site. The systems were designed to be relatively mobile for potential portability and automated to reduce the labor costs required to operate the systems.

Two Mobile Data Acquisition Systems were fabricated and programmed to support the multiple device testing needs at the FC*Tec* and PNSY (Figure 4). The purpose of these systems is to collect data to determine the basic operating characteristics of the TE Devices. Typically, hot plate temperature, coolant temperature in, and coolant temperature out, would be recorded. Also recorded would be Ambient Air Temperature, TE System Voltage, TE Device Current, Coolant System Flow Rate, and Electronic Load Resistance. *CTC* was to download this for analysis, as necessary, via a dedicated phone line connection.

A Single TE Device Test Stand with Data Acquisition was fabricated to determine the optimum operating parameters of the TE Devices. This test stand has the capability to control the heat source temperature throughout the operating temperature range of the TE Device. A dedicated chiller system could be added to the test stand to add the capability of controlling the cold side temperature and flow rate. *CTC* facility chilled water could also be used for cooling purposes. Data collected by this system would be archived at *CTC* for analysis.

Multiple Device Test Stand Objectives

The expected capability of the Control and Data Acquisition (CDAQ) Systems for the multiple device test stands are as follows:

- Provide an automated means for collecting critical process and operating parameters, which will be required to assess the results of the tests performed on the TE Devices.
- Provide long-term storage for the data acquired.
- Provide a means for electronically disseminating the data to *CTC*, LTI, and ERDC/CERL personnel for analysis.
- Control the test stand components to provide automated test execution where possible. This feature expands the number of hours available for performing TE device tests giving 24-hour test capability.

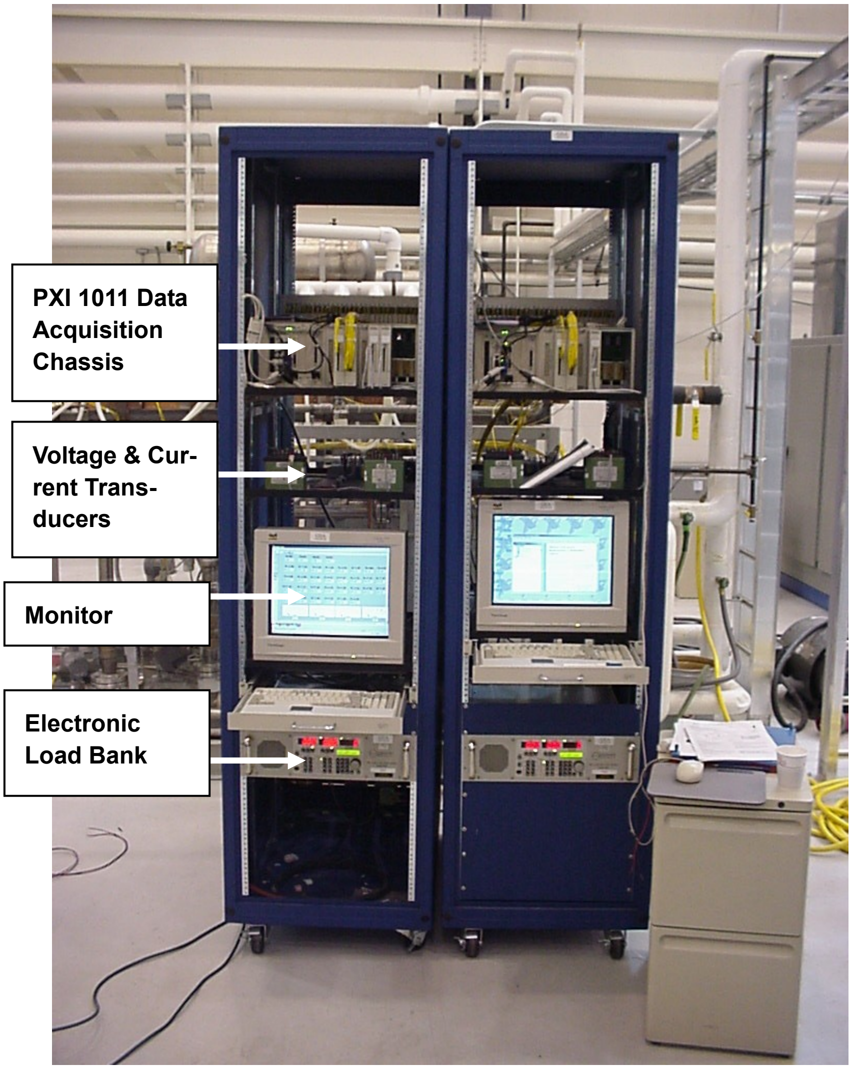

Figure 4. Thermoelectric multiple device test stands (Johnstown and Portsmouth Units).

3.3.1.1 Control & Data Acquisition System Description of Multiple Device Test Stands for Johnstown and Portsmouth

The CDAQ for the multiple device test stands, as shown in Figure 4, are identically configured equipment with the main components consisting of a 19-in. rack mount cabinet and a computer based data acquisition system to process the thermoelectric system variables listed below:

- TE device "hot side" temperature
- ambient air temperature
- coolant temperature inlet of device
- coolant temperature outlet of device
- coolant flow rate

- device output voltage
- device output current
- device output power
- electronic load settings of the Dynaload Resistive Load Bank.

On the multiple device test stand, the voltage, current, and power is a combined measurement of all the TE Devices connected in series and terminated at the input terminals of the electronic load bank. The "hot side" temperature, coolant inlet temperature and coolant outlet temperature are taken for each individual device (Figures 5 and 6, respectively).

The CDAQ continuously monitors the system variables and displays them in the Main Screen of the data acquisition software on the monitor. The main screen also allows the user to define the sample rate and file path for saving the data (Figure 7).

Configuration screens are available to configure the various electronic load bank parameters and setup/enable the automatic operation feature (Figures 8 and 9, respectively). The CDAQ collects the data at a user specified sample rate for a 24-hour period. At 12:00 AM each day, the CDAQ automatically saves the data to the local hard drive as a user named spreadsheet file with the current date automatically appended to the file name, then generates a new file with the new current date appended to it. For the Portsmouth test stand, the data files will be automatically transmitted via modem to the Johnstown, PA facility network at a predetermined time.

Single Device Test Stand Objectives

The expected capability of the CDAQ for the single device test stand was to:

- Provide an automated means for collecting critical process and operating parameters, which will be required to assess the results of the tests performed on the TE Devices.
- Provide long-term storage for the data acquired.
- Provide a means for electronically disseminating the data to *CTC*, LTI, and ERDC/CERL personnel for analysis.
- Control the test stand components to provide automated test execution where possible. This feature expands the number of hours available for performing TE Device tests giving 24-hour test capability.

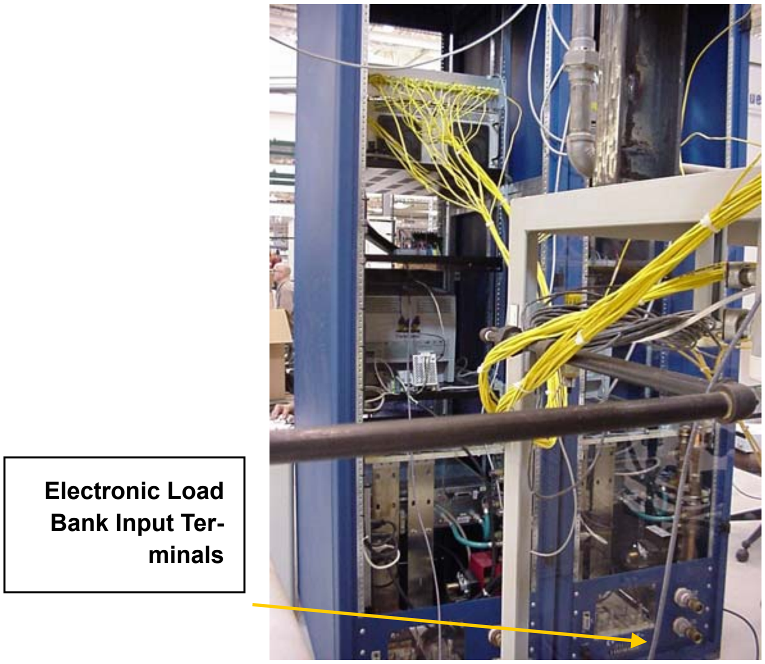

Figure 5. Rear view of thermoelectric data acquisition cabinet—multiple device test stand.

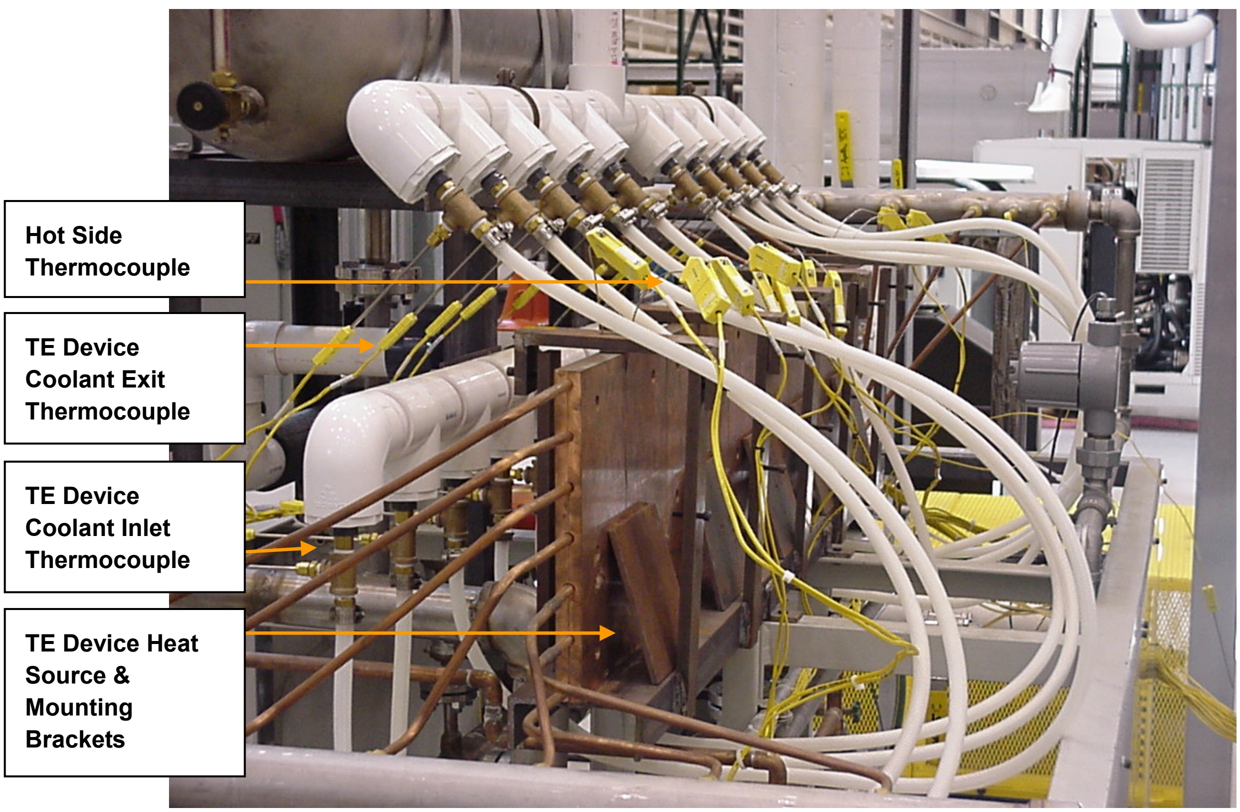

Figure 6. Thermoelectric device mounts—multiple device test stand.

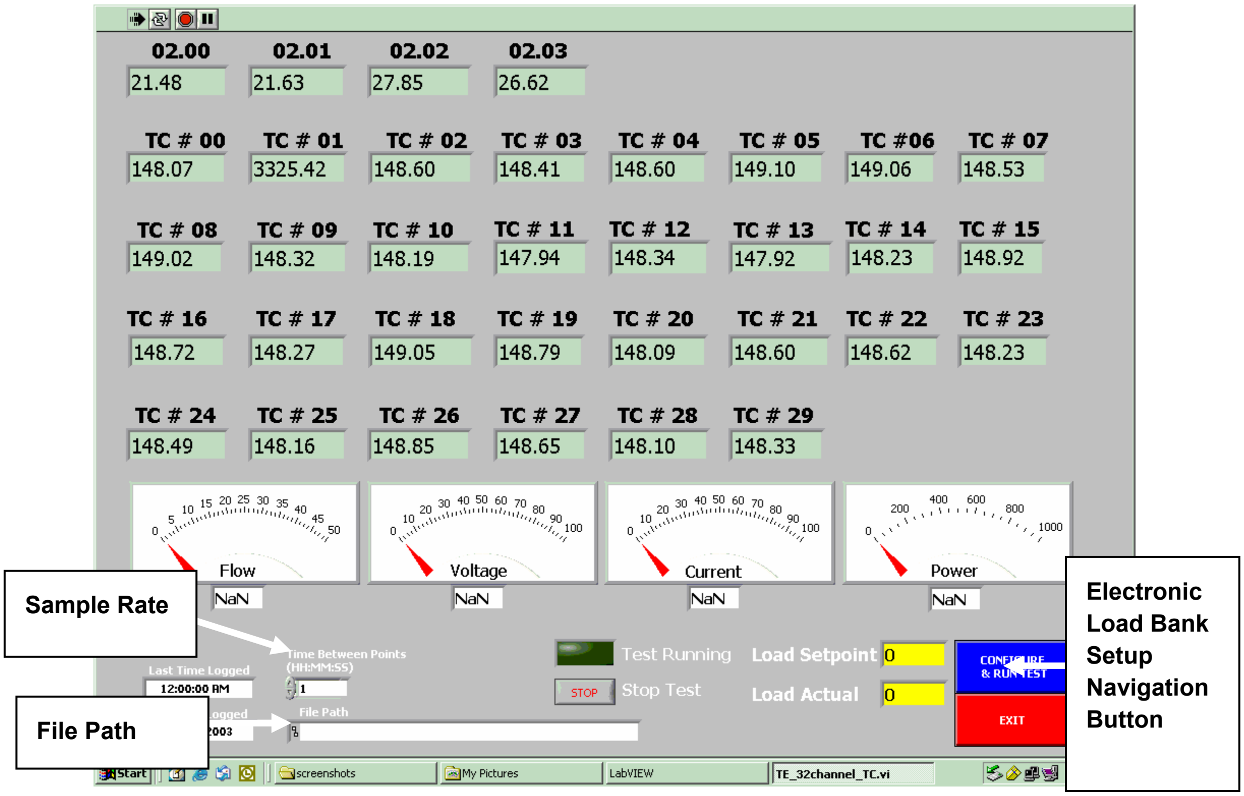

Figure 7. Data acquisition software main screen—multiple device test stand.

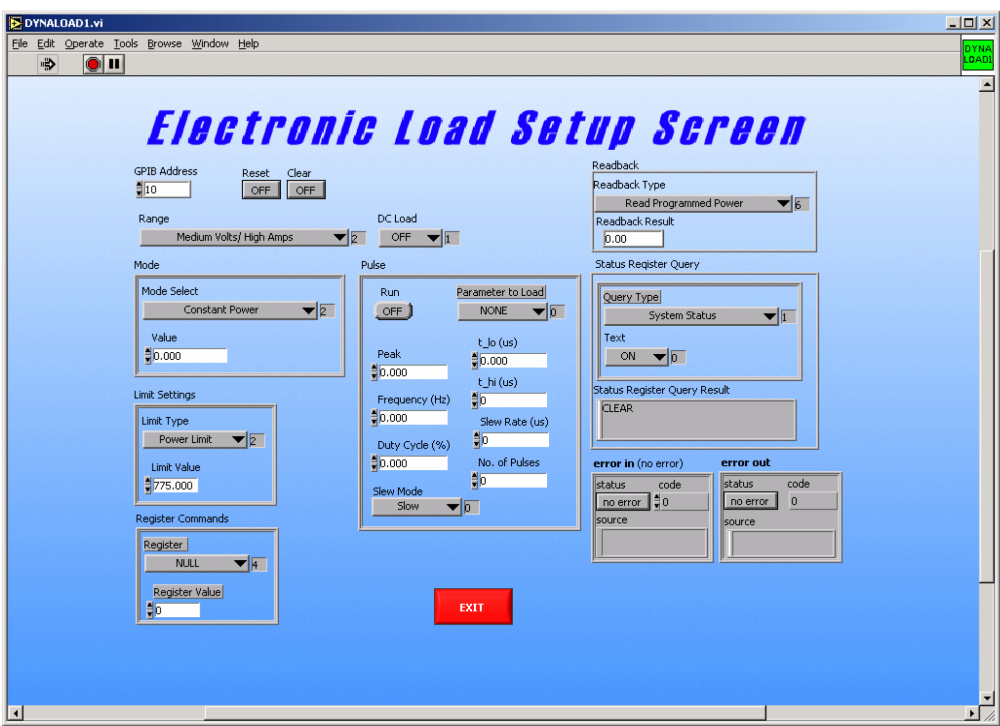

Figure 8. Electronic load bank setup screen—multiple device test stand.

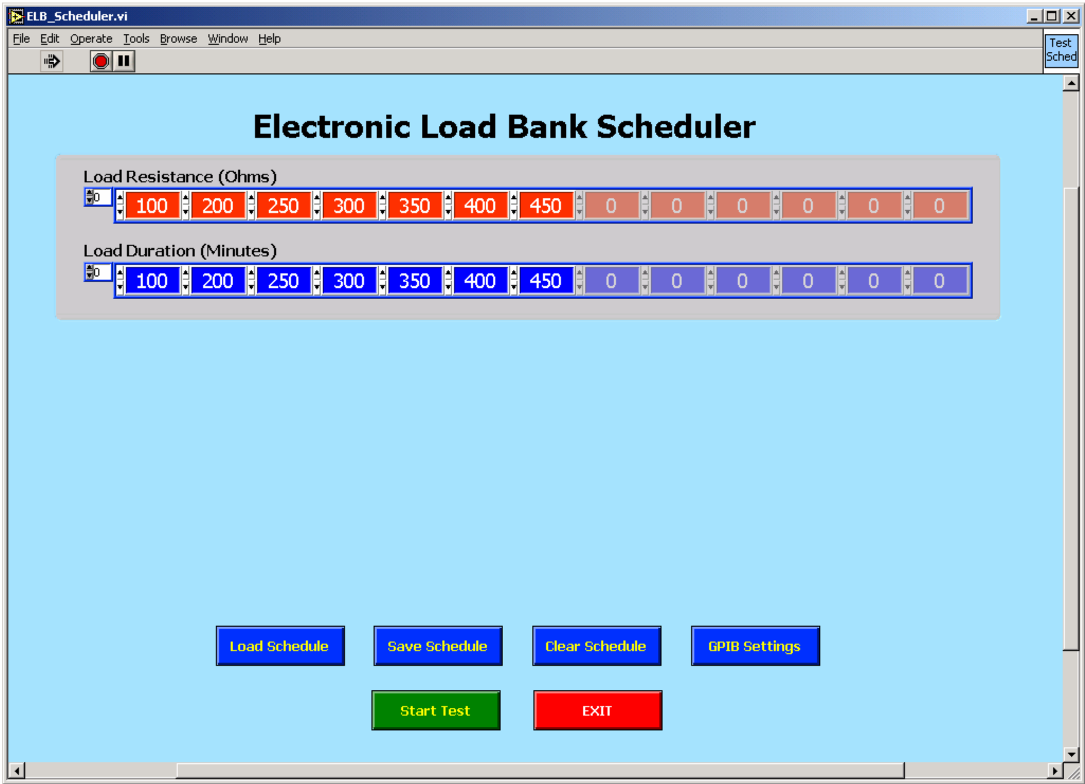

Figure 9. Electronic load bank automatic operation configuration screen—multiple device test stand.

Control and Data Acquisition System Description of Single Device Test Stand

The main components of the CDAQ for the single device test stand (Figures 10, 11, and 12) consist of an aluminum frame, separate aluminum frame TE Device mount (Figure 11), chiller/heat exchanger compartment to provide coolant to the TE Device, and a computer based data acquisition system to process the thermoelectric system variables listed below.

- TE device “hot side” temperature
- ambient air temperature
- coolant temperature inlet of device
- coolant temperature outlet of device
- coolant flow rate
- device output voltage
- device output current
- device output power
- electronic load settings of the Dynaload resistive load bank
- ceramic heaters & heater controllers
- TE device mount load cell.

Figure 10. Thermoelectric single device test stand.

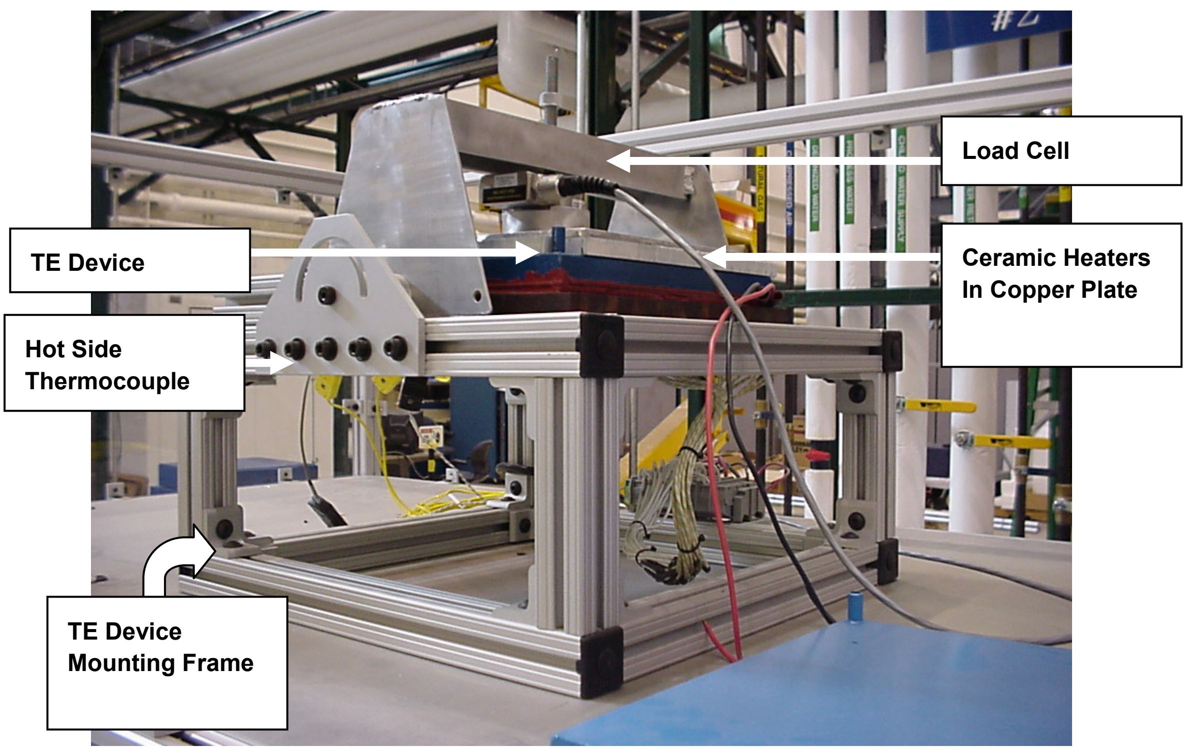

Figure 11. Thermoelectric device mount—single device test stand.

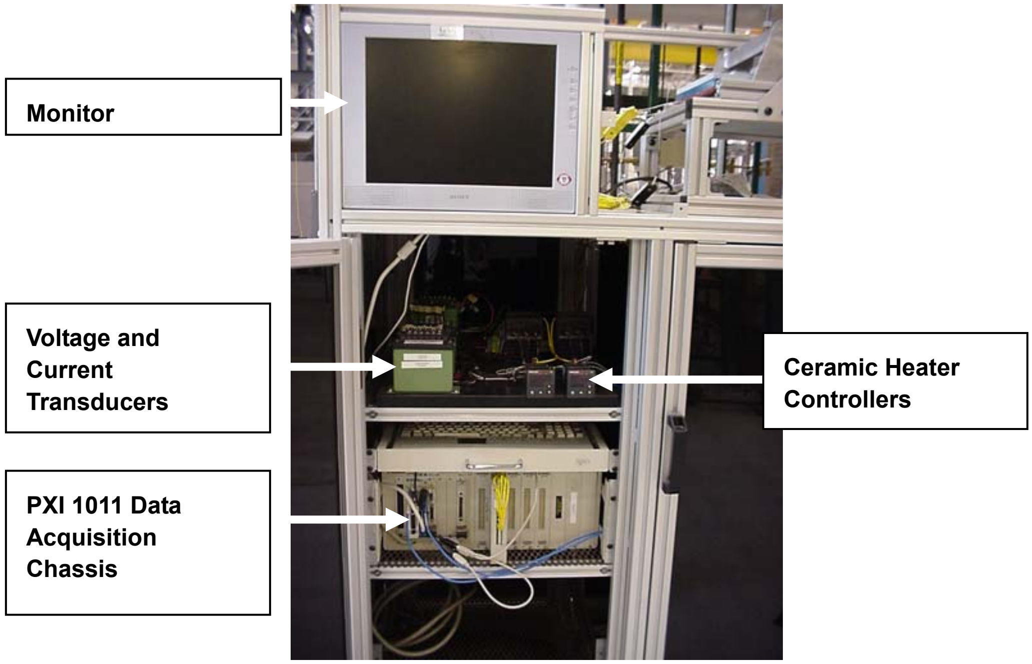

Figure 12. Data acquisition compartment—single device test stand.

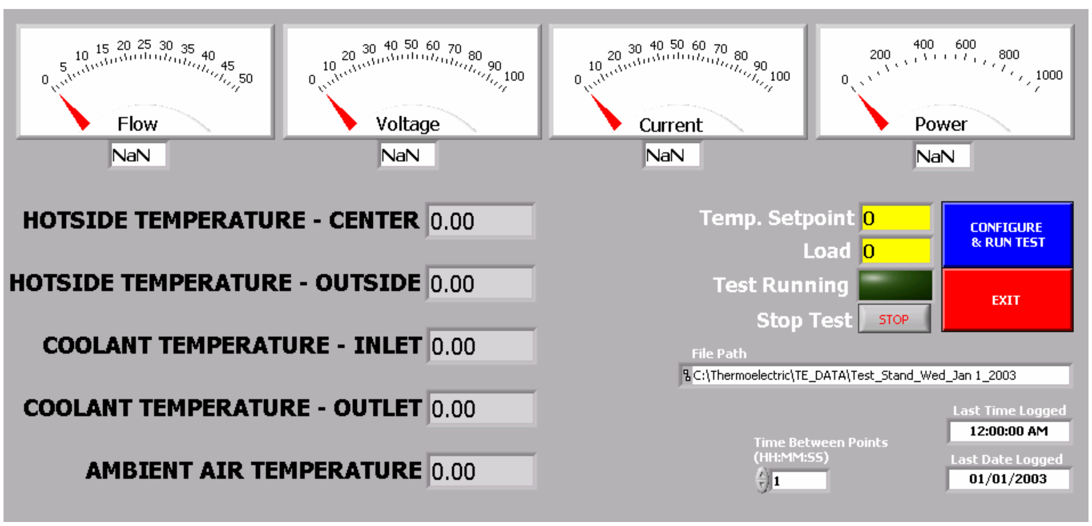

Figure 13. Data acquisition software main screen—single device test stand.

The CDAQ continuously monitors the system variables and displays them on the data acquisition software Main Screen. The main screen also allows the user to define the sample rate and file path for saving the data (Figure 13). Configuration screens are available to configure the various electronic load bank parameters and setup/enable the automatic operation feature (Figures 8 and 9, respectively). The CDAQ collects the data at a user specified sample rate for a 24-hour period. At 12:00 AM each day, the CDAQ automatically saves the data to the local hard drive as a user named spreadsheet file with the current date automatically appended to the file name, then generates a new file with the new current date appended to it. In addition, the CDAQ also provides software control of the ceramic heaters and hot side temperature via temperature setpoint and a thermocouple feedback loop. A load cell is used to determine the amount of force required to achieve and maintain sufficient surface-to-surface contact, which is also read and displayed on the main screen.

Demonstration Briefcase Design and Development

A portable technology demonstration system was developed to enable personnel to demonstrate the technology in any location. This capability would allow public demonstrations of small TE Devices in operation to educate peers and the public on the capabilities of TE Generation Devices.

Demonstration Briefcase Objectives

The expected capabilities of the Demonstration Briefcase are as follows:

- portable stand-alone enclosure located at the FC*Tec* in Johnstown, Pennsylvania, which will serve as a test-bed or can be used for public demonstrations
- controllable heat source and controllable cooling device on opposing sides of a single TE Device
- resistive load capable of dissipating the generated power of the TE device
- appropriate sensors to monitor system parameters.

Demonstration Briefcase Capabilities Description

The Demonstration Briefcase (Figures 14 and 15) was designed and built to be a portable, stand-alone, lightweight unit, which can be used for public demonstration of Thermoelectric Devices. The unit's main components consist of a durable hard shell plastic case suitable for travel and mounting of internal hardware, heat exchanger to provide coolant to the TE Device, thick film heater with heater controller. Voltage and current measurement devices with digital readout displays, flat cement-on thermocouples for feedback to the heater controller and measurement of hot side and cold side temperatures provide feedback to the operator. A DC to DC voltage converter regulates the varying input voltage to a constant 12 Volt DC output voltage which powers a series of electrical load elements with individual switches to increase or decrease the total load. A single 110 Volt AC power cord is required and used to power the heater, cooling system and digital readout displays. The demonstration briefcase does not contain a computer/software driven CDAQ system.

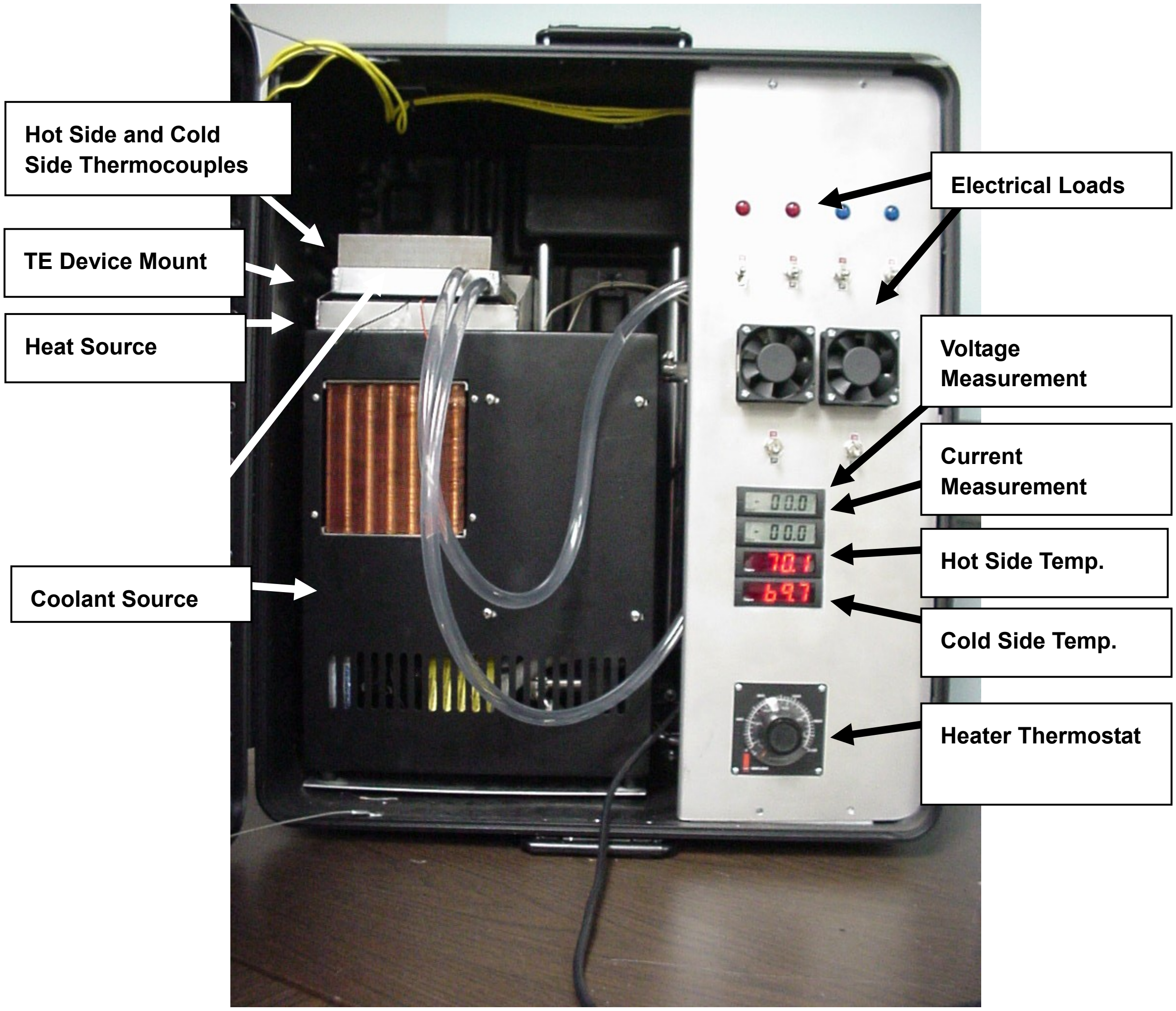

Figure 14. Thermoelectric demonstration briefcase—open view.

Figure 15. Thermoelectric demonstration briefcase.

The Thermoelectric Demonstration Briefcase Specifications are:

- heater maximum temperature: 240 °C @ 1300 Watts
- heat exchanger dissipation: 4440 BTU/hour (1300 Watts)
- case dimensions: 25 in. L x 22 in. W x 14 in. H
- current DC electrical load of 12 Watts (can be increased).

Task 4 TE Wafer Research and Development

Description of TE Wafer Technology

This task was revised from TE Device Demonstration to TE Wafer Research and Development when initial testing of the TE Device prototypes demonstrated significantly less than expected electrical power generation. Appendix C briefly documents specific test procedures and test results of TE Devices received from LTI. It was determined that the project would gain the most value by focusing the remaining resources on the test, evaluation, and development of a baseline of operating characteristics of the TE wafers being manufactured by LTI at both the New Hampshire and Italy facilities. The wafers are the smallest subset of the TE Device or as previously discussed in the introduction, a thermocouple.

The test stands designed, procured, and fabricated in Task 3 were designed to test completed TE Devices having an electrical output capacity of approximately 1,000 watts. A single pair of TE wafers was expected to have an electrical output of less than 1 watt. The test stand equipment could not be used to perform the TE wafer testing due to the instruments range and resolution. The heat source and cooling system of the briefcase demonstration kit was used as the foundation of the test fixture. Alternate instrumentation, having the range and resolution necessary for this level of testing, was used for monitoring the wafer electrical performance. All testing and data collection were done manually. Future efforts should design, procure, and fabricate an automated test stand specifically for TE wafer testing to allow for consistent, automated control, and data acquisition.

Figure 16 shows the test fixture used to determine the operating characteristics of the TE wafer material pairs. This fixture enabled the operator to select a temperature for the hot plate while the cold plate generated the required temperature differential. A simple dead weight was used to provide the compressive force needed to maintain the surface-to-surface contact required for good thermal conductivity. Thermally and electrically conductive grease, impregnated with silver, was used to increase the thermal and electrical conductivity of the wafers and the circuit. This fixture evaluated a single wafer pair per test.

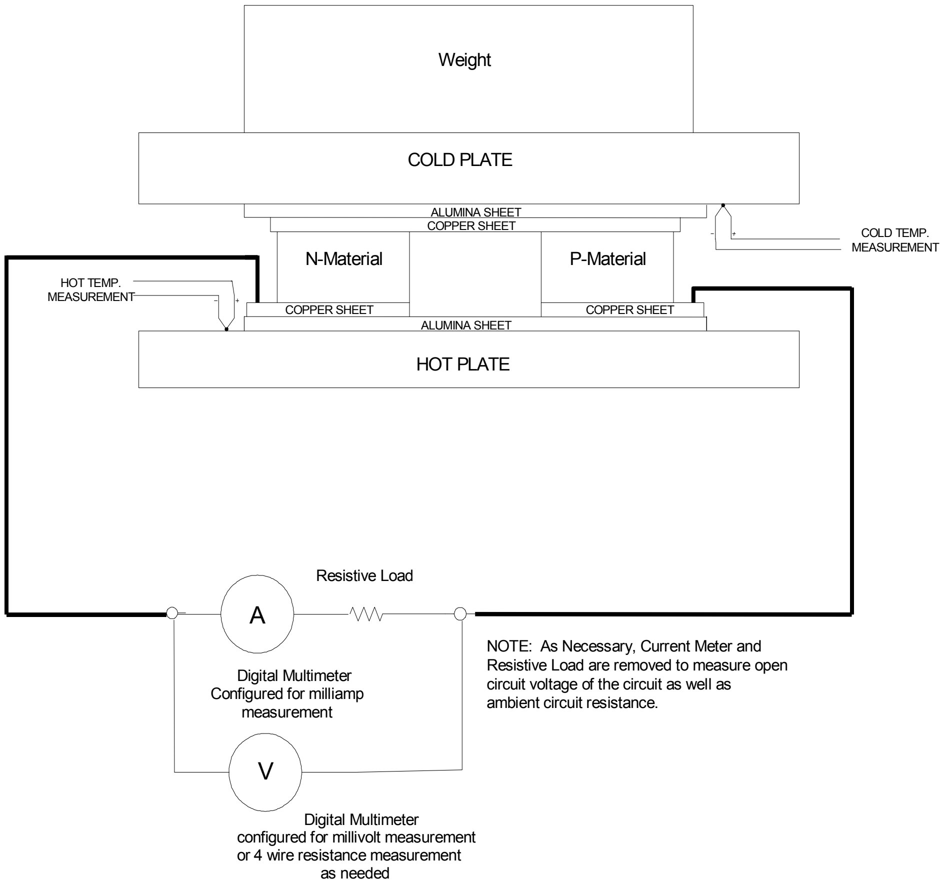

Figure 16. Thermoelectric wafer test fixture.

LTI performed all TE material processing and provided *CTC* with TE wafers to test. The TE material powders are mixed and processed using LTI's proprietary method. The result of this process is an ingot of either the N-type or P-Type semiconductor material. This ingot is then sawn into wafers.

Each wafer pair was inserted into the test fixture. Then the pair was stepped through various temperature differentials while the electrical output was monitored. The ideal circuit has a minimal electrical resistance caused by interfacing the TE wafers to the circuit as well as electrical test equipment. This ohmic contact can be difficult to repeat using the silver conductive grease and is the probable cause for some minor variations in wafer pair resistance measurements. The following is a brief description of the test procedures followed.

Description of Wafer Testing

1. An electrically and thermally conductive grease, containing silver particles, was applied to both sides of each wafer, with care not to allow a grease induced cur-

rent path along the side of the wafer from top to bottom. If this path occurred it would create a short circuit and bypass the TE Material. While using this grease, the test result demonstrated the lowest electrical resistance and highest, most consistent electrical energy output. To provide as close to ideal test conditions as possible, this grease was used throughout testing.

2. Copper foil was used to complete the series electrical circuit between the N and P wafer. Wire was soldered onto separate copper foils to provide a current path to the resistive load and multimeters.
3. Alumina sheets were used to electrically isolate the wafer circuit from the hot and cold plates.
4. The Watlow thick film hot plate is capable of temperatures over 240 °C and is manually controlled by a thermostat.
5. The cold plate heat exchanger is constructed of aluminum and attached to a closed loop cooling system. A small pump flows water through the aluminum plate, the water then flows through a condenser or another heat exchanger blowing ambient air through it. Removing the thermal energy from the water and exhausting it into the room.
6. Thermocouples were used to monitor hot plate temperature as well as cold side temperatures. Digital indicators provided feedback to the operator.
7. A deadweight, weighing approximately 10 lb, was placed on top of the cold plate to provide compression and ensure consistent surface contact of the wafer circuit, hot and cold plates. Several weights were tested and the block selected maintained the most consistent internal wafer pair resistance measurement.

The room temperature resistance of the wafer circuit was measured using a multimeter. A resistor near this value was selected and used as the circuit load or the wafer pair was tested as an open electrical circuit (no load). Two separate multimeters were used, one as a millivolt meter and the other as a milliamp meter.

The *CTC* Wafer Test Equipment consisted of:

1. Yokogawa Model 7562 digital multimeter
2. Fluke model 8050A digital multimeter
3. Watlow thick film heater
4. Watlow heater controller
5. Type K thermocouples
6. Solid state cooling systems low flow cold plate
7. Thermatron compact closed loop cooling system.

Multiple pairs of TE material wafers were received from LTI and their subcontractor in Italy. These wafers were tested using the previously mentioned methods. Dr. Rossi stated that the expected electrical energy production of a single pair should be approximately 300 millivolts at a temperature differential of 100 °C, but none of the tested TE wafer pairs performed as expected. The typical measured output of a single pair varied between 1 and 45 millivolts at a 100 °C temperature differential during open circuit testing and dropped slightly for matched load testing. The electrical performance of the LTI NH wafers was less than those received from the laboratory in Italy. This could have been due to material processing and equipment operation learning curves. Although these results were not as good as previously expected, they were still comparable to existing BiTe thermoelectric material performance. LTI personnel were confident that with additional experimentation and process familiarization the issues could be resolved. Figures 17 and 18 show results of TE wafer testing of both the 12mm diameter wafers manufactured in New Hampshire and the 4mm square wafers manufactured in Italy. Sample data files are presented in Appendix D for review. Appendix D also contains the procedures and sample results of testing conducted by LTI at its laboratory in New Hampshire.

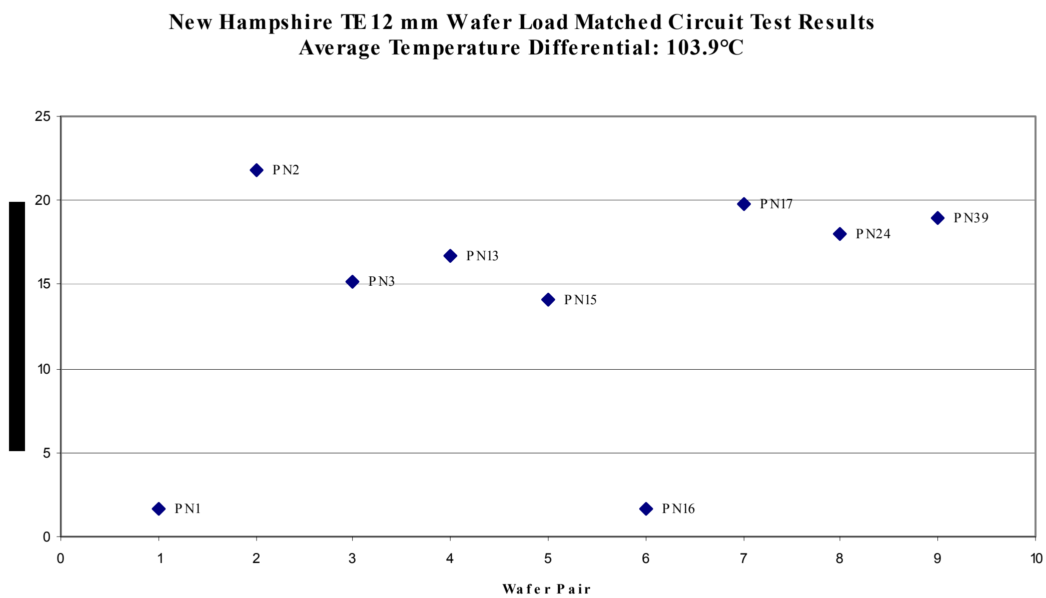

Figure 17. New Hampshire TE wafer test results.

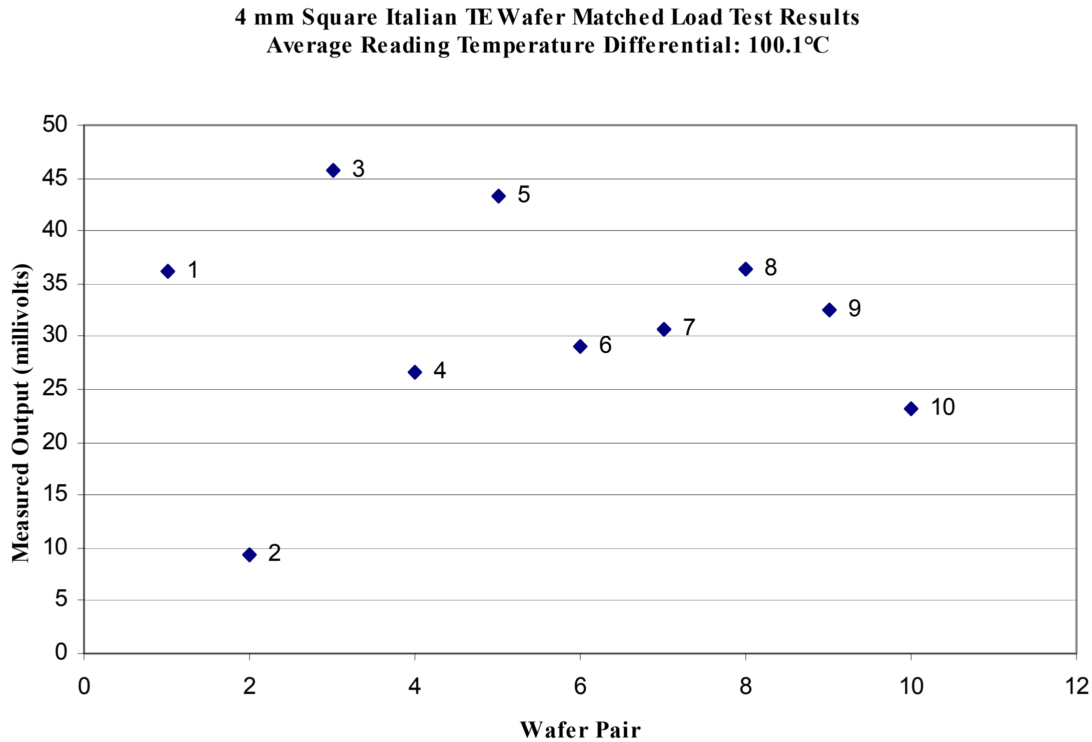

Figure 18. Italian TE wafer test results.

Task 5 Manufacturability Assessment

CTC, in cooperation with LTI, performed a high level assessment of the product and the manufacturing process and materials used to determine if manufacturing costs of the TE Devices can be reduced. Although a functional prototype was not available, the current design was disassembled and evaluated. Based on existing technology, some recommendations were developed:

- feasibility of using recycled materials to reduce manufacturing costs
- TE material wafer testing to determine baseline material operating properties
- improved TE Device prototype assembly process methods.

Recycled Material Investigation

The use of recycled material was briefly investigated to reduce the cost of the TE Device. Since the TE wafer materials are unique, no source of recycled TE material was found. The investigation evaluated the potential use of recycled materials in the cooling tank used to create the “cold side” of the temperature differential. The investigation also evaluated the board materials, which the TE wafers are mounted to.

Thermo-conductive polymers revealed that they are not as efficient at diffusing heat, when compared to ceramic board materials already in use (Alumina, Beryllium) as well as the existing metal construction of the cooling tank. Thermally conductive polymers typically range from 1 to 20 W/m-K, when compared to non-thermally conductive polymers, which are conductive around 0.2 W/m-K. A polymer was found that had a conductivity of 30 W/m-K named CoolPoly E200 manufactured by Cool Polymers, Inc., USA. Compared to aluminum casting alloys, which range from 50 to 100 W/m-K, or pure aluminum, which is 236 W/ m-K, most polymers do not conduct heat comparatively. The typical TE Device operating characteristics demonstrate that the greater the temperature differential, the greater the electrical output. Clearly, aluminum is currently a better choice in this situation.

In addition to the broad investigation of thermoplastics, Commercial-Off-The-Shelf (COTS) components were researched to determine potential cold plate options. Specifications of the current aluminum cold plate were used as a baseline of comparison. No COTS thermally-conductive plastic cold plates with adequate specifications were found.

TE Wafer Material Testing

These tests are documented in the previous section, Task 4 Thermoelectric Wafer Research and Development, and also in Appendix D.

TE Device Prototype Manufacturing

The existing TE Device design was evaluated and recommendations were provided to LTI and their subcontractor to potentially enhance operation of the TE Devices.

LTI TE Device Original Design

The TE Devices received from LTI's subcontractor were 12-in. square and approximately an inch thick (Figure 19). The first 24 devices received in a single delivery, were of consistent construction. A mild steel, hollow tank (blue painted area in Figure 19), approximately 0.75-in. thick, provided cooling when chilled water was flowed through it.

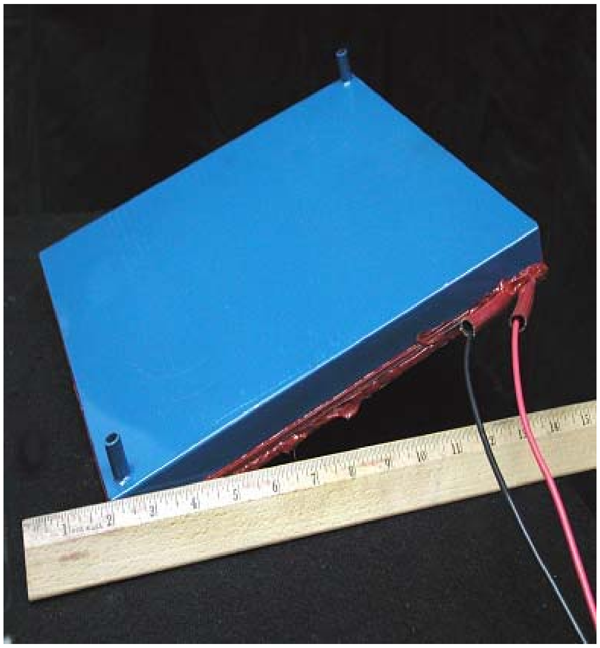

Figure 19. Typical LTI TE device.

This tank was attached by an adhesive to a sheet of circuit board material made of fiberglass or phenolic. Multiple "mini-devices" were attached to the opposite side of the circuit board material. The mini-devices were approximately 1.5-in. square and contained multiple TE material pairs soldered into an electrical series circuit and mounted between two alumina sheets.

These mini-devices were soldered together, electrically in series, and the circuit was completed by attaching 14 AWG lead wires on the positive and negative side of the circuit. These leads were the interface to the device. A 12-in. square copper sheet was attached to the opposite side of the grid of mini-tiles. The TE Device was sealed with a high temperature RTV (orange area of Figure 19).

TE Device Design Recommendations

To provide recommendations and attempt to perform a design of the TE Device, some background is required to understand the TE Device operation and how its performance can be optimized. The TE materials are compounds similar to those commonly used throughout the thermoelectric industry. LTI has a proprietary composition and manufacturing process, which will not be discussed, but the information is typical to all TE Device operation.

TE Device Design Considerations

As mentioned in Section 1.0, the optimization of the electrical power generation properties of these materials has been researched extensively over the years by multiple academic and commercial organizations, and continues today. The work completed under this task simply attempts to apply some of the knowledge gained to the present TE Device design and improve on the design.

The electrical energy production of the LTI TE Device is dependent on several basic factors, primarily:

- temperature differential
- thermal conductivity
- internal electrical resistance of the TE device.

The TE materials solely convert thermal to electrical energy but the overall device design can provide an operating platform that provides minimal loss of efficiency due to the balance of the TE Device.

The temperature differential of the TE Device must be uniform, for the device to operate optimally. The entire hot and cold surface area requires consistent temperature gradients across the surface area. If this does not occur, portions of the device or “cold spots” may act as an electrical load reducing the overall device operating efficiency. Multiple factors affect this consistency, but the focus for this effort should be strictly on the TE Device design. It was assumed that the heat source would be large enough and consistent enough to provide the ideal operating condition.

The internal electrical resistance of the TE Device has a direct correlation to the overall TE Device operation. LTI’s subcontractor attempted several designs to reduce the device’s electrical resistance. According to Dr. Andrea Rossi, the TE Device power production is dependent on the TE Material surface area in contact with the conductive pad and it’s contact resistance. Previously, soldering and electrically conductive adhesives were used. These had inconsistent results. To avoid significant labor costs and environmental and safety concerns of high temperature solders, it may be wise to avoid solders. These solders generally contain high quantities of Lead and/or Cadmium, which are considered hazardous to health. Several mechanical assembly methods have potential to eliminate the need for solders.

The thermal conductivity is also critical to the overall TE Device operation. It is assumed that the heat source is ideal and can provide all the thermal energy required. TE power generation is dependent on the material's ability to convert thermal energy into electrical energy. The materials are proprietary and will not be discussed here, but the overall design of the mechanical packaging of the device has a significant affect on its overall efficiency. Generally, the device should have excellent thermal conductivity except for the TE wafer materials themselves. The ideal TE material should have a high electrical conductivity and a low thermal conductivity to allow the materials time to "convert" the thermal energy to electrical energy. The thermal energy should be forced through the TE materials and not allowed to "bypass" directly to the cold plate. Materials with these characteristics are not very common, so current research is broadening towards a Phonon-Glass-Electron-Crystal (PGEC) approach. Clathrates and Skutterudites may meet the challenges of becoming the ideal thermoelectric material. The idea behind these materials is to have thermal properties associated with an amorphous crystal structure such as glass, giving a low thermal conductivity, while still retaining good electronic properties.

Current Design Issues

Issues found with LTI's original design are:

1. It showed poor consistency in internal device resistance.
2. Solder melted at low temperatures.
3. The cooling tank had poor mechanical stability (expanded with water pressure).
4. The cooling tank corroded rapidly, contaminating facility chilled water system.
5. The original cooling tank had no baffles, and poor heat transfer consistency.
6. The second-generation cooling tank had baffles, but unknown heat transfer efficiency; it still had corrosion problems.
7. The material used for mounting the TE wafers had very poor thermal conductivity (fiberglass/phenolic circuit board material).
8. It had poor surface-to-surface contact of TE wafers to conductive pads, resulting in poor electrical and thermal conductivity.
9. TE wafers were very brittle and break easily, affecting overall energy production.

Device Design Recommendations

These specifications were developed from e-mails and telephone conversation with Dr. Andrea Rossi and knowledge of potential applications.

- TE device electrical resistance of less than 5 ohms
- device designed to withstand operating temperature range of 0 °C to 300 °C

- cooling tank capable of removing significant amounts of thermal energy rapidly
- 0.5 to 5 L/minute coolant flow
- capable of handling normal facility chilled water line pressures of up to 60 psi
- constructed of corrosion resistant materials (aluminum, stainless steel, copper, etc.)
- use thermally conductive materials (copper, aluminum, etc.)
- mount TE wafers onto copper traces that are attached to a thermally conductive/ electrically nonconductive board
- operate in up to 95 percent humidity.

Using this data, the *CTC* design team developed four prototype designs to construct and test when functional TE wafers were made available. Although none of the prototypes were fabricated and tested, future efforts may benefit from the work accomplished. Each of the following prototype designs (Figures 20 to 24) are similar to the original 12-in. LTI TE Device in dimensions simply for ease of reference. Production models could be altered dimensionally for custom use applications. They each have a cold plate, top and bottom plate "circuit boards," TE wafers, and some method of attaching all components together.

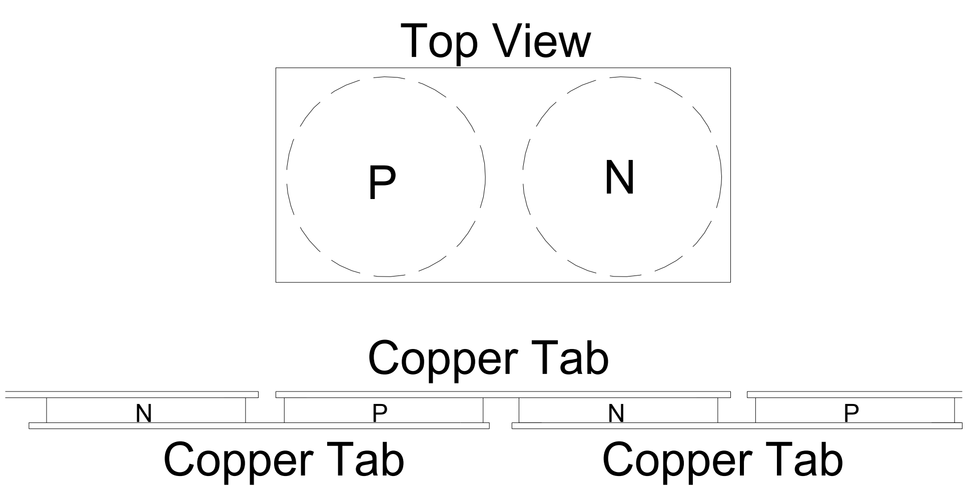

Figure 20. TE wafer configuration.

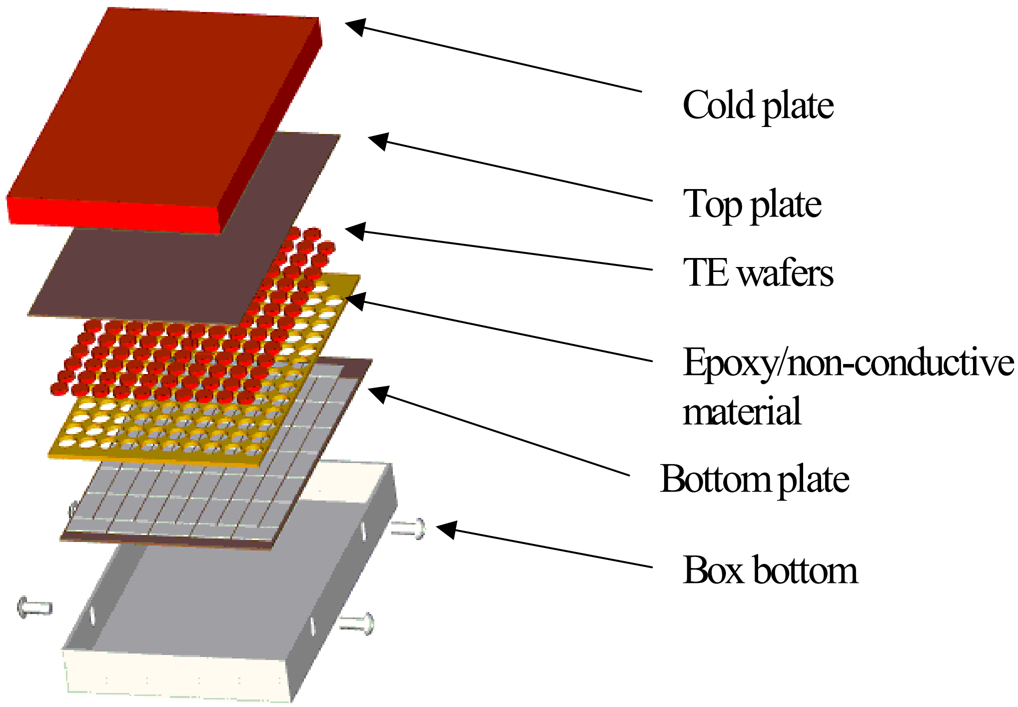

Figure 21. Prototype 1 design.

The circuit boards can be manufactured of alumina or beryllium oxide with copper traces bonded and etched on thin sheets of either of these materials. The electrical circuit should be simply a series circuit for the initial prototypes. Figure 20 shows how the typical TE wafer pair should be mounted between the board materials. These wafers could potentially be soldered, but the use of thermally and electrically conductive grease or epoxy is recommended to interface the TE wafers to the circuit.

The first design, Prototype 1, Figure 21, is based around a custom cold plate. This cold plate would have threaded inserts in the outer edge. These inserts would be used, in combination with the box bottom, to mechanically hold the components together as a completed device. As appropriate, thermally conductive grease would be used to increase thermal conductivity through the device components and a method of forcing the thermal energy through the TE wafers. This will also allow a small amount of thermal expansion while maintaining thermal and electrical contacts.

The next design, Prototype 2 (Figure 22), is similar to Prototype 1 but does not require a custom cold plate. This could reduce the overall manufacturing cost, but there may be a small performance cost due to adding another material boundary that will add thermal resistance. The cooling tank could be held in place by thermally conductive adhesives or by some other mechanical device. This design adds a top plate to mechanically hold the components together as a completed device. As appropriate, thermally conductive grease would be used to increase thermal conductivity through the device components and a method of forcing the thermal energy through the TE wafers. This will also allow a small amount of thermal expansion while maintaining thermal and electrical contacts.

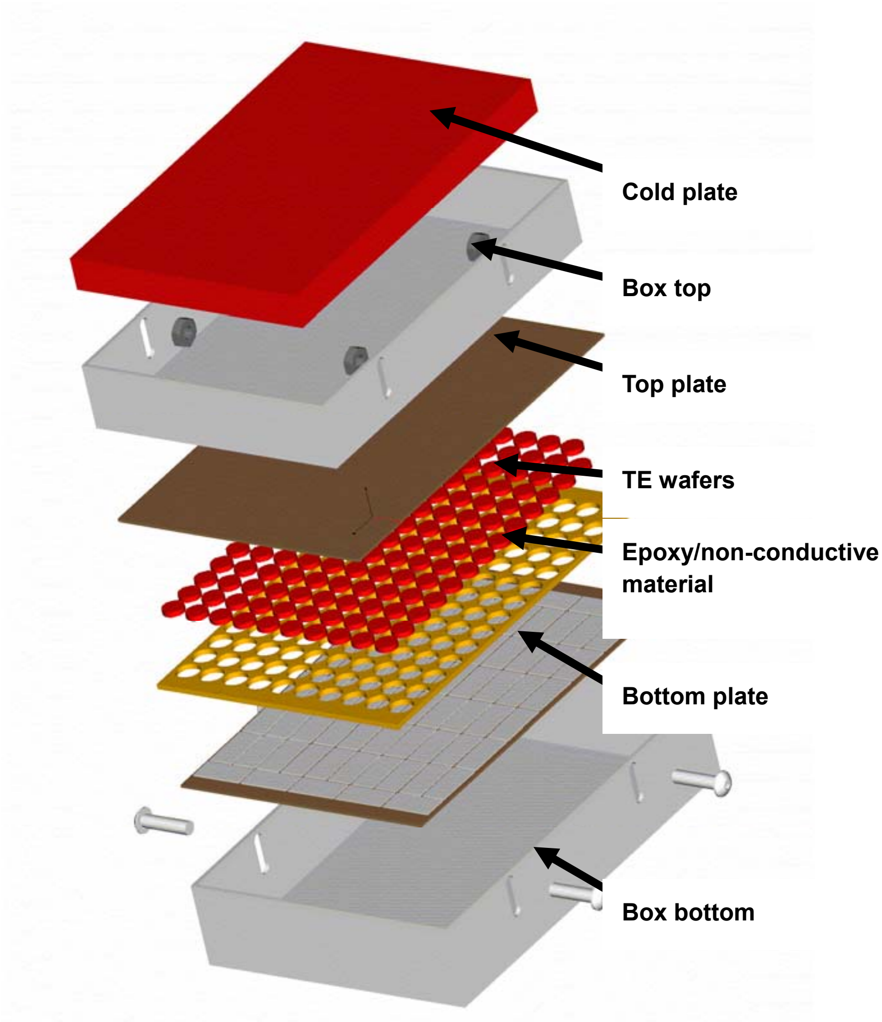

Figure 22. Prototype 2 design.

The third design, Prototype 3 (Figure 23), is almost identical to the second prototype but instead of using an adhesive or compressive force to hold the cold plate in place, the box top is simply used to mechanically compress it with the remaining device components. As appropriate, thermally conductive grease would be used to increase thermal conductivity through the device components and a method of forcing the thermal energy through the TE wafers. This will also allow a small amount of thermal expansion while maintaining thermal and electrical contacts.

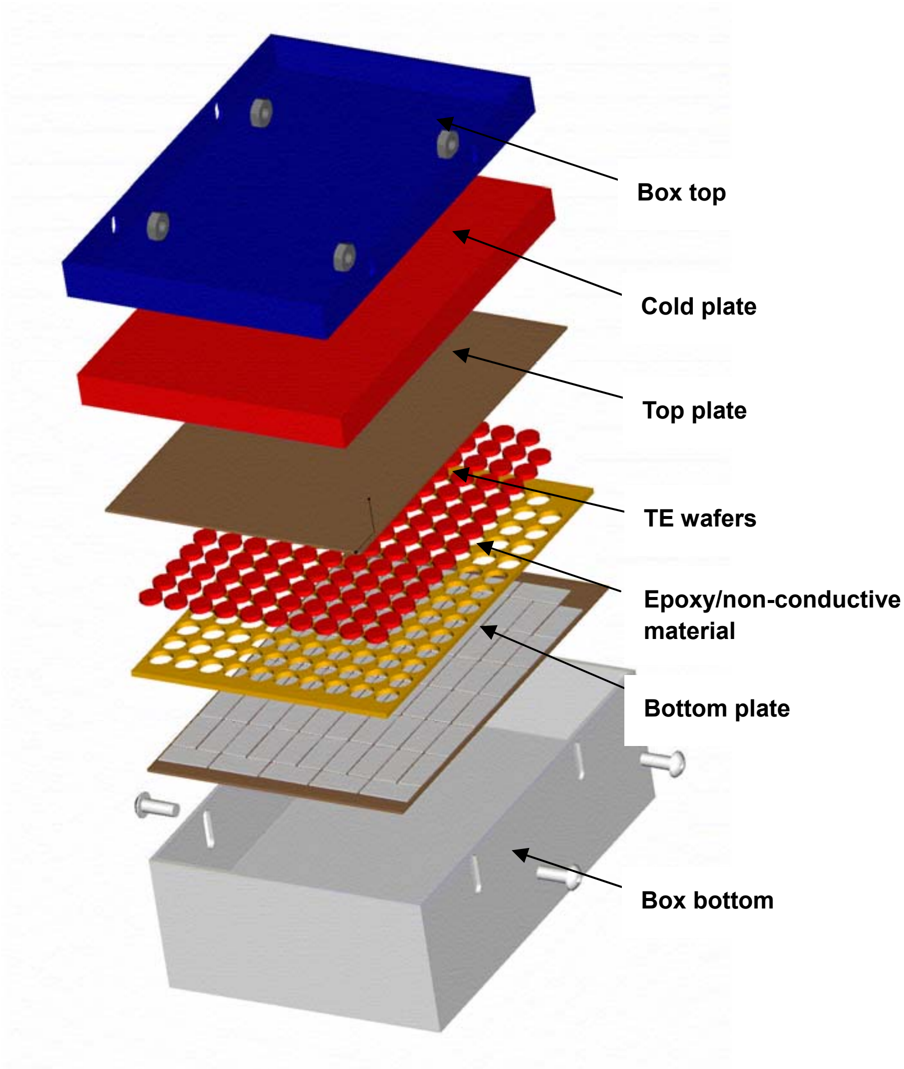

Figure 23. Prototype 3 design.

The final design, Prototype 4 (Figure 24), is similar to the previously described designs. The components are simply assembled, the completed assembly is then compressed in some fixture and the bottom box is welded to the cold plate. This method is simple but permanent, where the other designs allow reopening the device if necessary. This method may not be best for prototyping, but once a level of confidence in device operation is established, it may be the best design. As appropriate, thermally conductive grease would be used to increase thermal conductivity through the device components and a method of forcing the thermal energy through the TE wafers. This will also allow a small amount of thermal expansion while maintaining thermal and electrical contacts.

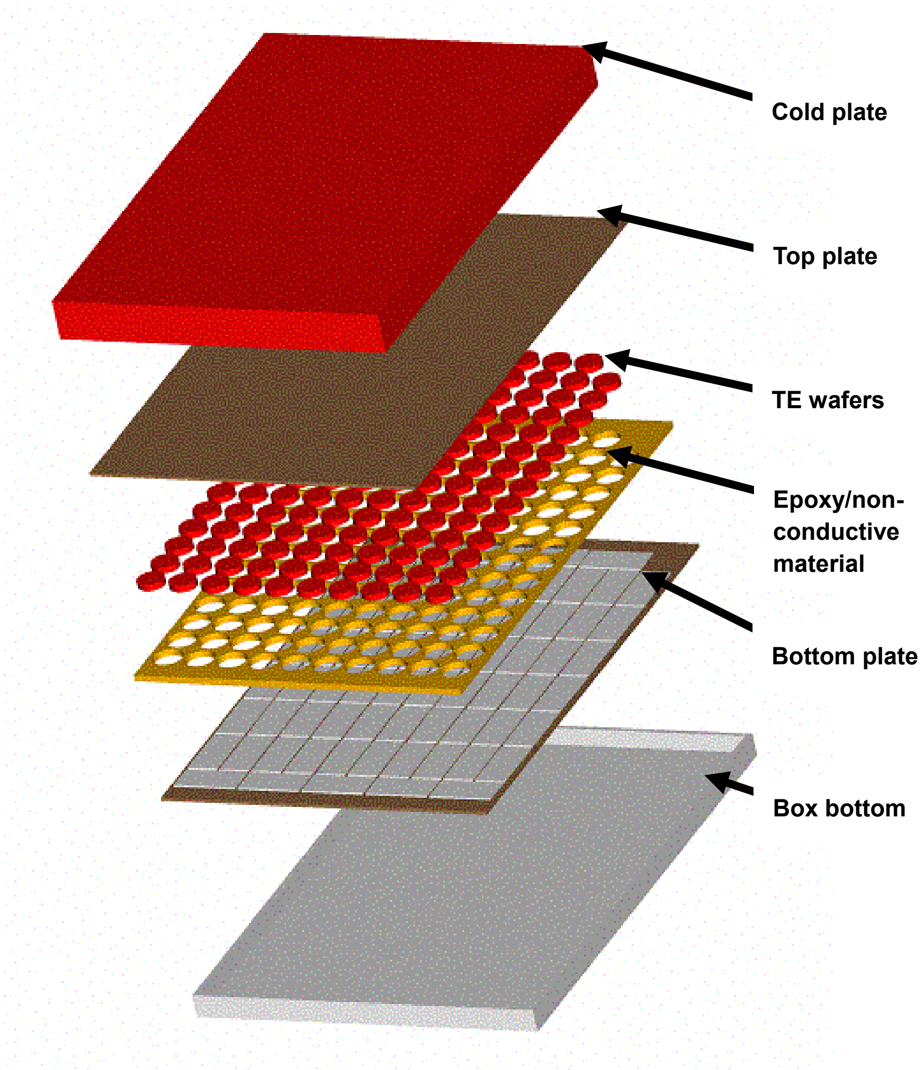

Figure 24. Prototype 4 design.

Other potential methods of allowing for thermal expansion were investigated, including the use of wave springs and/or a flexible cooling bladder. These were later ruled out due to complexity, manufacturing costs, and poor thermal conductivity of potential bladder materials.

4 Lessons Learned

This project presented many challenges throughout the 2-year period of performance. Initial expectations when the project kicked off were that this project would be very consistent with previous test and evaluation technical efforts, in regard to demonstrating the TE Device operation. These expectations were not the reality that was encountered. The following are brief notes of interest to assist future endeavors:

- An aggressive start evaluating demonstration sites and designing test stands proved necessary when equipment and material delays were encountered. The test stands were completed and ready for the December 2001 receipt of TE Devices, but only due to the aggressive schedule.
- Many TE Devices were damaged during overseas shipping because they were transported using only light cardboard boxes with minimal bubble wrap protection. The LTI subcontractors were immediately notified of this problem, and this issue will be addressed in the future.
- "Overnight" deliveries to Italy typically require a week or more to reach their destination due to customs.
- Communication to the Italian subcontractor was difficult at best. E-mail communications were slow and language misunderstandings caused delays throughout the initial project efforts while troubleshooting the malfunctioning of the TE Devices. All possible efforts should be made to work with companies familiar with engineering and business practices of the United States.
- Testing TE Devices and wafer materials is a science of its own. Measuring the internal resistance of a TE Device or a single wafer pair proved challenging. (The multimeter applied a current through the TE materials, inducing the Peltier effect, which caused errors in measurements.)
- During the initial stages of the Application Study, the 11 September 2001 terrorist attack occurred. The subsequent response in National Security measures made accessing necessary information difficult. This caused significantly more face-to-face interviews and travel, which had not been originally foreseen.

5 Summary and Conclusions

In summary, ERDC/CERL, CTC and LTI accomplished a study and ranking of potential DOD applications which would benefit from the integration of TE Devices to increase the systems overall operating efficiency. Test stands and procedures were also developed to evaluate TE Device operating characteristics and performing testing of TE wafer pairs. LTI established its own laboratory and bench scale production facility in New Hampshire. Although there is significant evidence to support further real world testing of TE Devices in DOD applications, neither current available production meets the ~16 percent efficiency requirement, nor are TE Devices readily available to perform system integration.

As part of a Department of Energy project titled, "Assessment of Efficiency Increases and Economics of Application of Thermoelectric Apparatus in Fossil Power Plants" (Task DE-AT01-98FE65489, TD No. 15), a small prototype TE Device manufactured by Dr. Andre Rossi was tested at the University of New Hampshire in 2000. This TE Device demonstrated significant power generation (100 watts continuous) and a thermal to electrical conversion efficiency of 16 percent. These results could not be duplicated during this effort. LTI is continuing research and development work to achieve the TE Device level of operation demonstrated in the Parsons study.

The Application Study demonstrated the potential cost benefits of integrating ~16 percent efficient TE Devices into DOD applications. Based on the results of this study, it is recommended that further research be conducted to identify and evaluate the potential of TE Devices through field-scale demonstrations at military and non-military facility applications. This additional research should be accomplished regarding integration of TE Devices into large-scale waste heat generators. This work would lead to refined estimates of cost for TE Device application and allow the calculation of cost/benefit and return on investment. Demonstrations would also allow the collection of defensible data necessary to penetrate the market with the technology.

The work accomplished during this project developed prototype designs to integrate TE Devices, but could not be accurately tested and evaluated without functional TE Devices. It was apparent that a complete redesign of present LTI TE

Device configuration is required. Although a greater understanding of approaches to large-scale integration has been acquired, continued work is necessary to allow future technologies to be readily integrated into large-scale systems. Although current COTS TE Devices do not have the thermal-to-electrical energy conversion efficiencies required to allow a cost-effective integration, using them now as a test platform could significantly reduce the learning curve once higher operating efficiencies are realized.

Appendix A: Application Study Report

Identify & Evaluate Broad Applications for Thermoelectric Devices

for

The Department of Defense
Application Study
Final Report

for

Contract Number 5TS5701C256

Submitted to

The U.S. Department of Defense,
U.S. Army Corps of Engineers,
Engineering Research and Development Center;
Construction Engineering Research Laboratory

by

Concurrent Technologies Corporation (CTC)
and
Leonardo Technologies, Inc. (LTI)
September 9, 2003

US Army Corps of Engineers ®
Construction Engineering Research Laboratory

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1 EXECUTIVE SUMMARY

Thermoelectric (TE) power generation results from electricity that is induced in particular materials by a temperature differential. This is known as the "Seebeck Effect." Historically, the cost of thermoelectric power generation has been high due to limitations in material knowledge and associated processing issues. Recent technology developments, based on advances in material science and advanced manufacturing techniques, have demonstrated a high potential for reduced production costs.

Leonardo Technologies Inc. (LTI) has demonstrated their thermoelectric innovation as a cost-effective energy-producing alternative that is efficient and environmentally benign. Initial testing of LTI's innovations demonstrate an approximate three-fold increase in energy conversion and potentially a ten-fold decrease in fabrication cost per kW of electrical generation capacity. It is projected that under mass production, the cost per kW of thermoelectric devices could approach that of combined-cycle gas central power plants, the least expensive power generation alternative, at about $500/kW – with the added economic benefit of no fuel costs.

The U.S. Department of Defense (DOD), U.S. Army Corps of Engineers, Engineering Research and Development Center, Construction Engineering Research Laboratory (ERDC/CERL) sponsored this study to evaluate the potential range of applicability, energy efficiency, clean production and economic advantages of thermoelectric technology application in fuel cell, traditional and potential power generation units. Related applications discovered through the interview and literature search process of this study have also been noted. For the purposes of this study, applications were divided into applications at fixed defense facilities and applications at non-facility locations such as weapons systems, vehicles and sensors. To determine the potential benefits of the installation of TE devices at the facility level, case studies of facilities from each of the Armed Services were performed. Also, the findings of previous studies performed for the Department of Energy's (DOE's) Office of Fossil Energy (FE) and Office of Industrial Technologies (OIT) were leveraged for this report. The potential benefits of TE devices extend into the U.S. utility/non-utility power generation and Industries of the Future Sectors in addition to the DOD. Table 1 summarizes the findings of the reports for FE and OIT and for the DOD.

The results of this study will assist the development of a demonstration of LTI's TE technology at a defense facility. This report documents the findings germane to facility and non-facility applications within the DOD:

- TE devices have the potential to generate 464,000 MWh of electricity each year when applied to low-grade waste heat (LGH) generated from military applications. This equates to:
- 53 MWe of generation capacity
- $34.5 million cost avoidance for the production of electricity
- 1.5 billion BTUs of energy production from normally discarded LGH
- 268,000 barrels of oil equivalent saved annually

- 21,000 metric tons per year savings in carbon emissions.
- Potential savings are in the area of $250,000 per year from a typical facility's utility bill.
- Over 40 specific applications were identified and ranked within these sectors.
- The TE device is environmentally benign and requires no fuel for the production of electricity.

Based on the results of this study, it is recommended that further work be conducted to identify and evaluate the potential of TE devices through field-scale demonstrations at defense facilities. This work would lead to refined estimates of cost for TE device application and allow the specific determination of financial cost/benefit and return on investment.

Background: Many defense applications generate waste heat. In most instances, this waste heat still contains significant quantities of energy above ambient conditions, but it no longer has value for that particular situation. This energy is generally termed low-grade waste heat. The benefits of capturing and reusing this energy have many advantages, including:

- Increasing the generating capability of existing power plants
- Improving overall energy efficiency of processes
- Decreasing total energy use
- Reducing the environmental impact of power generation and industrial processes, thus reducing thermal pollution from facilities. This pollution reduction may help in facility permitting
- Enabling facilities in non-attainment zones to increase power generation without a related increase in emissions
- Reducing maintenance and noise
- Reducing the thermal signature of equipment, increasing battlefield survivability
- Transforming an undesirable, unusable waste product, LGH, into a high value feedstock, namely direct current (DC) electricity, which is in high demand at many facilities.

Ranking: This study identified discrete processes, within the DOD, that are potential locations for thermoelec-

Table A1. Potential Annual Benefits of TE Device Application

Sector	Electricity Generation (MWh)	Generation Capacity (MWe)	Cost Avoidance ($1M)	Oil Equivalent Saved (thousands of barrels)	Carbon Emissions Savings (metric ktons)	Number of Potential Applications
Defense	464,000	53	34.5	268	21	43
Utility/non-utility power generation (CTC & LTI 2001b)	603,000,000	68,000	45,000	355,000	41,200	57
U.S. Industries of the Future (*CTC* & LTI 2001a)	74,000,000	8,400	5,500	43,000	5,000	101

tric technology. More than 40 specific applications were identified. For each application there were many potential locations for consideration. These applications were then ranked based on the quality and quantity of low-grade heat available, effects on process performance, equipment issues, and potential electric generation.

Due to National Security issues surrounding defense and other government activities, many documents normally available through literature and Internet searches were restricted from public availability. These documents included detailed layouts of facilities, reports on energy consumption, and specifications of equipment. Therefore, many of the assumptions in this report were made without the benefit of detailed information available before September 11, 2001.

2 INTRODUCTION

For the Department of Defense (DOD), energy is the lifeblood of many processes and systems that are fundamental to the operation of both facilities and equipment. The volatility in energy prices, and especially the potential unreliability of energy delivery, increases the price of maintaining a high state of operational readiness. The operation of most equipment and many facilities' processes generate waste heat. Most of the time, this waste heat still contains significant quantities of energy above the ambient temperature. However, it no longer has value for that plant or piece of equipment and is generally termed low-grade waste heat (LGH).

A new composite of an existing technology, thermoelectric (TE) power generation, may enable increased power generation and efficiency through integrated designs and minor retrofitting of existing power plants and utilizing waste heat from conventional power generation.

For coal-fired steam cycle power plants, the gross efficiency of converting the energy in the fuel to electricity is 30 - 35 % (U.S. DOE-EIA 2001a) with net electricity generated closer to 25 % of coal energy input (U.S. DOE-EIA 2001b). State-of-the-art combined-cycle power plants fired by natural gas can reach 60 % gross efficiency (Gas Turbine World 2000). In either case, there are significant amounts of energy released to the atmosphere through the stack, condenser, or other equipment. This energy is at a temperature or form that no longer has value for that plant and is generally classified as LGH.

Alternatives that increase the fuel and energy efficiency of existing equipment is a desirable way to increase the overall capabilities of a unit or facility by providing additional electrical power for advanced control and operations. Additionally, since the DOD uses approximately 1.2 % of all energy consumed in the United States (Defense Science Board, 2001), even a modest improvement in the overall energy efficiency of equipment and facility processes could make a significant impact on total energy use. Also, reductions in energy consumption for defense applications reduce the environmental impact of these applications, including regulated pollutant emissions such as NO_x, SO_x and particulates, as well as the greenhouse gas, CO_2.

2.1 Background

Thermoelectric devices can be utilized as cooling, heating or power generation. The Peltier effect is the phenomenon whereby the passage of an electrical current through a junction consisting of two dissimilar metals creates a temperature differential. One side will cool and the opposite side will heat. The use of TE Devices as coolers is widespread particularly in computer processor and laser diode applications. The use of TE Devices as power generators is significantly less common. The Seebeck Effect is the phenomenon where electrical current will flow in a closed circuit made up of two dissimilar metals when the junctions of the metals are maintained at different temperatures. This phenomenon has been well documented and utilized for temperature measurement throughout industry and academia as thermocouple devices. N-type and P-type semiconductor materials are welded to form a basic thermocouple. Thermocouples can be made up of several types of materials. The thermocouples utilized for temperature measurement have been developed for their repeatable millivolt output across a known temperature range. A Type K thermocouple consists of a junction of Nickel Chromiun and Nickel Aluminum with a traceable operating range of –300 to +1250°C. Bismuth Telluride is commonly used in TE cooling devices as well as power generation. Several types of materials demonstrate good thermoelectric properties such as Silicone Germanium, Lead Telluride, research is continuing to investigate and improve the performance of these materials.

The use of TE Devices as alternative energy sources has been investigated with limited success. Manufacturing costs and limited power generation efficiency (on the order of 2%–4%) have previously prohibited the economical, large-scale production and use of the TE Devices as a viable alternative energy source. To obtain an acceptable return on investment, any TE Device utilized would need to operate at a thermal to electrical energy conversion efficiency of approximately 15%. Historically thermoelectric power generation has only been used in small-scale exotic applications such as satellites and ocean weather stations.

Recently, however, Leonardo Technologies Inc. (LTI) has addressed these issues and developed a more economical TE Device that has previously demonstrated an order of magnitude increase in power generation efficiency in preliminary laboratory investigations. The LTI device is therefore potentially suitable for supplemental electric power generation from fuel cells and other sources of waste heat.

Recently, however, technology developments, based on advances in material science and advanced manufacturing techniques, have demonstrated high potential for a substantial reduction in production costs per kW of capacity.

Leonardo Technologies Inc. (LTI) demonstrated their thermoelectric innovation (Figure 1) based on advances in material science and reduced production costs on a boiler at the University of New Hampshire (Parsons 2000). The result of this innovation is an efficient and environmentally benign, cost effective energy-producing alternative.

The U.S. Army Corps of Engineers, Engineering Research and Development Center, Construction Engineering Research Laboratory (ERDC/CERL) sponsored this study to evaluate the potential range of applicability, energy efficiency, clean production and economic advantages of thermoelectric technology within DOD facilities' power generation units, industrial processes and other facility applications. Additionally, the evaluation was conducted for equipment and weapons platforms. This evaluation includes:

- Identification of germane, broad thermoelectric applications
- Brief technical evaluation of applications and benefits
- Prioritization of applications based on anticipated benefits and application timeliness.

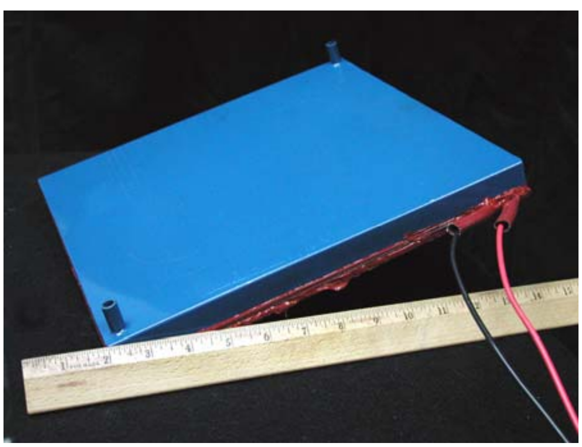


Figure A1. LTI thermoelectric tile.

Teaming with Concurrent Technologies Corporation (*CTC*), LTI has secured DOD funding to identify and quantify applications and develop a model TE device for electrical generation and industrial process applications. While significant benefit is expected in this demonstration program for the DOD, the benefits of TE devices also extend into other areas, such as the power-generation and general industrial sectors. Previous studies for the Department of Energy's (DOE's) Office of Fossil Energy (FE) and Energy Efficiency and Renewable Energy (EERE) Industrial Technologies programs were leveraged to evaluate the broad range of applicability, energy efficiency, clean production and economic advantages of thermoelectric power generation systems for sectors identified within the DOD.

2.2 Thermoelectric Value and Benefits

By creatively adapting the principles of the Seebeck Effect, LTI has demonstrated the effectiveness of their innovative thermoelectric technology at the University of New Hampshire. These improvements brought about a three-fold increase in energy conversion and approximately a 10-fold decrease in fabrication cost per kW of electrical generation capacity. It is projected that under mass production, the cost per kW of thermoelectric devices could approach that of combined-cycle gas central power plants, the least expensive power generation alternative, at about $500/kW—with the added economic benefit of no fuel costs.

The current configuration for thermoelectric tiles (Figure 2) provided by LTI is roughly the size of 1-foot square floor tiles and 1-inch thick, including an integrated water-cooled jacket. Other configurations are possible and are being developed for applications identified in this and other studies. A single 1-foot square tile can potentially generate approximately one (1) kW of power, with a 300°C (572°F) differential temperature, ΔT.

Figure 2 depicts a typical thermoelectric application in a process stream. The tile can be applied to any hot surface or integrated within a process heat stream (Q) such as flue gas, radiant heat or steam. The temperature differential applied across the tile, considering the water-cooled jacket, is converted to direct current (DC) electricity. An inverter can be used to convert the DC electricity to alternating current (AC) electricity.

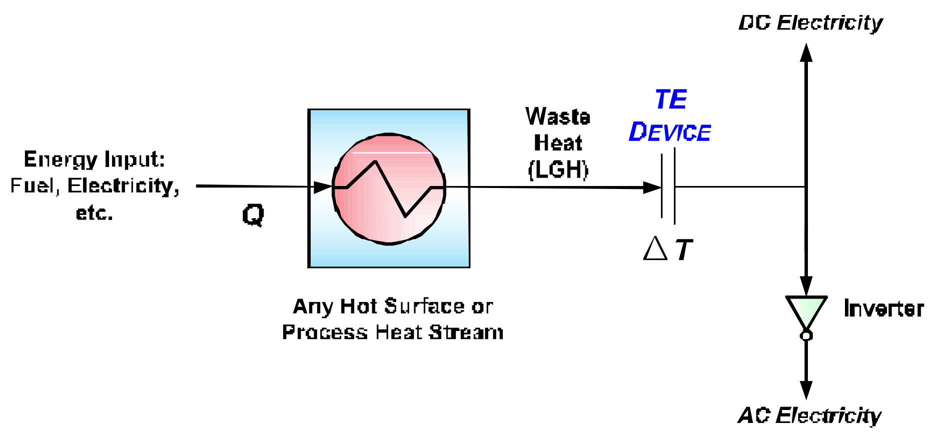


Figure A2. Typical thermoelectric operation.

The deployment of TE devices can provide advantages for the operation of a power plant, industrial facility or individual pieces of equipment. The generation of electricity from LGH provides added value. Several additional benefits are achievable through the implementation of TE devices using waste heat sources:

- Reduces thermal pollution from a facility. This may help in permitting a plant.
- Enables industries in non-attainment zones to increase power generation without a related increase in emissions.
- TE devices have no moving parts.
- TE devices reduce the thermal signature of equipment, increasing battlefield survivability.
- Improves the fuel efficiency of field equipment such as generators, sensors and communications gear, improving a unit's warfighting capability.
- Transforms an undesirable, unusable waste product, LGH, into a high value feedstock, DC electricity, that is in high demand at industrial facilities.

2.3 Approach

This study identifies major sources of LGH primarily within DOD facilities, but non-facility applications such as weapons systems and equipment were also examined.

These sources of LGH within the DOD were identified through:

- Review of mechanical power producing methods (e.g., engines) and applications where those methods are implemented or installed

- Interviews with military facility and energy managers
- Review of the efficiency of these power production methods and the component thermal processes.

Data gathered was utilized to estimate the total quantity of waste heat produced per year by a number of selected facilities. This study estimates the potential for the total amount of power generated by TE devices for typical facilities, and these values can reasonably be extrapolated for other DOD facilities.

The list of applications was narrowed down to a manageable number of potential demonstration opportunities based on review of the anticipated thermoelectric device performance, waste heat characteristics and replication potential for the processes.

- As part of this study, the project team performed the following tasks:
- Identified and provided a brief technical description for broad thermoelectric applications. These descriptions of potential applications were based on a series of face-to-face and telephone interviews of military facility and energy managers, as well as literature and Internet reviews.
- Conducted a brief, high-level evaluation of each application to assess technical and economic benefits.
- Met with senior and technical representatives of DOD to review the list of potential applications and to determine their relative interest in specific applications.

Interviews were conducted with representatives from both government and industry. Initially, contacts were made with DOD representatives. The interviews were conducted using a standard questionnaire developed specifically for this study. Information gathered during the interviews was used to identify potential applications for TE devices. The interviews also led to other sources of information and references. Each application developed through interviews or research was characterized by temperature range and other factors (Annex A).

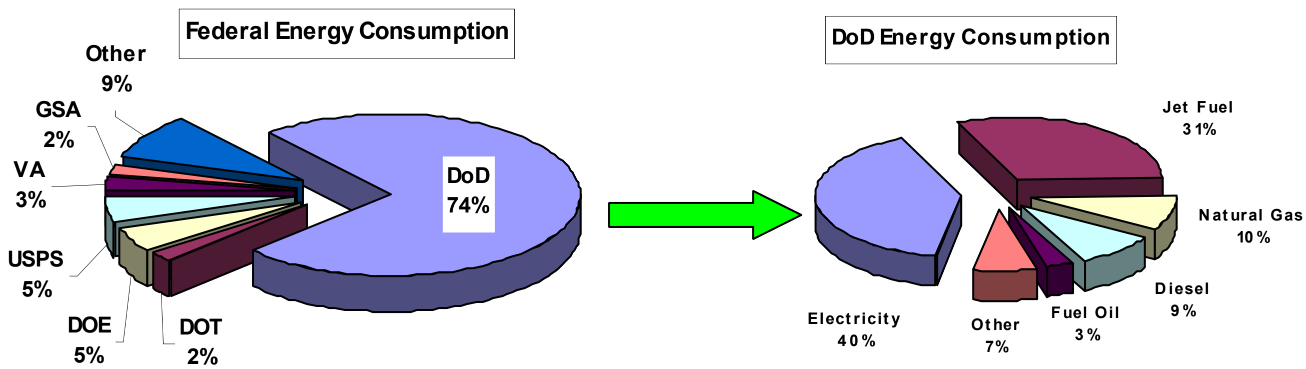
Criteria were developed and used to rank each of the applications. These criteria were weighted based on relative importance. Each application was ranked versus the criteria and a weighted score was calculated (Annex B). This process allowed for a prioritized list of applications based on the weighted score.

A database was established to store project information including, but not limited to: contacts, interviews, technology applications and high-level descriptions, and application ranking.

2.4 DOD Energy Consumption

Data for 1999, the most recent consistent data available, indicate that the U.S. Government consumes approximately 1.6 % of the nation’s energy, with the DOD consuming 74 % of that total, as indicated in Figure 3. Of the DOD’s total energy use, operations and training consume approximately 58 % and facilities and non-tactical vehicles consumed 42 %.

In spite of its unique role in the nation’s defense, various Executive Orders and legislation requiring improvements in energy efficiency are still applicable to the DOD, but due to the high priority assigned to operations and training, most energy-saving efforts have focused on facilities and non-tactical, non-deploying support vehicles. This study will reflect that focus by emphasizing facility applications for demonstration purposes, but non-facility applications will also be briefly examined.



- For 1999, total U.S. energy consumption was 96.77 quads
- Federal energy use was 1.6% of the U.S. total (1.65 quads)
- DOD energy use was 1.2% of the U.S. total and 74 % of the Federal total (1.16 quads)
- 58% of DOD energy use attributable to operations and training
- 42% of that energy is consumed by buildings and non-tactical vehicles

Figure A3. DOD energy consumption

In particular, this report documents the potential that TE devices have to assist the DoD in meeting the goals of Executive Order 13123 that requires a yearly 1.25 % reduction in energy consumed per square foot by DoD facilities from baseline energy consumption data developed for 1985. As well, TE devices can also contribute to the DoD's compliance with Executive Order 12759 which directs all federal agencies to improve the energy efficiency of their buildings and industrial facilities by 30 % from 1985 to 2005. Assuming a low to moderate installation rate (approximately 10 % per year of available sites) of the TE devices, that only 25 % of the waste heat generated can be utitlzed and that 16 % of that heat is converted directly to electricity by the devices, TE devices have the potential to lower the DoD's total facility energy consumption by 0.4%

per year. Using 1999 data as a baseline, this equates to savings of 4.6 billion BTU per year and the potential to generate 1.4 GWh/year.

3 INTERVIEWS AND LITERATURE SEARCH

The goal of this study was to develop a broad list of applications for the TE device for DOD facilities and non-facilities. This section discusses the methods for identifying and developing information on these applications.

3.1 Process

The starting point in generating a list of potential applications was to conduct a search for DOD facility energy managers and other personnel, both military and civilian, that were knowledgeable about energy issues. These people were interviewed with the purposes of:

- Informing the program managers about the TE device and its capabilities
- Identifying potential applications in the power generation industry for use of TE devices
- Identifying additional contacts that can provide information on potential applications of TE devices
- Identifying potential demonstration sites for field trials and demonstrations of integrated TE system installations on process heating equipment
- Obtaining guidance on program direction and applicability
- Obtaining guidance related to specific applications for TE devices.

To reach these objectives, the DOD personnel were queried for general recommendations where large quantities of waste heat are available. The interviewees were then asked about opportunities to incorporate TE devices into existing or planned DOD programs, as well as potential sites for a demonstration of TE devices. Finally, in order to develop evaluation criteria, interviewees were asked by what means they would evaluate the applications of TE devices.

From these interviews, a database of potential applications was developed. This database has been further expanded with information from a literature and Internet search. A listing of some persons contacted for this study is included as Annex C.

3.2 Findings

A list of more than 40 potential applications for TE devices for the DOD has been compiled from the interviews and other aforementioned sources. Information from these sources has been collected and incorporated into the database of applications. Summaries of each potential application are presented in Annex A. Additionally, Section 4 of this report presents more detailed information on these applications, including an estimate of the electricity generation potential. Section 5 presents criteria for ranking the applications along with individual application rankings.

In order to provide an estimate of the total potential electricity generation of TE devices, a comprehensive database of energy consumption by the DOD was sought. However, Internet searches, literature reviews, and direct communications with the DOD's Federal Energy Management Program (FEMP) staff have indicated that military energy consumption data is not consolidated in a consistent or comprehensive format.

Two data sources were utilized during the preparation of this report that did provide a partial segment of the required information. The first is the Defense Utilities Energy Reporting System (DUERS). This system was designed to provide the DOD with energy-use data for trend analysis and measurement of compliance with executive and Congressional mandates. As such, DUERS does not provide information at the facility level. Instead, data is provided by the Defense Fuel Supply Center, which receives its data from individual facilities. Although DUERS provides data that is useful for large-scale assessments, much of the facility-level information, such as prime mover and method of fuel consumption, is not rolled up into DUERS.

Also utilized was the Renewables and Energy Efficiency Planning (REEP) database. The REEP program was designed by the Construction Engineering Research Laboratory (CERL) of the Army Corps of Engineers, Engineer Research and Development Center (ERDC) to provide a quick broad overview of potential resource savings at DOD facilities. In order to perform these calculations, REEP contains equipment capacity and limited fuel consumption data for over 200 DOD facilities. However, the data in REEP was found to be dated and incomplete for some of the facilities examined. For example, heating equipment that is listed for Hill AFB is no longer in place due to energy conservation upgrades and replacements that were performed using Energy Savings Performance Contracts (ESPCs) that were developed since REEP was last updated. As well, there are significant omissions of entire facilities, such as Portsmouth Naval Shipyard in New Hampshire. Therefore, the use of REEP was limited to general projections and to verify data from FEMP's annual report to Congress on energy usage in federal facilities. Annex D contains the summary report developed from the REEP database.

3.3 Case Studies

Due to the inadequacy of the existing data sources, case studies of the potential benefits of TE devices were performed on a number of individual facilities. The goals of these case studies were to develop credible base data for extrapolation to the entire DOD and to highlight the small-scale benefits of TE devices to facility energy managers. A facility from each service branch was sought in order to provide as comprehensive a picture as possible. Electricity prices used to calculate savings were 1999 in order to maintain consistency. However, energy use at military facilities is dynamic due to continual upgrades and replacement of old, inefficient equipment. Full versions of each case study are presented in Annex D.

3.3.1 Watervliet Army Arsenal

For the Army, Watervliet Arsenal (WVA) was selected. WVA is the country's sole manufacturing facility of large caliber cannon in volume and as such is home to a number of large industrial processes that produce significant amounts of LGH. The energy consumption data for all major processes equipment for WVA is listed in a Process Energy and Pollution Review performed on the facility by the U.S.

Army Corps of Engineers (USACE 1999). From these data, the percentage of heat available to TE devices was calculated using figures established in a previous report for the DOE's OIT (*CTC* & LTI 1999). The 16 % efficiency of the TE tiles established by a report published by Parsons, Inc. (Munson 2000) was then applied to the available waste heat to yield the total number of BTUs that TE devices could capture. This number was then converted to kWh and local utility rates were used to calculate the potential savings. A similar process was used for the facility's heating equipment listed in the REEP database. The potential electricity generation from TE devices converting WVA's available LGH is 1,562 MWh per year with a potential savings of $160,000 yearly.

3.3.2 Portsmouth Naval Shipyard

Portsmouth Naval Shipyard (PNSY) in Portsmouth, New Hampshire was chosen to represent the Navy. PNSY provides industrial and engineering support for nuclear submarine maintenance and inter-service regional maintenance. Raw data for PNSY's utility usage were drawn from its 1999 Unified Cost Accounting Report (UCAR), a spreadsheet that all naval facility managers are required to submit each year (PNSY 1999). As with WVA, PNSY produces LGH as a by-product of both its industrial processes and in support of normal facility operations. The potential electricity generation from TE devices converting this LGH is 4,315 MWh and could save the installation over $500,000 per year.

3.3.3 Marine Corps Base Quantico

Marine Corps Base Quantico (MCBQ) is located in northern Virginia and is primarily a training facility. The UCAR for this facility was also used to generate the results for this case study (MCBQ 1999). Therefore, energy usage due to industrial processes is not present here. However, with TE application to the heating system alone, the devices have the potential to generate 2,419 MWh of power yearly, saving the base $141,000 in avoided utility bills.

3.3.4 Hill Air Force Base

Hill Air Force Base (HAFB), located in northern Utah, is responsible for Air Force-wide item management, depot-level overhaul and repair for all types of aircraft support systems. Data from FEMP reports and boiler inspections were used to develop this case study (FEMP 2000 & Williams 2000). Due to its location and mission, HAFB has the potential to generate electricity from TE devices in both heating and industrial applications. This potential amounts to 2,439 MWh per year with a projected savings of $130,000 to the base.

4 APPLICATIONS OF TE DEVICES

The major areas of energy use that this study focuses on are facility systems, which are potential sources of LGH. Generally, these systems use one or more fuels such as natural gas, coal or petroleum as the primary source of energy. These systems produce and discharge waste heat in the form of gases or liquids at relatively high temperature and offers the potential for application of TE devices to recover part of the LGH for generation of electrical power.

4.1 Methods of TE Device Integration

Several methods of incorporating TE devices into the facilities of electric power plants have been identified. These methods will be discussed briefly below. This will be followed by sections detailing the applications identified during the course of the interviews, literature search and other steps.

4.1.1 Hot Surfaces

The surfaces of equipment associated with the burning of fuels are often hot and may be insulated. This insulation may be present to improve the process efficiency, or in certain circumstances, the insulation may primarily be in place to reduce surface temperatures to those safe for operation personnel. The unavoidable loss of energy, even if reduced by insulation, may be useful in generating electricity by the placement of TE devices on equipment surfaces in such a way as to not adversely affect the primary process (e.g., making steam), while also generating economically viable quantities of DC electricity. For plant locations where thermal energy is radiated from equipment or the process itself, TE devices could be mounted in locations with thermal radiation absorbing materials to capture this radiant energy for conversion into electricity.

This method of generating electricity with TE devices mounted on equipment surfaces represents one of the simplest applications with the possibility of integration into existing facilities and equipment. One limitation of this approach is the amount of electricity that can be generated is determined by the available surface area of the equipment that is amenable to the installation of the TE devices and the surface temperature. Each facility would need to be individually assessed for its potential to be retrofit with TE devices.

4.1.2 Gas Heat Exchanger

The amount of energy contained in a gaseous flow, such as the exhaust gas from burning fuel for power generation, can be quite large. For example, in Diesel engines, the percentage of energy from the fuel contained in the hot exhaust is in the range of 22 to 35 % (Heywood 1988). To convert a significant fraction of this energy into electrical power, adequate surface area is required for energy to flow through and contact the TE devices. Therefore, a heat exchanger could be designed with the TE devices integrated into the configuration, creating the surface area for the hot exhaust to generate electricity in a compact space. This type of design has been discussed in three reports from Parsons, Inc. (1999, 2000, and 2001) with the latter two providing preliminary designs of such heat exchangers in the applications discussed.

4.1.3 Condenser Heat Exchanger

In both power generation and industrial settings, steam is often generated that is vented to the atmosphere for safety and other reasons, or may be simply condensed as in steam generating power cycles. The latent heat of vaporization for water is quite large and represents an LGH source that could be converted into electricity with TE devices. As discussed above, a compact heat exchanger, this time condensing the steam, could be designed to integrate the TE devices and increase the heat transfer and electricity generation area. This type of design has also been discussed in the three reports from Parsons, Inc. (1999, 2000, and 2001) with the latter two providing preliminary designs of such heat exchangers in the applications discussed. The size of such an integrated condenser is projected to be much larger than conventional due to the low thermal conductivity of the TE material compared to the materials of construction used in condensers (Parsons 2000).

4.1.4 Liquid Heat Exchanger

In some industrial settings, high temperature heat transfer liquids, such as Dowtherm heat transfer fluids, may be used to provide the process heat for driving certain industrial processes, or could be used for cooling of equipment, such as Diesel generators. For situations where this energy may be simply dissipated, it could be passed through a liquid heat exchanger where this energy is transferred through integrated TE devices to generate electricity as the equipment is being cooled.

4.1.5 Low Heat Rate Areas

There are likely to be locations at facilities where the process temperature is high enough to properly drive the optimal operation of the TE device while the rate of heat transfer per area (heat flux) may not be adequate to create the temperature differential needed within the TE device. This situation could be improved by circulating a small quantity of gas or high-temperature liquid to acquire the energy content available and then passing this fluid through a smaller heat exchanger where the TE tiles are integrated to cost effectively generate electricity from the waste heat. The trade-off of a smaller area of TE device required compared to the manifolding necessary would need to be weighed for cost considerations.

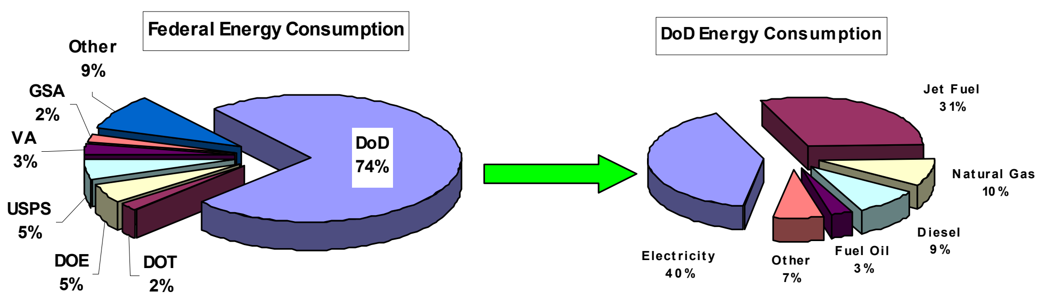
Exhaust stacks are one plant location where the gas temperature may be high enough, but the low flow velocities in the stack are not high enough to provide the necessary heat flux through the TE modules for optimal operation (Parsons 1999).

4.2 Facility Applications

Facility operations represent a significant portion of the DOD's energy consumption. On facilities, energy consumption can be divided into three primary categories: on-site electricity generation; heating, ventilation and air conditioning (HVAC); and industrial processes. The potential locations of these operations and the electricity generation potential are discussed below. Fuel cells are also discussed since they have the potential to become important generators of electricity in the future.

The approach used to determine the amount of electricity that could potentially be generated with TE devices integrated into electric power facilities is based on several reports generated by Parsons, Inc. (1999, 2000, 2001) for the U.S. DOE Office of Fossil Energy. These reports analyzed specific applications and locations in common electric power facilities to determine their potential electric power generation using TE devices. The applications and locations analyzed included the steam condenser, flue gas stack, gas turbine, internal combustion engine exhaust and hot surfaces of large furnaces. In the following analyses, it is these percentage increases in power generation that are applied to the actual amount of electricity generated by a class of prime movers.

Figure 4 provides a projection that the potential TE devices have to reduce the total energy expenditure of the DOD. The current trend data was calculated using 1999 consumption, the last year for which data is available. Using the 1999 figure, it is expected that the DOD will continue to reduce its facility energy consumption by 1.5 % per year on average. This reduction is consistent with the trend of previous years. The projection of DOD energy usage with TE device utilization was based on an average 10 % LGH capture from all facility applications, and a moderate rate of introduction and installation (approximately 10 % of available LGH per year) of TE devices starting in 2003. From 2003 to 2010, TE technology has the potential to reduce DOD facility energy consumption from 205,000 to 175,000 Billion BTUs.



- For 1999, total U.S. energy consumption was 96.77 quads
- Federal energy use was 1.6% of the U.S. total (1.65 quads)
- DOD energy use was 1.2% of the U.S. total and 74 % of the Federal total (1.16 quads)
- 58% of DOD energy use attributable to operations and training
- 42% of that energy is consumed by buildings and non-tactical vehicles

Source: Annual Report to Congress on Federal Government Energy Management and Conservation Programs, FY1999, U.S. Department of Energy, 1999.

Figure A3. DOD energy consumption.

4.2.1 Power Generation

On-site electricity generation at military facilities using central plants creates significant amounts of LGH that could be captured by TE devices for additional electricity generation. The current trend of privatization of facilities' utilities services will likely move back towards on-site electricity generation due to increased security and reliability concerns. From the overall energy consumption data contained in the DOD portion of the annual report to FEMP, it is estimated that the DOD consumes 130,744 billion BTUs to generate electricity. By tapping a modest three (3) % of LGH from the various methods of conventional power generation, TE devices have the potential to generate 183,865 MWh per year. At an average cost of electricity of $0.075/kW hr in the U.S., widespread utilization of TE devices applied to electricity generation equipment could save over $14 million per year.

4.2.1.1 Steam Cycle

The steam cycle has long been the workhorse method for generating electricity using various forms of the

Rankine thermodynamic cycle (e.g., reheat, regeneration, supercritical). These central power plants can exceed 1,000 MWe in generating capacity. More than 50 % of the electricity generated in the U.S. in 1999 came from coal, which almost exclusively uses the steam cycle for power production (U.S. DOE-2001b).

As materials and designs for steam turbines have improved, the boiler pressure and turbine inlet temperatures have increased, thus improving the efficiency of converting the fuel energy into electricity. Even with this relentless progress, the gross efficiency of the steam cycle has only reached about 40 % (Cengel and Boles 1994).

The limitation in converting the fuel energy into electrical energy imposed by nature indicates significant quantities of energy are available, but are not easily converted into electricity. The two biggest sources of heat energy that are lost to the atmosphere from fossil fuel-driven steam cycles are the hot flue gas and the condenser.

The hot flue gas contains significant quantities of energy that could be converted into electricity with TE devices. The temperature of the gas entering the flue at 100 to 200°C (212 to 400°F, Munson 1999) would generally be high enough to approach the optimum value for electricity generation with TE devices. However, the rate of heat transfer possible in the flue may be too low to optimally drive TE devices. This type of application would be categorized as, and potentially utilized through, a low heat rate area method as discussed in Section 4.1.5. Based on the temperatures available in the flue gas, it is estimated that the electrical output of a steam power plant could be increased by two (2) % through the use of TE tiles (Munson 2000).

For those power plants requiring removal of particulates from the flue gases, electrostatic precipitators are typically employed. It may be possible to integrate TE modules into these devices. This represents an interesting opportunity since precipitators are already incorporated into power plants and require the flue gases to flow through arrays of charged parallel plates. Furthermore, precipitators are already designed to handle the temperatures that are optimal for TE device operation and operate on DC power (PPC Industries 2001), the same as generated by TE devices.

The other location in the steam cycle where energy is purposely transferred to the atmosphere is the condenser, which completes the steam cycle. Parsons (Munson 2000) indicates that possibly 20 % of the energy from the fuel in power plants is transferred to the atmosphere through the condenser. Their estimate is that the electrical power produced by a plant could be increased 17 % if this energy could be converted to electricity with TE devices integrated into a condenser heat exchanger (Munson 2000). The drawback noted in this report is that the temperature of the condensing steam is relatively low, 40°C (100°F). In general, the higher the temperature differential up to the TE material limit, the more TE power generated per area of tile. Therefore, they concluded these low temperatures in the condenser would not be cost effective in generating electricity. Furthermore, the characteristics of the TE material are such that the required volume of the condenser would be increased by five to 10 times.

Hot surfaces are another method of converting waste heat into electricity with TE devices. Parsons (Munson 2000) gives details on a specific power plant where upper enclosure areas contain steam or furnace gases ranging from 200 to 340°C (400 to 650°F) or even higher. Each of the four units at this plant has approximately 8,000 ft^2 (750 m^2) that could be made available for installation of TE tiles. At the moderate surface temperatures available on these units, the electric power generating capacity of this plant is estimated to increase by more than one (1) % of its total current output. This represents an opportunity for retrofitting many existing power plants with TE devices to increase generating capacity through an increase in efficiency, requiring no additional consumption of fuel or generation of regulated emissions.

To give some perspective on the amount of electricity that could be generated from incorporating TE devices into steam cycle power plants, the quantity of electricity generated in 1999 by utilities and nonutilities was 2,280,000 million kWh (U.S. DOE-EIA 2000c and 2000d). The potential electricity that could be generated from TE/condenser, TE/heat exchanger and hot surfaces is 388,000, 45,600, and 22,800 million kWh, respectively for a total potential additional annual generation of 456,000 million kWh from steam cycle power plants.

4.2.1.2 Gas Turbines

Another method of generating electricity is using a gas turbine operating in a simple cycle. With these systems being of relatively small size, easy to cycle on and off, and their availability off the shelf, they are sometimes used for load peaking by utilities or industrial facilities and can be installed quickly. These power plants range in capacity from approximately 30 kWe microturbines for small industrial settings to more than 100 MWe for utility electric generation facilities.

In a simple cycle gas turbine, efficiencies range from 25 to 30 % (Munson 2000). In the microturbine analyzed by Parsons, the hot exhaust contains over 60 % of the energy from the fuel and exits at approximately 270 °C (520 °F). The result of incorporating TE devices into this microturbine exhaust would give rise to a four (4) % increase in the amount of electricity generated. Exhaust temperatures for simple cycle gas turbines currently available can range from this value to approximately 600°C (1100°F, Gas Turbine World 2000). By incorporating a gas heat exchanger with integrated TE devices into these turbines, the energy of the exhaust could be converted into electricity, potentially increasing electrical output by even more than four (4) % with the higher temperature exhaust that is generally available.

Since a heat exchanger is not directly coupled to the turbine, it could be possible to retrofit integrated TE heat exchangers into existing turbine installations to increase capacity and efficiency. Analysis of the pressure drop imposed by the heat exchanger, and the effect on turbine backpressure and performance would need to be assessed, as was done by Parsons (Munson 2000).

On simple cycle gas turbines, there may also be locations with hot surfaces where TE devices can be installed and retrofit into existing facilities.

The electricity generated for simple cycle gas turbines in 1999 is 62,700 million kWh (U.S. DOE-EIA 2000c, U.S. DOE-EIA 2000d). With a four (4) % increase in generating capacity by incorporating a TE/heat exchanger into existing gas turbines, an additional 2,500 million kWh of electricity could potentially be generated annually.

4.2.1.3 Internal Combustion

Internal combustion engines, primarily Diesel engines, are used to generate electricity. Example applications of Diesel generators are for back-up power and for remote power generation. Gasoline powered, spark ignition engines are not used as often for generating electricity. However, one current DOE-National Energy Technology Laboratory project is to use 18 250 Hp, V8 engines to generate high voltage electricity from coal bed methane gas (Northwest Fuel Development, Inc. 2001). A general description of the energy generation potential from incorporating TE heat exchangers into these engines is given below.

The overall efficiency of a Diesel engine in converting the energy of the fuel into mechanical power is approximately 36 % (Munson 2001). As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using TE devices. The engine jacket rejects heat through the radiator while additional energy is available in the hot engine exhaust.

According to the Parsons (Munson 2001) report, a heat exchanger for the exhaust with integrated TE modules could generate electricity equal to approximately five (5) % of the mechanical power of the engine. This additional power would require no additional fuel consumption.

The coolant from the engine jacket can contain approximately 17 - 30 % of the energy of the fuel (Munson 2001). The coolant can range from 75°C (165°F) hot water to 120°C (250°F) steam depending on the design of the cooling system. According to this report, a diesel generator producing steam routed through a condenser with TE devices integrated could generate electricity equal to 10 % of the mechanical power of the engine. Similar to the engine exhaust TE application, this additional power would be produced from LGH that would otherwise be vented to the atmosphere and therefore, requires no additional fuel consumption for its generation.

Table A2. Efficiency improvement of fuel cells incorporating TE devices.

Fuel Cell Type	Operating Temperature	Efficiency	Percent Waste	Increase in Generation	Final Efficiency	Efficiency Improvement
Polymer Electrolyte	176ºF (80ºC)	40%	60%	9.60%	49.60%	24%
Alkaline	149-428ºF (65-220ºC)	60%	40%	6.40%	66.40%	11%
Phosphoric Acid	401ºF (205ºC)	37-42%	60%	9.60%	49.60%	24%
Molten Carbonate	1202ºF (650ºC)	45%	55%	8.80%	53.80%	20%
Solid Oxide	1112-1832ºF (600-1000ºC)	45-65%	45%	7.20%	62.20%	13%

4.2.1.4 Fuel Cells

Fuel Cells are rapidly being developed as a more efficient means of generating electricity while producing minimal regulated emissions. Many military facilities have installed fuel cells for electricity generation. There are five different varieties of fuel cells and each has different operational characteristics, including operating temperature and efficiency.

Due to the evolving nature of these devices, it is difficult to identify specific methods of using the waste heat. However, generally, there will be some exhaust from each of these at the operating temperatures listed in Table 2. Therefore, the higher temperature fuel cells approach or exceed the optimal temperature for TE device operation. Incorporation of TE devices into fuel cells could reasonably be expected to increase the efficiency by five (5) to ten (10) %. That is, for a Polymer Electrolyte Fuel Cell (PEFC) that is 40 % efficient at converting fuel energy into electricity, the incorporation of TE devices to convert the 60 % waste thermal energy could reasonably be expected to increase the overall efficiency to 49.6 % efficient. This assumes LGH energy available is converted at 16 % efficiency by the TE devices. Table 2 lists the five fuel cell types with their efficiency of converting the fuel energy into electricity, the range of operating temperatures and the possible increase in efficiency by incorporating TE devices (Fuel Cell Handbook 2000).

Though some of the higher temperature fuel cells can operate on existing fuels such as natural gas directly, some of the lower temperature fuel cells must be operated on hydrogen. Therefore, to use readily available fuels, such as gasoline or natural gas, a fuel reformer must be used to convert this fuel into the hydrogen required. These processing steps generally occur at higher temperatures than the fuel cells and may be an additional source of waste heat that could be used to generate electricity with TE devices that is close to the optimum TE operating temperature. For example, conversion of gasoline to hydrogen requires reformer temperatures in excess of 650°C (1200°F, Fuel Cell Handbook 2000).

One specific application of TE devices with fuel cells that has been analyzed is a hybridized fuel cell/gas turbine system (Munson 2001). The conclusion was that adding a TE heat exchanger to this optimized system would not be effective since the addition of the TE heat exchanger negatively affects the performance of the turbine. However, the efficiency of using a gas turbine to extract additional energy from the hot fuel cell exhaust could be compared to the efficiency of using TE devices instead. The true comparison of the two hybridized systems, fuel cell/gas turbine and fuel cell/TE, will need to be compared on the basis of life-cycle costs.

4.2.1.5 Waste-to-Energy

One of the methods used to dispose of the municipal solid waste (MSW) produced in the United States is combustion. Approximately 33.5 million tons, or 16 % of the MSW stream, was disposed of in this manner in 1995 (U.S. EPA 1997). Facilities where energy recovery occurs, generally producing steam or electricity, are classified as waste-to-energy (WTE) combustion facilities. All facilities where MSW is burned are potential candidates for generating electricity with TE devices.

For the WTE facilities with steam production for process purposes or generating electricity with a steam cycle, the same applications for generating TE electricity could be used as discussed in section 4.2.1.1 for steam cycle fossil energy power plants. These applications include flue gas, electrostatic precipitator, condenser, and hot surfaces.

Those plants that do not currently incorporate energy recovery capability would lend themselves to generating a greater amount of electricity through the hot flue gases than those that have energy recovery already incorporated into the combustion equipment alone. Other locations where TE devices could be incorporated to generate electricity are hot surfaces of equipment and electrostatic precipitators.

For the destruction of hazardous waste materials, incineration is one method of disposal. Though some hazardous waste materials are disposed of through industrial kilns such as cement and lightweight aggregate kilns, some waste is burned in dedicated hazardous waste incinerators (U.S. EPA 2001). These facilities represent additional sites where TE devices could be incorporated to generate electricity from waste heat. Specific applications include flue gases, hot surfaces, and electrostatic precipitators.

4.2.1.6 Solar

The solar energy reaching the earth is tremendous in its quantity; to serve the entire electric needs of the U.S., a site 100 miles on a side is all that would be required. However, only in certain locations such as the Southwest United States, is sunshine reliable enough to be attractive (U.S. DOE 2001a). In 1999, 320 million kWh were generated using solar thermal methods (U.S. DOE-EIA 2000c, U.S. DOE-EIA 2000d). For solar thermal electricity generation, several methods are used to concentrate the solar energy to boil water, or heat oil or other fluid that is later used to make steam, which is then used to run a conventional steam cycle (U.S. DOE 2001a).

The locations in the steam cycle that are available to incorporate TE devices are similar to those listed in section 4.2.1 for fossil fuel-based steam cycles. The obvious exception for solar is the lack of exhaust gases and electrostatic precipitator. Therefore, the primary locations would be in the condenser and other hot surfaces. For example, incorporating TE devices into condensers could potentially generate an additional 50 million kWh annually from the 320 million kWh of solar thermal electricity generated in 1999 (U.S. DOE-EIA 2000c, U.S. DOE-EIA 2000d) based on increasing the power generated by the 16 % as discussed in Parsons (Munson 2000).

One particular solar thermal method, power tower systems, can generate about 10 MW of power and have thermal storage capability to generate electricity at night (U.S. DOE 2001a). These facilities may be particularly attractive for incorporating TE devices. This method concentrates the sun's energy with thousands of mirrors onto a receiver, heating a molten salt to temperatures of 1050°F (565°C) from its "cold" storage tank at 550°F (290°C, U.S. DOE 2001a). These temperatures are at or above the range of temperatures where TE devices operate optimally.

Besides the central and distributed power generation capability of solar power stations, TE devices can be adapted to use solar energy as a source of heat to generate small quantities of electricity in a portable or small-scale application. Such a new application is enabled by the development of efficient TE devices and run by direct solar radiation. With a small, mirrored dish concentrating the solar energy onto a small TE device located at the focal point, the temperature of the TE material could reach that for optimal generation of electricity. Such a device could be made small and lightweight for portable applications, or scaled up for larger applications.

4.2.2 Heating, Ventilation and Space Conditioning

Of the 217,958 BBTU used by the DOD in facility operations in 1999, approximately 40 % was consumed in some form of heating, ventilation or space conditioning process (FEMP 2001). Assuming a modest five (5) % capture of LGH from these processes and 16 % TE device efficiency, TE devices could generate 163,436 MW/yr. Location of TE devices would be similar to steam-cycle electricity generation, including hot piping, boilers, and condensers. Electrical transformers are also potential candidates for TE application. For large transformers, these enclosures can reach temperatures of over 200° F without space conditioning. TE devices could reduce the need for cooling these enclosures and increase the efficiency of the transformers.

4.2.3 Industrial Processes

To support the DOD's mission, its industrial facilities contain multiple types of energy-intensive processes. These processes include curing, drying, fluid heating, metal heating and metal melting. In 1999, the DOD consumed 32,910 billion BTUs in its industrial processes (FEMP, 2001). The DOD does not aggregate its industrial energy consumption data by process type, but by assuming a five (5) % heat capture from these processes and 16 % TE device efficiency, TE devices could generate an additional 79,400 MWh annually, saving the DOD more than $3 million per year in electricity bills.

Table A3. Estimates for potential electricity generation for DOD applications (1999).

Process	Estimated Consumption (Billion BTU)	Potential % of Consumption Available for TE Devices	Potential TE Device Electricity Generation/yr (MWh)
Electricity Generation	130,774	3	183,865
Heating Systems	87,183	4	163,436
Industrial Processes	32,910	5	79,400
Non-facility applications	162,000	5	38,000
TOTAL			464,701

4.3 Non-Facility Applications

In 1999, the DOD consumed nearly 600,000 billion BTUs of energy in vehicle and equipment operations (FEMP, 2001). Jet fuel accounted for 73 % of this total, leaving 162,000 billion BTUs that could be tapped by TE device application. Assuming that the majority of non-aviation vehicles are Diesel-powered, TE devices could generate almost 38,000 MWh of electricity for these vehicles. With a cost of approximately $1.05 per gallon of diesel fuel in 1999 (DOE OTT 2000), and a conservative estimate of a one (1) % efficiency improvement, application of TE devices to vehicles has the potential to save the DOD almost $7 million per year in fuel costs.

4.3.1 Land Vehicles

In support of its mission, the DOD uses a variety of land vehicles. Diesel engine sizes for some large trucks reach up to 450 kW (600 hp, Kenworth Truck Company 2001). The efficiency of converting the energy of the fuel into the mechanical power is approximately 36 % (Munson 2001), and two major sources of waste heat are available, hot exhaust and engine jacket coolant. These could be used to generate electricity with a heat exchanger or condenser and integrated TE modules. According to Munson (2001), the hot exhaust and the jacket coolant could generate electrical power equivalent to approximately five (5) % and ten (10) %, respectively, of the Diesel engine mechanical output. Therefore, the electrical power generation capability is 22.5 kW (30 hp) and 45 kW (60 hp) for an exhaust heat exchanger and condenser, respectively. The electrical power could be used for accessory electrical needs, or even accessory mechanical power needs such as superchargers or air conditioning driven by electrical motors that are currently being driven by mechanical take-offs from the engine directly. Engineering considerations for incorporating TE devices into locomotives include the space constraint of incorporating heat exchanger(s), the potential effect on engine back pressure and performance, and appropriate cooling of the TE module.

The situation with automobiles is similar to that described above for trucking. In this case, the engine size is significantly smaller and the potential for incorporating a heat exchanger or condenser with integrated TE devices may be even more limited, particularly generating steam in the cooling system. One difference is that spark ignition automotive engines are less efficient than diesel engines and 34 to 45 % of fuel energy is contained in the exhaust. Furthermore, with automotive engines approximately 25 - 28 % efficient at maximum power (Heywood 1988), the thermal energy in the exhaust of an automotive engine could generate electrical power of 20 - 25 % of the mechanical output of the engine. For an engine with mechanical output of 150 kW (200 hp), up to 30 kW (40 hp) of electrical power could be produced. Similar to the trucking applications, the electrical power could be used for accessory electrical needs, or even accessory mechanical power needs. For example, air conditioning could be driven by electrical motors instead of being driven by mechanical take-offs from the engine directly as is currently the case.

4.3.2 Ships

In the U.S. Navy, the sources of motive power include gas turbines, diesel engines, steam power and nuclear (U.S. Navy 2001c, 2001d, 2001e, 2001f and 2001g). The first three sources burn fossil fuels and therefore, have stacks emitting hot exhaust gases as one location that could be tapped with gas heat exchangers and integrated TE devices. In this and other locations on vessels, the additional electrical power from the TE devices could be used to provide some fraction of the on-board electrical needs. To the extent that this electrical power replaces power normally supplied by shipboard engines and generators, the size of these engines and generators could be decreased or the total power capacity of the power plant is simply increased. Furthermore, since some of the electrical power would be generated from LGH that is otherwise vented out the stack, the fuel requirements could be decreased, thus increasing the range of the existing fuel stores. Specific examples of gas turbine and Diesel powered ships are provided.

Gas Turbine: The marine gas turbine power plant, LM2500, provides the power for Destroyers (DD, DDG), Frigates (FFG) and Cruisers (CG). These ships have four, two, and four LM2500's on each ship, respectively. With approximately 110 ships of these classes in operation, and nearly 400 turbines total (U.S. Navy 2001d, 2001e and 2001f), this represents an opportunity to develop a system to improve several classes of ships with one development program.

According to Parsons (Munson 2000), converting the energy of the exhaust of a microturbine into electricity with a TE device would increase the power produced by four (4) %. With full power output of an LM2500 at approximately 25 MWe (33,000 hp, Gas Turbine World 2000), nearly one (1) MWe of additional power capacity could be generated by an integrated TE heat exchanger at full engine power. With a full power exhaust temperature reported for the LM 2500 at approximately 550°C (1030°F), the potential exists to generate nearly 4 MWe of additional electrical power from the exhaust flow of this engine. This represents nearly a 16 % increase in the mechanical power of the engine itself.

Diesel: Thirteen Patrol Coastal (PC) ships in the U.S. Navy fleet have four Diesel engines on board, each rated at 2.5 MWe (3350 horsepower, U.S.

Navy 2001g). The overall efficiency of a Diesel engine in converting the energy of the fuel into mechanical power is approximately 36 % (Parsons 2001). As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using TE devices. The engine jacket rejects heat through the radiator while additional energy is available in the hot engine exhaust.

According to Parsons (Munson 2001), a heat exchanger for the exhaust with integrated TE modules could generate electricity equal to approximately five (5) % of the mechanical power of the engine. Therefore, on this basis, each of the four (4) diesel engines aboard each PC could generate approximately 125 kWe of electrical power for on-board use with no additional fuel consumption.

The coolant from the engine jacket can contain approximately 17 - 30 % of the energy of the fuel (Munson 2001). The coolant can range from 165°F (75°C) hot water to 250°F (120°C) steam depending on the design of the cooling system. According to Parsons (Munson 2001), a diesel generator producing steam routed through a condenser with TE devices integrated could generate electricity equal to 10 % of the mechanical power of the engine. On this basis, the total power produced from this method from the four engines on-board a single PC ship would be approximately one (1) MWe of power. As above, this additional power would be produced from LGH that would otherwise be vented to the atmosphere and require no additional fuel consumption for its generation.

Future ships: The U.S. Navy has a program, the Integrated Power Systems Program, to develop the systems and components to move shipboard electric power and electric propulsion power systems towards a "more electric ship" concept (U.S. Navy 2001b). One aspect of this system is that it would use DC distribution (U.S. Navy 2001a). Thermoelectric devices generate high quality DC electricity from waste heat sources.

4.3.3 Support Equipment

Aside from ships and land vehicles, the DOD uses numerous types of equipment in support of field operations. Two pieces of field equipment, portable generators and radar systems, would be particularly well-suited to TE integration.

Portable generators, such as the Army's Tactical Quiet Generator (TQG) provide lightweight, efficient and survivable electric power generation for field units. TQGs range from 5kW to 200 kW and produce LGH analogous to the fixed diesel generators mentioned above (U.S. Army 1999). In addition to the increased fuel economy that installation of TE devices would provide to TQGs, the heat signature from the generators would also be reduced, improving battlefield survivability.

Application of TE devices to portable radar equipment would also produce similar benefits. Many larger, truck-based sensor systems require a separate cooling system for the transmitter element (FAS 2002). Application of TE devices to the transmitter elements of these systems would reduce or even eliminate cooling requirements, increasing the efficiency of the equipment. As well, the heat signature of the radar would be reduced, enhancing survivability.

Some field applications where electricity is required may also require a highly reliable, lightweight, low noise source such as a small catalytic combustor burning available fuels (i.e., propane, diesel) that could provide the heat source for a TE device.

For example, to generate 100 W of DC electricity, approximately 100 cm^2 (0.1 ft^2) of TE module would be required. Using inlet and exit temperatures of the hot gas near the optimum for the TE device, approximately 45 g (1.6 oz) of propane fuel would be required to operate at this power level for one hour (Peterson, 2001).

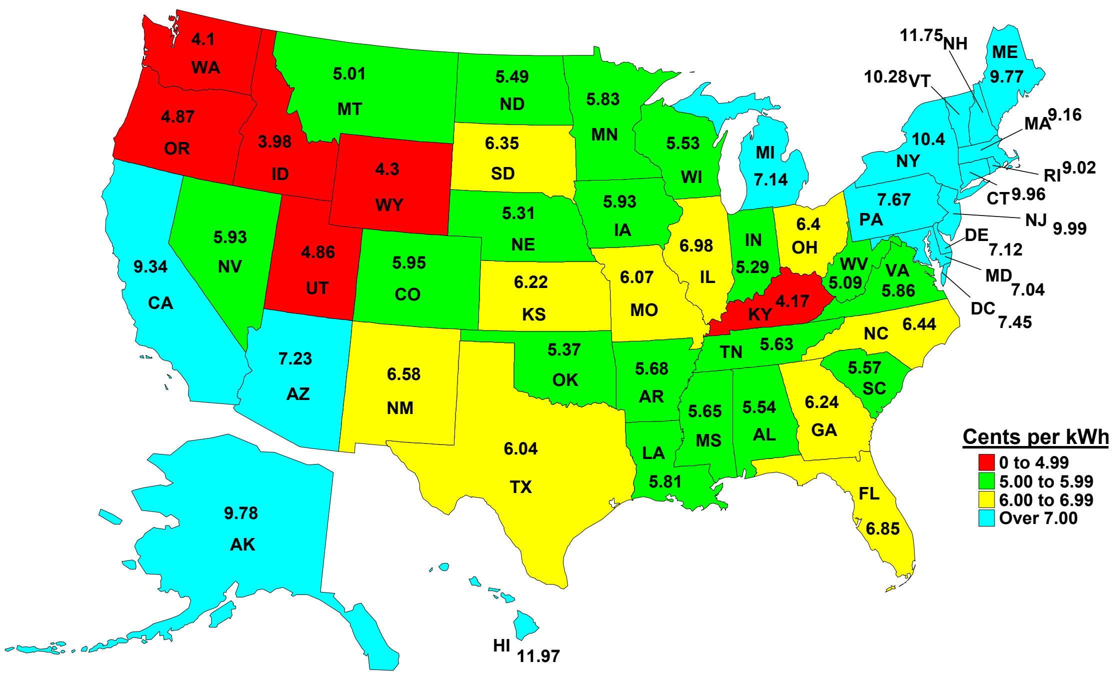


Figure A4. Average retail electricity price in 1999 for all sectors.

4.4 General Application Summary

Based on available data for energy consumption by the industry, it is estimated that potential electricity generation by use of an efficient TE device when paired with DOD applications is approximately 464,000 MWh of electricity per year. The estimate accounts for LGH generated from facility and non-facility applications. An average electric generation efficiency or conversion efficiency of 16 % paired with a percentage of recoverable LGH appropriate for the process was used for these estimates.

4.5 Economic Considerations

Use of a low temperature heat recovery device to produce electricity provides an attractive economic opportunity for the DOD in saving cost of electric power for both facility and non-facility applications. Based on the most current data available for the year 1999, cost (kWh) of electricity across the USA is shown in Figure 5 (U.S. DOE-EIA 2000). The cost varies from a low value of approximately five (5) cents/kWh in the Northwest states where hydroelectric power is the primary source to as high as twelve (12) cents/kWh in the Northeast-New England states. For the most industrialized states in the Midwest and Southwest, the cost is in the range of six (6) to seven (7) cents/kWh. Not reflected in this map are the results of deregulation, which has led to increased prices for electricity in some areas such as California to greater than 13 cents/kWh (California Energy Commission 2001).

We have seen substantial increase in energy prices including the price of electricity and based on this general trend, an average avoided cost for electricity of 7.5 cents/kWh has been used for calculations of the potential cost savings. Table 1 (Page 1) shows potential electricity generation of 464,000 MWh through the use of TE devices for waste heat recovery. Based on avoided cost of 7.5 cents/kWh, the estimated savings are greater than $34.5 million per year. This cost savings will continue to benefit the user for the entire life of the device. No additional cost of fuel or major operating and maintenance expenses, that are commonly required for electricity generation, transmission and distribution for a power supply company, will be incurred by the end user. Assuming that the life of TE devices is 10 years and electricity price increases at a rate of three (3) % per year, the expected future value of avoided cost for electricity in military facility and non-facility applications is estimated at $402 million. Other directives and incentives for the utilization of TE devices are described in the section below

4.5.1 Privatization

DOD Reform Initiative Directive No. 9 states that all military departments are to develop a plan for privatizing all reasonable utility systems by September 30, 2003 (DOD, 1998). Privatization allows facility commanders to focus on core defense missions by relieving them of the burden of maintaining and upgrading on-site utility equipment. It is expected that, by privatization, the role of facility commanders will shift from owner/operator to that of a smart utility service customer. TE devices will provide facility commanders another tool to assist them in making the most intelligent energy consumption choices.

4.5.2 ESPCs, UESCs & DSMs

In spite of the long-term financial and environmental benefits of TE devices, many base commanders may not have discretionary funds to finance the installation and operation of the devices at their base. Multiple options, however, are available to finance energy-efficient improvements.

Energy Saving Performance Contracts (ESPCs) are sponsored by FEMP and enable Federal agencies to improve the energy efficiency of their facilities through upgrades without requiring Federal appropriations for incurred capital costs. Through an ESPC, an energy service company (ESCO) arranges financing to develop and install energy conservation measures (ECMs). The ESCO guarantees that the improvements will result in a specified level of annual savings to the Federal customer, and that these savings will be sufficient to pay the ESCO over the life of the contract. After the contract ends, all additional cost savings accrue to the federal agency.

Utility Energy Service Contracts (UESCs) are similar to ESPCs**,** except that the utility company providing service to the Federal facility assumes the role of the ESCO.

Demand Side Management (DSM) programs are utility company incentives offered to customers for reducing energy consumption and demand. DSMs allow utilities to obtain additional capacity with a definite capital investment. Rebates, energy surveys or rate reductions are typical incentives offered to the customers to encourage the installation of energy efficient equipment. Unlike ESPCs and UESCs, however, DSMs do involve cost-sharing of the improvements by the facility.

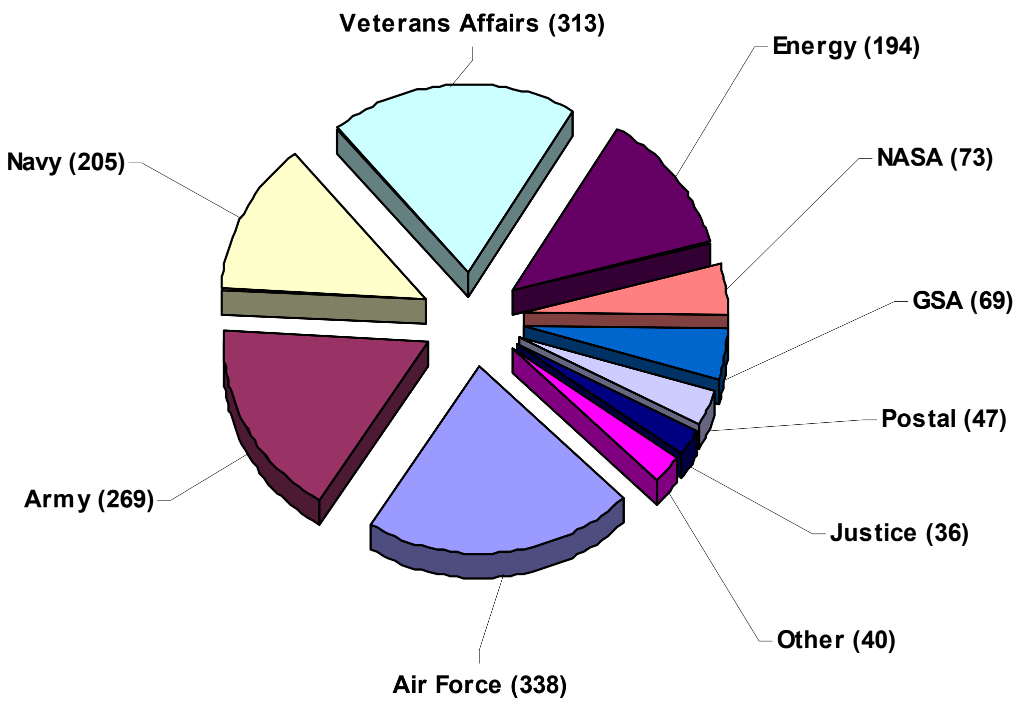


Figure A5. Potential CHP capacity (MWe) for major Federal Agencies (FEMP 2002b)

Utilization of ESPCs, UESCs and DSMs are potential methods to integrate TE devices for military facility applications. The ESCO would have to propose TE use as an ECM in its proposal.

4.5.3 Combined Heat and Power

FEMP also sponsors a program to promote the use of Combined Heat and Power (CHP) at federal facilities as a Distributed Energy Resource (DER). CHP is the sequential production of two forms of useful energy—typically electricity and heat—from a single fuel source, similar to cogeneration. It offers extraordinary benefits in terms of energy efficiencies and emissions reductions by optimizing the use of LGH that would otherwise be wasted when generating power. Where facilities cannot privatize their electrical generation equipment, TE devices could allow facility commanders to take advantage of the unique benefits offered by CHP.

The utilization of CHP to replace central power generation, which is common at several military facilities, can reduce carbon emissions by up to 30 % (FEMP 2002a). The use of TE devices as a form of CHP helps to remove two common barriers for CHP implementation: the integration of TE devices does not require a large capital investment common to many CHP systems; and integration of TE devices does not have the complexity common to many CHP systems.

FEMP developed a market assessment for the potential implementation of CHP applications at Federal facilities (FEMP 2002b). Of the potential 1584 MWe CHP capacity for all Federal agencies, 812 MWe (51 %) can be attributed to military facilities (See Figure 6).

4.5.4 Supply Integrity

Due to the increased threat level to military facilities and civilian infrastructure, it becomes imperative that those facilities that generate their own power or those that have back-up generators in the event of blackouts have reliable, efficient and ample power generation available. TE devices have significantly lower installation costs and lower maintenance requirements than other replacement equipment. TE devices offer facility commanders the ability to cost effectively increase their normal or emergency electricity generation capacity. This allows facilities to more effectively perform their functions in the event of a nearby attack or catastrophe, including consideration of Homeland Security issues.

4.5.5 Environmental Benefits

DOD Instruction Number 4715.4 states that it is the policy of the Department to reduce pollution through improvements in energy efficiency and activities that improve resource utilization (DOD, 1996). Widespread use of TE devices in both facility and non-facility applications would greatly contribute to compliance with this policy.

4.6 Engineering Considerations

Successful integration of TE devices into military applications requires some portion of an engineering investigation. Each application has unique design and implementation requirements. These requirements will affect individual installation costs and must obviously be considered prior to integration of the TE devices. Some general considerations that apply to all applications are as follows:

- Capturing the waste heat energy and transferring it to the TE Device
- Providing a source to cool the opposite side of the TE Device
- Ensuring the heat recovery surface for the TE materials is within acceptable temperatures
- Reviewing the structural concerns for the Application
- Coupling the electrical energy to a DC or AC power system.

4.6.1 Capturing Waste Heat

Hot surfaces and flue gases are the primary sources of LGH in the applications being considered. A methodology that can effectively transfer heat from the LGH source through the TE device is highly application dependent. LGH source material, shape, insulation requirements and available space surrounding the source must be carefully considered when designing a heat transfer method. Multiple styles of heat exchangers are available and custom systems, although costly, may be required as well to obtain maximum heat transfer. Insulation of the integrated TE devices must also be considered, to increase the efficient capture of thermal energy and direct it through the TE device(s).

There are certainly other approaches that should be considered in developing a detailed design for capturing the energy content of the waste heat and converting it into electricity with TE devices. Some alternate approaches could include:

- Large surface area insert(s)
- Moldable inner surface of a flue gas stack
- Tubular shape(s) that can be used as a gas-liquid or gas-gas heat exchanger.

4.6.2 Cooling the TE Device

A method of cooling must be utilized to provide the necessary temperature differential for TE device electrical energy generation. Some applications may be located in a system or facility having a chilled water supply. After minimal engineering effort, and verification of chiller system capacity, the TE devices could be integrated into the existing system. Otherwise, a dedicated cooling method will be required. The cooling system capacity is dependent on the quantity of TE devices utilized, ambient air temperatures, and the source of waste heat. The utility cost of operating the cooling system is also a consideration in the system economic analysis.

4.6.3 Operating Temperatures

Another factor that must be incorporated into the TE device integration design is the temperature limits of the TE materials. Currently, the maximum temperature the TE materials will operate at is 300 °C (572 °F). There are several approaches to ensuring that the TE material does not exceed its temperature limit. The first is to reduce the waste heat temperature with a tempering heat exchanger located prior to the waste heat source entering the TE heat exchanger. This initial heat exchanger can be controlled so as to maintain an inlet temperature within the TE material limits at all times.

A second approach, utilizing flue gases as an example, is to dilute the hot flue gases to lower the temperature to within the TE material limits using a process slipstream. This dilution could be with ambient air, with recirculated flue gases that have already been cooled or even with a water spray. If dilution is the approach taken, it is simple to implement and dilution with the smallest addition to the mass flow would be desirable, while considering the cost of implementation.

The third approach to maintaining the TE materials within limits is to incorporate some thickness of insulation between the hot LGH source and the TE device. This insulation will be greatest at the entrance and taper to no insulation when the flue gas temperature reaches tolerable limits. This option may be the most expensive due to the unique design dependent on the inlet temperature and flow. Although with a modular design, flexibility could be gained.

These considerations will depend on the thermal resistances between the bulk flue gas and the cooling side of the TE device and will require more detailed engineering investigation than is provided within this report. Of course, the optimum solution may be one that incorporates some or all of the above approaches.

4.6.4 Structural Concerns

Any modification to an existing LGH application will require investigation into structural capabilities of the installation. The TE device(s), electrical interconnects, electrical monitoring systems, cooling system, plumbing, mounting assemblies and insulation weights must be factored into the system design and integration.

4.6.5 Electrical Energy Distribution

The TE device generates DC electrical energy. This energy generation is directly proportional to the temperature differential across the TE materials. If an application's temperature cycles from hot to cold through a given time period, the voltage available will increase and decrease proportionally. A method of maintaining a regulated DC or inverting and supplying AC to a distribution system will be necessary. These methods all effect the overall efficiency of the system, but most power conditioning systems are approximately 90 % efficient. Appropriately sized DC-DC converters are readily available. AC inverters are also available but may also require a DC-DC converter to maintain a consistent input voltage. In some instances a system of DC-DC converters, batteries, and an inverter may be required. Photovoltaic power systems are commonly configured this way so that when interruptions in power generation occur, the system still maintains a source of electrical energy for a period of time.

The utilization of DC or AC power is dependent on application requirements. If a need exists for a DC energy source, this is the most efficient and least costly to implement. The integration of a system to supply AC power into the utility grid would be the least efficient and most costly to implement, and would require significant engineering.

4.6.6 Other Considerations

As a result of the interrelationship of these engineering and economic factors, the ideal situation is when the entire waste heat available is transferred through the TE device at its maximum performance temperature. This will produce the most electrical energy per unit area (and per unit cost).

In implementing TE devices on or into a LGH system, one must take into consideration operational characteristics of the LGH system. For an example such as an exhaust stack, the proper dispersal of the exhaust gases must be considered. The elevated temperature of the exhaust gases creates a draft that may be used to exhaust the flow, as well as draw the combustion air into the furnace. Lowering the flue gas temperature reduces this draft and incorporating a heat exchanger could increase the pressure drop to the point where a fan must be added to induce the proper flow. Furthermore, dispersal of the exhaust gases into the atmosphere is related to the gas temperature with dispersal enhanced as the gas temperature rises.

For exhaust stacks, depending on the degree of air-dilution requirements that will increase total gas volume and stack dimensions (height and diameter), it may be necessary to use a higher capacity internal draft fan to avoid pressurizing the heating elements, due to additional pressure drop resulting from the presence of the TE device.

These design considerations are imperative to the engineering evaluation that should be performed before any implementation of the TE Devices. Often simple heat transfer and flow calculations will determine how a TE Device installation may be integrated into a facility LGH process.

4.6.7 TE Device Design Specifications

Design specifications for the 12-inch square TE device, as currently configured, are listed below:

- Water flow through cooling tank = 0.6 to 1 L/minute
- Water Pressure < 10 psi
- Current Output ~ 1-10 Amps Maximum
- Voltage Output ~ 8-80 VDC
- Power Output ~ 8-800 Watts
- Down Pressure ~ 40 lb (Pressing Device onto heat source)
- Minimum Temperature Differential (ΔT) = 100°C (212°F, Hot Side Temperature - Cold Side Temperature.)
- Maximum Hot Side Temperature = 300°C (572°F)
- Optimum Temperature Differential (ΔT) - TBD (~ 200°C to 280°C [392°F to 536°F])
- Approximate weight (with empty cooling tank): 13 lb.

4.7 Specific Applications

A list of 43 specific facility and non-facility applications were identified through interviews as well as literature and Internet reviews. Specific applications are documented in Annex A. A breakdown of the total number of applications by type is listed below:

- Facility (28)
  - Electrical Energy Generation
  - HVAC
  - Industrial Processes
- Non-Facility (15)
  - Vehicles
  - Ships
  - Support Equipment

5 APPLICATION RANKING

Specific applications for the TE devices were identified during the course of this study. For each application, there may be many locations for TE installation. These applications were identified through interviews as well as literature and Internet reviews. In order to evaluate the most promising alternatives for application of TE devices, several criteria were developed to allow consensus ranking of the possibilities. Below are detailed descriptions of the technical evaluation criteria and definitions of the ratings for each criterion.

5.1 Ranking Criteria

The ranking criteria were developed specific to application of TE devices for DOD installations and are useful as a tool for selection of the best alternatives. Five (5) criteria were developed to select the best applications: 1) quality of LGH, 2) quantity of LGH, 3) effects on process performance and energy use, 4) process equipment application issues, and 5) expected benefit of power generated. A detailed explanation of each criterion follows.

5.1.1 Quality of LGH

An important factor to consider for application of the TE device is the quality of LGH. One very specific consideration is whether the temperature varies. This will affect the ability of the overall system to deliver a constant output of electricity.

It is important to determine the medium representing the LGH (i.e. gas, liquid, solid, etc.). Some streams, as mentioned earlier, are more amenable to utilization of the TE device. One must consider any deleterious affects that could be caused by the medium. These concerns include reactivity of gases, which may include corrosivity, oxidizing/reducing environments, etc. Also, the presence of particulates such as soot, oxides, dust or insulation could hinder TE device applications.

The presence of condensable vapors could potentially affect the TE surface performance and there may be other physical/chemical properties of the LGH medium that could alter system performance.

Additionally**,** a determination must be made concerning the available pressure in a flue gas stream and whether it is sufficient to allow for any additional pressure that may be caused due to application of the TE device (i.e. placement of the device in gas stacks).

5.1.2 Quantity of LGH

Obviously, the TE device will not be effective if the flow of the LGH stream is insufficient to produce electricity in a cost-effective manner. The available energy content (Btu/hr) is based on the ambient temperature discharge of the LGH stream. Higher temperatures can be accommodated through engineering controls (i.e. use of diluted slip-streams), but lack of sufficient temperature for the medium (about 350°F to 600°F) will not allow optimum performance of the TE device. A secondary consideration is the latent heat of the vapor component, if present.

It is important to determine the availability of the LGH stream. Does it vary with time (i.e. a continuous or batch process)? Continuous streams that will allow the TE device to provide a constant load of electricity are preferred. If the LGH stream is variable, it should be predictable and regular.

5.1.3 Effects on Process Performance and Energy Use

The TE device will be ineffective if it hinders equipment performance, survivability or military readiness. Engineering consideration must be given to requirements of the TE devices to use additional power or other type of energy for cooling the cold side of the device. Cooling may be provided by on-site chillers, cooling towers or river water. Availability and proximity will affect cost effectiveness.

A major consideration when extracting heat from a process stack is determination of any detrimental effects on air permits. This is particularly true if the TE device application affects the buoyancy of a stack plume and thus air dispersion. Additionally, if the LGH stream contains contaminants such as sulfur, lowering the temperature below the dew point may result in production of acid mist.

One must also consider whether a pressure drop (backpressure) will have any detrimental affect on the process performance (i.e. production rate—power production, derating of the heating equipment burners or furnaces, pressurizing of the furnace and resultant hot gas leakage).

5.1.4 Process Equipment Application Issues

Process equipment application issues are important in engineering a TE system in any facility or non-facility setting. A poorly planned system could interfere with normal operations and thus offset any advantage gained through application of the technology. There must be a reasonable amount of space for TE device installation/mounting. Additionally, the DC power may require an inverter to supply plant AC electricity requirements, thus adding to installation costs. Typically, these issues can be satisfied through engineering controls.

Issues may include collection of heat from the point of availability or proximity to an adequate cooling water supply for the TE device cold junction. Other issues may be related to installation location (i.e. mounting on duct walls, need for extra surface area for the TE device to capture a reasonable fraction of the heat, need for a heat exchanger, etc.).

5.1.5 Expected Benefit of Power Generated

Application of the TE device will be much more valuable if the plant or process has need for and use of DC power. Typical plant applications include electronic controls, programmable logic controllers (PLCs), bar code readers, fans and overhead cranes.

In the demonstration phase, the willingness and cooperation of the host site during the test/demonstration period will be critical in obtaining defensible test data.

- Ultimately, expectations of the facility commander or equipment owner may be:
- Reduced cost to generate electricity
- Ability to peak shave existing power requirements
- Ability to sell power back to the grid
- Ability to provide an uninterruptible power supply
- Production of power with a low heat signature
- Improvement of battlespace survivability
- The enabling ability to provide electricity in remote areas
- Self sufficiency in the area of power production

5.2 Application of Criteria

In order to satisfy ranking of alternatives, the individual criteria were given a weighting factor according to overall importance. The following weights were applied for ranking technologies:

- Quality of LGH (15 %)
- Quantity of LGH (25 %)

- Effects on Process Performance and Energy Use (20 %)
- Process Equipment Application Issues (10 %)
- Expected Benefit of Power Generated (30 %)

For each evaluation criterion, technology applications were ranked using a 100 point scale. Each criteria score was then weighted according to its importance and a composite score for each application was calculated. The composite score of multiple reviewers was averaged to obtain the final score on a 100 point scale.

5.3 Ranking Results

Table 4 provides a summary of ranking results for processes for the DOD applications. Detailed ranking results are contained in Annex B. TE devices have the potential to produce approximately 464,000 MWh of electricity annually from military facility and non-facility applications.

Table A4. Criteria Scoring for Facility and Non-Facility Applications

Ranking Based on Criteria	Average Score	Area of Application	Potential Electricity Generation/yr (MWh)	Number of Applications
1	70.5	Non- facility, Ships	17,000	4
2	64.2	Facilities, Industrial Processes	79,400	6
3	61.2	Facilities, Electricity Generation	183,865	20
4	61.1	Facilities, HVAC	163,436	2
5	58.0	Non-facility, other	N/A	2
6	49.8	Non- facility, vehicles	18,000	3
7	44.7	Non-facility, support equipment	3,000	6
Total			464,701	43

6 CONCLUSIONS

More than 40 specific applications for TE devices were identified in this study. A key advantage when applying TE devices to facility and non-facility applications is the fact that the devices can be mounted on hot surfaces, in hot gas streams, along processes to absorb radiant heat, or they can be integrated in stacks or process insulation. This versatility allows the thermoelectric systems to be integrated within industrial processes while causing minimal impacts on the process.

It was shown in Table 1 (Page 1) that TE devices have the potential to generate 464,000 MWh of electricity each year when applied to LGH generated from military processes. This translates annually to greater than $34.5 million cost avoidance for the production of electricity and results in approximately 1.5 billion BTUs of energy production from normally discarded LGH. Additionally, this equates to 268,000 barrels of oil equivalent annually. The potential production of 460,000 MWh of electricity each year is equivalent to generation capacity of about 53 MWe at 100 % utilization.

Additionally, the TE device is environmentally benign and the TE device itself requires no fuel for the production of electricity. The carbon emission factor (CEF) for combustion of natural gas is 14.47 kg of carbon per million BTU (U.S. DOE-EIA 2000e). The CEF for combustion of coal is about 25.7 kg of carbon per million BTU. Taking an average for the range of fuels considered in this report, the CEF for fuels supplied to power generation, as well as cogeneration, is about 20 kg of carbon per million BTU. Using this number, the carbon emission savings per year would be approximately 21,000 metric tons.

Based on the results of this study, it is recommended that further work be conducted to identify and evaluate the potential of TE devices through field-scale demonstrations at military facility and non-facility applications. This work would lead to refined estimates of cost for TE device application and allow the calculation of cost/benefit and return on investment. Demonstrations would also allow the collection of defensible data necessary to penetrate the market with the technology.

Bibliography

Cengel, Y.A. and Boles, M.A., *Thermodynamics: An Engineering Approach*, Second Edition, New York, McGraw-Hill, Inc., 1994.

Concurrent Technologies (*CTC*) & Leonardo Technologies, Inc. (LTI),. 2001a, *Evaluate & Demonstrate Broad Applications for Thermoelectric Devices for DOE's Office of Industrial Technologies.*

CTC & LTI. 2001b, *Evaluate & Demonstrate Broad Applications for Thermoelectric Devices for DOE's Office of Fossil Energy*.

Defense Science Board Task Force, 2001, *More Capable Warfighting Through Reduced Fuel Burden*, Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, Washington, D.C.

Federal Energy Management Program, 2002a, *FEMP CHP Program Overview* fact sheet, ORNL 2002-01949a/rra, Retrieved January 14, 2003 from the World Wide Web: http://www.eren.doe.gov/femp/techassist/pdf/chp_prog_overvw.pdf.

Federal Energy Management Program, 2002b, CHP Potential at Federal Sites, Retrieved January 14, 2003 from the World Wide Web: http://www.eren.doe.gov/femp/techassist/pdf/federal_chp_mkt_assmt.pdf.

Federation of American Scientists (FAS). 2002, *US Land Warfare Systems*, Retrieved October 22, 2002 from the World Wide Web: http://www.fas.org/man/dod-101/sys/land/index.html.

Federal Energy Technology Center, 1999, *Vision 21 Program Plan*, Pittsburgh, Pennsylvania.

Gas Turbine World, 2000, *2000-01 Performance Specs: Performance Rating of Gas Turbine Power Plants for Project Planning, Engineering, Design & Procurement,* Volume 20.

General Electric Transportation Systems, *Locomotive Specifications*, Retrieved October 1, 2001 from the World Wide Web: http://www.getransportation.com/general/apps/freight_rail/reference/specs/specs.htm.

Heywood, J. B. 1988. *Internal Combustion Engine Fundamentals*, New York: McGraw-Hill, Inc.

Kenworth Truck Company, *T2000: A Revolution in Aerodynamics and Comfort*, Retrieved October 5, 2001 from the World Wide Web: http://www.kenworth.com/2100_vir_t2000.asp.

Marine Corps Base Quantico (MCBQ), 1999, Unified Cost Accounting Report.

Munson, C. L., 2000, *Assessment of Efficiency Increases and Economics of Application of Thermoelectric Apparatus in Fossil Power Plants*, Prepared for the United States Department of Energy, Office of Fossil Energy, Contract No. DE-AM01-98FE65271, Task DE-AT01-98FE65489, TD No. 15, Parsons.

Munson, C. L., 2001, *Optimization and Efficiency Improvements for Hybridized Fuel Cell/Gas Turbine Systems Through Use of Thermoelectric Apparatus*, Prepared for the United States Department of Energy, Office of Fossil Energy, DOE Contract No. DE-AM01-98FE65271, Task DE-AT01-98FE65489, TD No. 22. Parsons.

Munson, C. L., R. H. Gentile and C. Cassarino, 1999, *Study of Advanced Ideas on the Seebeck Effect in Semiconductors and Use of Thermoelectric Apparatus to Enhance Fossil Power Plant Efficiency*, Prepared for the United States Department of Energy, Office of Fossil Energy, Contract No. DE-AM01-98FE65271, Task DE-AT01-98FE65489, Parsons and Leonardo Technologies, Inc.

Northwest Fuel Development, Inc. 2001, *Integrated Power Generation System for Coal Mine Waste Methane Utilization: Preliminary Final Detailed Design and Operational Test Plan*, DOE Contract DE-FC26-01NT40980, Lake Oswego, Oregon.

Peterson, Richard, 2001, *Advanced Energy Systems: Small Packages,* Mechanical Engineering Magazine, American Society of Mechanical Engineers, July 2001.

PPC Industries, *Controlling Stack Emissions in the Wood Products Industry*, Gerry Graham, Retrieved August 9, 2001 from the World Wide Web: http://www.ppcesp.com/ppcart.html.

Portsmouth Naval Shipyard (PNSY), 1999, Unified Cost Accounting Report.

U.S. Army, 1999, *Weapons Systems Handbook*, OASA (RDA), 103 Army. Washington, DC.

U.S. Army Corp of Engineers (USACE), Engineer Research and Development Center, 1999, *Process Energy and Pollution Reduction (PEPR) Level I Review at the Watervliet Arsenal, New York,* TR99/92.

U.S. Department of Defense, 1996, *Instruction No. 4715.4 – Pollution Prevention*, Retrieved September 12, 2002 from the World Wide Web: http://www.denix.osd.mil/denix/public/ES-Programs/Pollution/Instruction/note1.html.

U.S. Department of Defense, 1997, *Department of Defense Reform Initiative Directive No. 49-Privatizing Utility Systems*, Retrieved August 9, 2002 from the World Wide Web: http://www.defenselink.mil/dodreform/drids/drid49.html.

U.S. Department of Energy, 2000, *Fuel Cell Handbook, Fifth Edition*, DOE/NETL-2000/1110, Morgantown, WV: National Energy Technology Laboratory.

U.S. Department of Energy, 2001a, *Concentrating Solar Power: CSP Technologies Overview*, Retrieved July 25, 2001 from the World Wide Web: http://www.energylan.sandia.gov/sunlab/overview.html.

U.S. Department of Energy, 2001b, *Geothermal Energy Program: Direct Use of Geothermal Resources*, Retrieved July 25, 2001 from the World Wide Web: http://www.eren.doe.gov/geothermal/geodirectuse.html.

U.S. Department of Energy, 2001c, *Geothermal Energy Program: Geothermal Power Plants and Electricity Production*, Retrieved July 25, 2001 from the World Wide Web: http://www.eren.doe.gov/geothermal/geopowerplants.html.

U.S. Department of Energy, Electric Power Research Institute, 1991, *Industrial Process Integration, Project Summary Report*.

U.S. Department of Energy, Energy Information Administration, 1999, *Annual Energy Outlook 2000 with Projections to 2020*, DOE/EIA-0383(2000), Retrieved October 1, 2001 from the World Wide Web: http://www.eia.doe.gov/oiaf/archive/aeo00/.

U.S. Department of Energy, Energy Information Administration, 2000a, *Annual Electric Generator Report – Nonutility (Form EIA-860B Database)*, Retrieved November 9, 2001 from the World Wide Web: http://www.eia.doe.gov/cneaf/electricity/page/eia860b.html (last updated June 14, 2001).

U.S. Department of Energy, Energy Information Administration, 2000b*, Annual Electric Generator Report – Utility (Form EIA-860A Database)*, Retrieved November 9, 2001 from the World Wide Web: http://www.eia.doe.gov/cneaf/electricity/page/eia860a.html (last updated July 12, 2001).

U.S. Department of Energy, Energy Information Administration, 2000c*, Form EIA-906a Database, Monthly Nonutility Power Plant Data*, Retrieved November 9, 2001 from the World Wide Web: http://www.eia.doe.gov/cneaf/electricity/page/eia906nonu.html (last updated October 30, 2001).

U.S. Department of Energy, Energy Information Administration, 2000d*, Form EIA-906a Database, Monthly Utility Power Plant Database*, Retrieved November 9, 2001 from the World Wide Web: http://www.eia.doe.gov/cneaf/electricity/page/eia906u.html (last updated November 5, 2001).

U.S. Department of Energy, Energy Information Administration, 2000e, Assumptions to the Annual Energy Outlook 2000 with Projections to 2020, DOE/EIA-0554(2000), Table 2, Carbon Emission Factors, Retrieved October 22, 2001 from the World Wide Web: http://www.eia.doe.gov/oiaf/archive/aeo00/assumptions/tbl2.html.

U.S. Department of Energy, Energy Information Administration, 2001a, *Annual Energy Review 2000*, DOE/EIA-0384(2000), Retrieved November 16, 2001 from the World Wide Web: http://www.eia.doe.gov/aer.

U.S. Department of Energy. Energy Information Administration, 2001b, *Electric Power Industry Summary Statistics for the United States, 1998 and 1999*, Retrieved August 13, 2001 from the World Wide Web: http://www.eia.doe.gov/cneaf/electricity/epav2/ html_tables/epav2t1p1.html.

U.S. Department of Energy, Energy Information Administration, 2001c, *Existing Capacity at U.S. Electric Utilities by Prime Mover and Energy Source, 1999*, Retrieved July 6, 2001 from the World Wide Web: http://www.eia.doe.gov/cneaf/electricity/ipp/html1/t6p01.html.

U.S. Department of Energy, Federal Energy Management Program, 2001, *FEMP Annual Report to Congress, 1999*, Retrieved September 12, 2002 from the World Wide Web: http://www.eren.doe.gov/femp/aboutfemp/pdfs/annrep99_part1.pdf.

U.S. Department of Energy, Office of Industrial Technologies (DOE OIT), 1997, *Energy, Environmental, and Economics (E^3) Handbook,* Annex G, DOE/EIA-0383(2000), First Edition, Retrieved October 26, 2001 from the World Wide Web: http://www.oit.doe.gov/e3handbook/

U.S. Department of Energy, Office of Industrial Technologies and Industrial Heating Association, 2001*, Roadmap for Process Heating Technology: Priority Research & Development Goals and Near-Term Non-Research Goals to Improve Industrial Process Heating*.

U.S. Department of Energy, Office of Transportation Technologies (OTT) 2000, *Average Gasoline and Diesel Fuel Retail Prices, Jan. 1999 - April 2000,* Retrieved January 27 2003 from the World Wide Web: http://www.ott.doe.gov/facts/archives/fotw124.shtml

U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division, 1997, *Characterization of Municipal Solid Waste in the United States: 1996 Update, (No. EPA530-R-97-015*.

U.S. Environmental Protection Agency, Office of Solid Waste, 1996, *Proposed Revised Technical Standards for Hazardous Waste Combustion Facilities*, Retrieved August 2, 2001 from the World Wide Web: http://www.epa.gov/epaoswer/hazwaste/combust/cmbust.html (Last updated January 22, 1998).

U.S. Navy, *IPS: Integrated Fight Through Power*, 2001a, Retrieved October 11, 2001 from the World Wide Web: http://peos.crane.navy.mil/IPS/WhyDC.html.

U.S. Navy, *Integrated Power Systems (IPS) Program*, 2001b, Retrieved October 11, 2001 from the World Wide Web: http://peos.crane.navy.mil/IPS/index.html.

U.S. Navy, *Navy Fact File: Aircraft Carriers*, 2001c, Retrieved July 24, 2001 from the World Wide Web: http://www.chinfo.navy.mil/navpalib/factfile/ships/ship-cv.html.

U.S. Navy, *Navy Fact File: Cruisers-CG, CGN*, 2001d, Retrieved July 24, 2001 from the World Wide Web: http://www.chinfo.navy.mil/navpalib/factfile/ships/ship-cru.html.

U.S. Navy, *Navy Fact File: Destroyers-DD, DDG*, 2001e, Retrieved July 24, 2001 from the World Wide Web: http://www.chinfo.navy.mil/navpalib/factfile/ships/ship-dd.html.

U.S. Navy, *Navy Fact File: Frigates-FFG*, 2001f, Retrieved July 24, 2001 from the World Wide Web: http://www.chinfo.navy.mil/navpalib/factfile/ships/ship-ffg.html.

U.S. Navy, *Navy Fact File: Patrol Coastal Ships-PC*, 2001g, Retrieved July 24, 2001 from the World Wide Web: http://www.chinfo.navy.mil/navpalib/factfile/ships/ship-pc.html.

U.S. Nuclear Regulatory Commission, 2001a, *Fact Sheet: Dry Cask Storage of Spent Nuclear Fuel*, Retrieved August 14, 2001 from the World Wide Web: http://www.nrc.gov/OPA/gmo/tip/fsspentfuel.html.

U.S. Nuclear Regulatory Commission, 2001b, *Radioactive Waste: Production, Storage, Disposal (NUREG/BR-0216)*, Retrieved August 14, 2001 from the World Wide Web: http://www.nrc.gov/NRC/NUREGS/BR0216/br0216.html.

Williams, Sol, 2000. Boiler Capacity Inspections of Hill AFB.

Acronyms and Abbreviations

Term	Spellout
AC	Alternating current
Btu	British thermal unit
CERL	U.S. Army Construction Engineering Research Laboratories
DC	Direct current
DOE	Department of Energy
ERDC	Engineering Research and Development Center
EIA	DOE Energy Information Administration
FE	DOE Office of Fossil Energy
ID	Induced draft
kW	kilowatt
kWe	Kilowatts electricity
kWh	Kilowatt hour
LGH	Low grade heat
LTI	Leonardo Technologies, Inc.
MWe	Megawatts electricity
MWh	Megawatt hour
TE	Thermoelectric

Annex A: Applications

Report A01

Broad Applications of TE Devices by Location of Application

Facility

(1) Application: Closed Feedwater Heaters **Temperature Range:** 250 - 450 °F

Application Type: Electricity Generation, Steam Turbine **Type of Process:** Continuous

Description: In electricity generating plants operating on a steam cycle, the efficiency is increased by incorporating feedwater heaters into the system. Feedwater heaters use the large amount of energy available in the latent heat of vaporization of a small amount of steam to preheat the feedwater prior to its entering the boiler. One type of feedwater heater is a closed feedwater heater which is basically a heat exchanger transferring energy from condensing steam to the feedwater. This is an example of where an integrated thermoelectric/condenser could be applied. In this case, the available temperature difference may be higher than from low quality steam from the turbine exit.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(2) Application: Hot Surfaces **Temperature Range:** 100 - 1,000 °F

Application Type: Electricity Generation, Steam Turbine **Type of Process:** Continuous

Description: Fossil powered electricity generating plants have numerous locations in the facility where equipment surface temperatures are high and can approach 540°C (1000°F). Some of these locations could lend themselves to convenient application of thermoelectric (TE) devices for generating electricity from these hot surfaces. For some locations, removal of insulation and application of the actively cooled TE devices would negatively affect the underlying process of the equipment. However, other locations such as the "penthouse" enclosures at the top of the boilers have large expanses of flat surfaces that are readily accessible and would not be appreciably affected by the application of TE devices. In fact, the insulation on some equipment must be limited to keep the internal temperature from approaching damaging levels.

Each plant would need to be evaluated individually for its potential for generating electricity with TE devices in this manner. One example evaluated in Parsons (2000) was the Indian River Power Plant located in Millsboro, DE. Interior temperatures in the units probably ranged from 205 – 315°C (400 – 600°F) with uninsulated surface temperatures of 180 – 205°C (350 – 400°F). The potential area for application of TE devices approaches 930 m^2 (10,000 ft^2) on each unit with estimated average temperatures of 180°C (350°F). An additional 1.15 MW of electricity could be generated by the 90 MW Unit 1, for a 1% increase in net power generation for an estimated electricity cost of $2000/kW (Munson 2000).

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(3) Application: Flue Gases **Temperature Range:** 212 - 400 °F

Application Type: Electricity Generation, Steam Turbine **Type of Process:** Continuous

Description: Exhaust gases from the burning of fuels for electricity generation, process heating or other industrial applications are typically routed through a stack for dispersal into the atmosphere. In electricity generation facilities, these gases can range from 100 – 200°C (212 – 392°F) and could be used to generate additional electricity using thermoelectric (TE) devices.

Integration of the TE devices onto the stack walls could be one method for capturing the energy of the flue gases. However, several constraints are imposed on such an application to ensure proper operation and dispersal of the flue gases. The temperature of flue gases cannot be reduced too low, otherwise, the natural draft of the chimney effect will become too low. For exhaust containing sulfur or other corrosive compounds, condensation must be avoided, otherwise corrosion of materials could become a problem. Finally, to operate the TE devices at an effective temperature, the required rate of heat transfer between the hot gas and the TE devices may be higher than can be produced in the low velocity gas of the flue.(Munson 1999)

Corrosive - Acidic [X] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

Report A01
Broad Applications of TE Devices by Location of Application

Facility

(4) Application: Hot Surfaces **Temperature Range:** 500 - 700 °F

Application Type: Electricity Generation, Gas Turbine **Type of Process:** Continuous

Description: Fossil powered electricity generating plants have numerous locations in the facility where equipment surface temperatures are high and can approach 540°C (1000°F). Some of these locations could lend themselves to convenient application of thermoelectric (TE) devices for generating electricity from these hot surfaces. For some locations, removal of insulation and application of the actively cooled TE devices would negatively affect the underlying process of the equipment. However, other locations such as the "penthouse" enclosures at the top of the boilers have large expanses of flat surfaces that are readily accessible and would not be appreciably affected by the application of TE devices. In fact, the insulation on some equipment must be limited to keep the internal temperature from approaching damaging levels.

Each plant would need to be evaluated individually for its potential for generating electricity with TE devices in this manner. One example evaluated in Parsons (2000) was the Indian River Power Plant located in Millsboro, DE. Interior temperatures in the units probably ranged from 205 – 315°C (400 – 600°F) with uninsulated surface temperatures of 180 – 205°C (350 – 400°F). The potential area for application of TE devices approaches 930 m^2 (10,000 ft^2) on each unit with estimated average temperatures of 180°C (350°F). An additional 1.15 MW of electricity could be generated by the 90 MW Unit 1, for a 1% increase in net power generation for an estimated electricity cost of $2000/kW (Munson 2000).

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(5) Application: Exhaust **Temperature Range:** 500 - 700 °F

Application Type: Electricity Generation, Gas Turbine **Type of Process:** Continuous

Description: Gas turbines can be connected to an electrical generator for producing electricity. At smaller electricity generating facilities, the system is many times not optimized with the use of a steam cycle or cogeneration. In one such case analyzed in the Parsons (2000) report, a 28.2 kilowatt (kW) microturbine that has been optimized with a recuperator produces 260 lb/hr of exhaust at 520ºF. By routing the turbine exhaust through a heat exchanger with TE devices integrated, an estimated 1.1 kW of additional electricity (4%) could be generated. The Cost of Electricity (COE) for this exhaust heat exchanger is $900/kW.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(6) Application: Condenser Cooling Water **Temperature Range:** 77 - 104 °F

Application Type: Electricity Generation, Combined Cycle **Type of Process:** Continuous

Description: In most large electricity generating plants, a steam cycle with steam turbines connected to a generator is used to make electricity.
The steam must be condensed with cooling water to complete the cycle. Nearly half of the energy released by the fuel is available in the cooling water prior to its routing to cooling towers or other thermal sink (Munson 1999). The temperature of the hot water exiting the condenser ranges

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

Report A01

Broad Applications of TE Devices by Location of Application

Facility

(7) Application: Closed Feedwater Heaters **Temperature Range:** 250 - 450 °F

Application Type: Electricity Generation, Combined Cycle **Type of Process:** Continuous

Description: In electricity generating plants operating on a steam cycle, the efficiency is increased by incorporating feedwater heaters into the system. Feedwater heaters use the large amount of energy available in the latent heat of vaporization of a small amount of steam to preheat the feedwater prior to its entering the boiler. One type of feedwater heater is a closed feedwater heater which is basically a heat exchanger transferring energy from condensing steam to the feedwater. This is an example of where an integrated TE device/condenser could be applied. In this case, the available temperature difference may be higher than from low quality steam from the turbine exit.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(8) Application: Hot Surfaces **Temperature Range:** 100 - 1,000 °F

Application Type: Electricity Generation, Combined Cycle **Type of Process:** Continuous

Description: Fossil powered electricity generating plants have numerous locations in the facility where equipment surface temperatures are high and can approach 540°C (1000°F). Some of these locations could lend themselves to convenient application of thermoelectric (TE) devices for generating electricity from these hot surfaces. For some locations, removal of insulation and application of the actively cooled TE devices would negatively affect the underlying process of the equipment. However, other locations such as the "penthouse" enclosures at the top of the boilers have large expanses of flat surfaces that are readily accessible and would not be appreciably affected by the application of TE devices. In fact, the insulation on some equipment must be limited to keep the internal temperature from approaching damaging levels.

Each plant would need to be evaluated individually for its potential for generating electricity with TE devices in this manner. One example evaluated in Parsons (2000) was the Indian River Power Plant located in Millsboro, DE. Interior temperatures in the units probably ranged from 205 – 315°C (400 – 600°F) with uninsulated surface temperatures of 180 – 205°C (350 – 400°F). The potential area for application of TE devices approaches 930 m^2 (10,000 ft^2) on each unit with estimated average temperatures of 180°C (350°F). An additional 1.15 MW of electricity could be generated by the 90 MW Unit 1, for a 1% increase in net power generation for an estimated electricity cost of $2000/kW (Munson 2000).

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(9) Application: Flue Gases **Temperature Range:** 212 - 400 °F

Application Type: Electricity Generation, Combined Cycle **Type of Process:** Continuous

Description: Exhaust gases from the burning of fuels for electricity generation, process heating or other industrial applications are typically routed through a stack for dispersal into the atmosphere. In electricity generation facilities, these gases can range from 100 – 200°C (212 – 392°F) and could be used to generate additional electricity using thermoelectric (TE) devices.

Integration of the TE devices onto the stack walls could be one method for capturing the energy of the flue gases. However, several constraints are imposed on such an application to ensure proper operation and dispersal of the flue gases. The temperature of flue gases cannot be reduced too low, otherwise, the natural draft of the chimney effect will become too low. For exhaust containing sulfur or other corrosive compounds, condensation must be avoided, otherwise corrosion of materials could become a problem. Finally, to operate the TE devices at an effective temperature, the required rate of heat transfer between the hot gas and the TE devices may be higher than can be produced in the low velocity gas of the flue. (Munson 1999)

Corrosive - Acidic [X] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

Report A01

Broad Applications of TE Devices by Location of Application

Facility

(10) Application: Deisel Generators, cooling **Temperature Range:** 250 °F

Application Type: Electricity Generation, Internal Combustion **Type of Process:** Continuous

Description: A Diesel engine can be connected to an electrical generator for producing electricity. The overall efficiency of a Diesel engine in converting the energy of the fuel into electricity is approximately 36% (SOURCE). As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using thermoelectric (TE) devices. The engine jacket normally rejects heat through the radiator while additional energy is available in the hot engine exhaust.
The coolant from the engine jacket can contain approximately 24% of the energy of the fuel. The coolant can range from 165ºF (75ºC) hot water to 250ºF (120C) steam depending on the design of the cooling system. According to Parsons (2001), a Diesel generator producing 2 Megawatt (MW) of electrical power, the engine jacket can produce approximately 1.4 lb/s (5000 lb/hr) of 250ºF (120ºC) steam, a net 200 kilowatts (kW) of electricity can be generated by routing the steam through a heat exchanger/condenser with TE devices integrated into it. This represents a 10% increase in electricity produced from the engine. The estimated Cost of Electricity (COE) is $900/kW for this application (Munson 2001 Annex D).

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates [ ]**

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(11) Application: Deisel Generators, exhaust **Temperature Range:** 800 °F

Application Type: Electricity Generation, Internal Combustion **Type of Process:** Continuous

Description: A Diesel engine can be connected to an electrical generator for producing electricity. The overall efficiency of a Diesel engine in converting the energy of the fuel into electricity is approximately 36%. As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using thermoelectric (TE) devices. The engine jacket normally rejects heat through the radiator while additional energy is available in the engine exhaust.
The engine exhaust can be nearly 800ºF and for a 2 Megawatt (MW) Diesel generator, can produce 25,000 lb/hr of exhaust carrying approximately 28% of the energy of the fuel with it out the exhaust stack. Routing the exhaust through a heat exchanger with TE devices integrated into it could generate an estimated 171 kilowatts (kW) of electrical power according to an analysis by Parsons (2001). Auxiliary devices (a water pump for circulating cooling water to the TE devices and a centrifugal fan to maintain appropriate back pressure on the Diesel engine) would consume approximately 80 kW. A net 91 kW increase in power could be generated for a 2 MW engine, a 5% increase. The estimated Cost of Electricity (COE) is $900/kW for this application.

Corrosive - Acidic [X] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

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(12) Application: Condenser Cooling Water **Temperature Range:** 77 - 104 °F

Application Type: Electricity Generation, Geothermal **Type of Process:** Continuous

Description: In most large electricity generating plants, a steam cycle with steam turbines connected to a generator is used to make electricity.
The steam must be condensed with cooling water to complete the cycle. Nearly half of the energy released by the fuel is available in the cooling water prior to its routing to cooling towers or other thermal sink (Munson 1999). The temperature of the hot water exiting the condenser ranges from 25-40ºC (77-104ºF). These temperatures are far below the optimum temperatures for generating electricity with thermoelectric (TE) devices. Therefore, this application was not considered for further analysis (Munson 1999).

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

Report A01
Broad Applications of TE Devices by Location of Application

Facility

(13) Application: Closed Feedwater Heaters **Temperature Range:** 250 - 400 °F

Application Type: Electricity Generation, Geothermal **Type of Process:** Continuous

Description: In electricity generating plants operating on a steam cycle, the efficiency is increased by incorporating feedwater heaters into the system. Feedwater heaters use the large amount of energy available in the latent heat of vaporization of a small amount of steam to preheat the feedwater prior to its entering the boiler. One type of feedwater heater is a closed feedwater heater which is basically a heat exchanger transferring energy from condensing steam to the feedwater. This is an example of where an integrated thermoelectric/condenser could be applied. In this case, the available temperature difference may be higher than from low quality steam from the turbine exit.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [ ]

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(14) Application: Hot Surfaces **Temperature Range:** 100 - 1,000 °F

Application Type: Electricity Generation, Geothermal **Type of Process:** Continuous

Description: Geothermal electricity generating plants have numerous locations in the facility where equipment surface temperatures are high and can approach 540°C (1000°F). Some of these locations could lend themselves to convenient application of thermoelectric (TE) devices for generating electricity from these hot surfaces. For some locations, removal of insulation and application of the actively cooled TE devices would negatively affect the underlying process of the equipment. However, other locations such as the "penthouse" enclosures at the top of the boilers have large expanses of flat surfaces that are readily accessible and would not be appreciably affected by the application of TE devices. In fact, the insulation on some equipment must be limited to keep the internal temperature from approaching damaging levels.

Each plant would need to be evaluated individually for its potential for generating electricity with TE devices in this manner. One example evaluated in Parsons (2000) was the Indian River Power Plant located in Millsboro, DE. Interior temperatures in the units probably ranged from 205 – 315°C (400 – 600°F) with uninsulated surface temperatures of 180 – 205°C (350 – 400°F). The potential area for application of TE devices approaches 930 m^2 (10,000 ft^2) on each unit with estimated average temperatures of 180°C (350°F). An additional 1.15 MW of electricity could be generated by the 90 MW Unit 1, for a 1% increase in net power generation for an estimated cost of electricity of $2000/kW (Munson 2000).

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(15) Application: Condenser Cooling Water **Temperature Range:** 77 - 104 °F

Application Type: Electricity Generation, Solar **Type of Process:** Continuous

Description: In most large electricity generating plants, a steam cycle with steam turbines connected to a generator is used to make electricity. The steam must be condensed with cooling water to complete the cycle. Nearly half of the energy released by the fuel is available in the cooling water prior to its routing to cooling towers or other thermal sink (Munson 1999). The temperature of the hot water exiting the condenser ranges from 25-40ºC (77-104ºF). These temperatures are far below the optimum temperatures for generating electricity with thermoelectric (TE)

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

Report A01

Broad Applications of TE Devices by Location of Application

Facility

(16) Application: Closed Feedwater Heaters **Temperature Range:** 250 - 450 °F

Application Type: Electricity Generation, Solar **Type of Process:** Continuous

Description: In electricity generating plants operating on a steam cycle, the efficiency is increased by incorporating feedwater heaters into the system. Feedwater heaters use the large amount of energy available in the latent heat of vaporization of a small amount of steam to preheat the feedwater prior to its entering the boiler. One type of feedwater heater is a closed feedwater heater which is basically a heat exchanger transferring energy from condensing steam to the feedwater. This is an example of where an integrated thermoelectric/condenser could be applied. In this case, the available temperature difference may be higher than from low quality steam from the turbine exit.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(17) Application: Hot Surfaces **Temperature Range:** 100 - 1,000 °F

Application Type: Electricity Generation, Solar **Type of Process:** Continuous

Description: Solar powered electricity generating plants have numerous locations in the facility where equipment surface temperatures are high and can approach 540°C (1000°F). Some of these locations could lend themselves to convenient application of thermoelectric (TE) devices for generating electricity from these hot surfaces. For some locations, removal of insulation and application of the actively cooled TE devices would negatively affect the underlying process of the equipment. However, other locations such as the "penthouse" enclosures at the top of the boilers have large expanses of flat surfaces that are readily accessible and would not be appreciably affected by the application of TE devices. In fact, the insulation on some equipment must be limited to keep the internal temperature from approaching damaging levels.

Each plant would need to be evaluated individually for its potential for generating electricity with TE devices in this manner. One example evaluated in Parsons (2000) was the Indian River Power Plant located in Millsboro, DE. Interior temperatures in the units probably ranged from 205 – 315°C (400 – 600°F) with uninsulated surface temperatures of 180 – 205°C (350 – 400°F). The potential area for application of TE devices approaches 930 m^2 (10,000 ft^2) on each unit with estimated average temperatures of 180°C (350°F). An additional 1.15 MW of electricity could be generated by the 90 MW Unit 1, for a 1% increase in net power generation for an estimated cost of electricity of $2000/kW (Munson 2000).

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [ ]

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(18) Application: Fuel Cells **Temperature Range:** 150 - 1,800 °F

Application Type: Electricity Generation, Other **Type of Process:** Continuous

Description: The Phosphoric Acid Fuel Cell (PAFC) is the only fuel cell technology that is commercially available. The efficiency in turning natural gas into electricity is approximately 40% while operating at 205°C (400°F). The operating temperature is high enough to cogenerate steam, resulting in efficiencies as high as 80% (Fuel Cell Handbook, 2000). If the steam generated was routed through a condenser with integrated thermoelectric (TE) devices, the efficiency of generating electricity could possibly be increased to nearly 50%.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(19) Application: Waste-fueled Generators **Temperature Range:** 200 - 500 °F

Application Type: Electricity Generation, Other **Type of Process:** Continuous

Description: One of the methods used to dispose of the municipal solid waste (MSW) produced in the United States is with combustion. Approximately 33.5 million tons, or 16 percent of the MSW stream was disposed of in this manner in 1995. Facilities where energy recovery occurs, generally producing steam or electricity, are classified as waste-to-energy (WTE) combustion facilities. All facilities where MSW is burned are potential candidates for generating electricity with TE devices.

Corrosive - Acidic [X] **Corrosive - Caustic** [X] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

Report A01

Broad Applications of TE Devices by Location of Application

Facility

(20) Application: Steam Boilers — **Temperature Range:** 200 - 300 °F

Application Type: Heating & Cooling, Steam Turbine — **Type of Process:** Continuous

Description: Many installations use a central heating system which produces steam from acentral boiler source, then distributes this steam to the various buildings on the installation via buried or above-ground piping. This steam is then used to heat spaces via hot-air convection throughout the space.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(21) Application: Incinerators — **Temperature Range:** 200 - 500 °F

Application Type: Industrial Processes, Other — **Type of Process:** Varying

Description: One of the methods used to dispose of the municipal solid waste (MSW) produced in the United States is with combustion. Approximately 33.5 million tons, or 16 percent of the MSW stream was disposed of in this manner in 1995. Facilities where energy recovery occurs, generally producing steam or electricity, are classified as waste-to-energy (WTE) combustion facilities. All facilities where MSW is burned are potential candidates for generating electricity with TE devices.

Corrosive - Acidic [X] **Corrosive - Caustic** [X] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(22) Application: Welding — **Temperature Range:** 300 - 1,400 °F

Application Type: Industrial Processes, Other — **Type of Process:** Varying

Description: Welding is used in many industrial processes to join two similar or dissimilar metals. The process temperature depends on the metal being heated and downstream process. Welding is carried out by using fossil fuels such as natural gas, other gases, fuel oils or by using electricity. Temperatures of welding can range from 300 to 1,400 degrees F.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(23) Application: Metal Heating & Melting — **Temperature Range:** 300 - 2,400 °F

Application Type: Industrial Processes, Other — **Type of Process:** Varying

Description: Metal heating is used by steel, aluminum, copper, brass, zinc and other metal industries prior to mechanical working such as rolling, forging, squeezing, etc. to change shape of the material being processed or as a step prior to further processing (melting, heat treating etc.). The process temperature depends on the metal being heated and downstream process requirements. For steel the temperature can be in the range of approximately 800°F to 2,200°F. For the aluminum industry, it can be 300°F to 1,100°F.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [X] **Condensable** [X] **Particulates** [ ]

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(24) Application: Compressed Air — **Temperature Range:** 200 - 500 °F

Application Type: Industrial Processes, Other — **Type of Process:** Varying

Description: Many industries use compressed air for their processes or assisting their processes. Such applications include dehydrating, agitation, as well as conveying, controls and actuators. According to the Compressed Air Challenge, an industry collaboration with support from DOE, compressors convert 80-93 percent of this electrical energy into heat. Compression elevates temperature of the subject gas to a range of about 200 to 350ºF prior to entering a cooler.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [X] **Condensable** [X] **Particulates** [ ]

Report A01

Broad Applications of TE Devices by Location of Application

Facility

(25) Application: Drying **Temperature Range:** 250 - 600 °F

Application Type: Industrial Processes, Other **Type of Process:** Varying

Description: The drying process usually involves evaporation of water from products or raw materials and can operate in the temperate range of 200°F to 500°F. It is carried out in gas- or oil-fired dryers or steam dryers. For fired systems the fuel can be gases such as natural gas or, in a few cases, liquid fuels. Many of these units discharge relatively clean flue gases (with the exception of mining industry) in the temperature range of 300°F to 500°F, depending on the process temperature and use of flue gas heat recovery devices.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [X] **Particulates** [ ]

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(26) Application: Nuclear Material Storage **Temperature Range:** 600 - 700 °F

Application Type: Industrial Processes, Other **Type of Process:** Continuous

Description: Nuclear fuel rods must be removed from active service after use of most of its total energy. Following removal, the fuel rods must be isolated and stored because they still emit high levels of radioactivity. The radioactive decay in these spent nuclear fuel rods continues to generate heat that must be dissipated during their long-term storage. According to Dan Young, RIO Technical Services (personal communication), temperatures of 600°F may be available in dry storage casks that is currently dissipated to the atmosphere. By integrating thermoelectric (TE) devices into the design of dry storage casks, electricity could be generated from the radioactive decay from the spent nuclear fuel. For some dry storage cask designs, it may be possible to externally retrofit an integrated TE/heat exchanger onto casks currently in long-term storage facilities.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(27) Application: Transformers **Temperature Range:** 200 - 300 °F

Application Type: Heating & Cooling, Other **Type of Process:** Continuous

Description: Electrical transformers are also potential candidates for TE application. For large transformers, these enclosures can reach temperatures of over 200° F without space conditioning. TE devices could reduce the need for cooling these enclosures and increase the efficiency of the transformers.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(28) Application: Condenser Cooling Water **Temperature Range:** 77 - 104 °F

Application Type: Electricity Generation, Steam Turbine **Type of Process:** Continuous

Description: In most large electricity generating plants, a steam cycle with steam turbines connected to a generator is used to make electricity. The steam must be condensed with cooling water to complete the cycle. Nearly half of the energy released by the fuel is available in the cooling water prior to its routing to cooling towers or other thermal sink (Munson 1999). The temperature of the hot water exiting the condenser ranges from 25-40ºC (77-104ºF). These temperatures are far below the optimum temperatures for generating electricity with thermoelectric (TE) devices. Therefore, this application was not considered for further analysis (Munson 1999).

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

Report A01

Broad Applications of TE Devices by Location of Application

Non-Facility

(29) Application: Engine exhaust **Temperature Range:** 200 - 800 °F

Application Type: Land Vehicles, Internal Combustion **Type of Process:** Varying

Description: A Diesel engine can be connected to an electrical generator for producing electricity. The overall efficiency of a Diesel engine in converting the energy of the fuel into electricity is approximately 36%. As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using thermoelectric (TE) devices. The engine jacket normally rejects heat through the radiator while additional energy is available in the engine exhaust.

The engine exhaust can be nearly 800ºF and for a 2 Megawatt (MW) Diesel generator, can produce 25,000 lb/hr of exhaust carrying approximately 28% of the energy of the fuel with it out the exhaust stack. Routing the exhaust through a heat exchanger with TE devices integrated into it could generate an estimated 171 kilowatts (kW) of electrical power according to an analysis by Parsons (2001). Auxiliary devices (a water pump for circulating cooling water to the TE devices and a centrifugal fan to maintain appropriate back pressure on the Diesel engine) would consume approximately 80 kW. A net 91 kW increase in power could be generated for a 2 MW engine, a 5% increase. The estimated Cost of Electricity (COE) is $900/kW for this application.

Corrosive - Acidic [X] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

(30) Application: Engine coolant **Temperature Range:** 200 - 300 °F

Application Type: Land Vehicles, Internal Combustion **Type of Process:** Varying

Description: A Diesel engine can be connected to an electrical generator for producing electricity. The overall efficiency of a Diesel engine in converting the energy of the fuel into electricity is approximately 36% (Parsons 2001). As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using thermoelectric (TE) devices. The engine jacket normally rejects heat through the radiator while additional energy is available in the hot engine exhaust.

The coolant from the engine jacket can contain approximately 24% of the energy of the fuel. The coolant can range from 165ºF (75ºC) hot water to 250ºF (120ºC) steam depending on the design of the cooling system. According to Parsons (2001), a Diesel generator producing 2 Megawatt (MW) of electrical power, the engine jacket can produce approximately 1.4 lb/s (5000 lb/hr) of 250ºF (120ºC) steam, a net 200 kilowatts (kW) of electricity can be generated by routing the steam through a heat exchanger/condenser with TE devices integrated. This represents a 10% increase in electricity produced from the engine. The estimated Cost of Electricity (COE) is $900/kW for this application (Munson 2001).

As with the Parsons (2001) analysis on Diesel generators producing electricity from the waste heat from the engine coolant, it may be possible to generate an additional 10% electricity through the use of the hot coolant with a TE device.

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates [ ]**

Report A01

Broad Applications of TE Devices by Location of Application

Non-Facility

(31) Application: Fuel Cells **Temperature Range:** 150 - 1,800 °F

Application Type: Land Vehicles, Other **Type of Process:** Varying

Description: The Phosphoric Acid Fuel Cell (PAFC) is the only fuel cell technology that is commercially available. The efficiency in turning natural gas into electricity is approximately 40% while operating at 205°C (400°F). The operating temperature is high enough to cogenerate steam, resulting in efficiencies as high as 80% (Fuel Cell Handbook, 2000). Other fuel cells currently in development are:

The Polymer Electrolyte Fuel Cell (PEFC) generates electricity from hydrogen and air. The cell operates at relatively low temperatures due to the solid electrolyte membrane. Therefore, temperatures near 80°C (176°F) are employed (Fuel Cell Handbook, 2000).

The Molten Carbonate Fuel Cell (MCFC) operates between 600 – 700°C (1110 – 1290°F) at an efficiency approaching 45% in converting the energy of fuel into electricity.

The Solid Oxide Fuel Cell (SOFC) operates between 800 – 1000°C (1472 – 1832°F) at an efficiency of approximately 45-65% in converting the energy of fuel into electricity (Fuel Cell Handbook 2000).

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(32) Application: Ships: nuclear **Temperature Range:** 200 - 800 °F

Application Type: Ships, Nuclear **Type of Process:** Varying

Description: Ships powered by steam turbines have equipment for generating the steam. There are numerous locations where thermoelectric (TE) devices could be applied to generate electricity with no increase in fuel consumption. Several examples of potential applications are exhaust heat exchangers, integrated TE/condensers, hot surfaces and flue gas.

Corrosive - Acidic [ ] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

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(33) Application: Portable generators, exhaust **Temperature Range:** 200 - 800 °F

Application Type: Field Support, Internal Combustion **Type of Process:** Continuous

Description: A Diesel engine can be connected to an electrical generator for producing electricity. The overall efficiency of a Diesel engine in converting the energy of the fuel into electricity is approximately 36%. As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using thermoelectric (TE) devices. The engine jacket normally rejects heat through the radiator while additional energy is available in the engine exhaust.

The engine exhaust can be nearly 800ºF and for a 2 Megawatt (MW) Diesel generator, can produce 25,000 lb/hr of exhaust carrying approximately 28% of the energy of the fuel with it out the exhaust stack. Routing the exhaust through a heat exchanger with TE devices integrated into it could generate an estimated 171 kilowatts (kW) of electrical power according to an analysis by Parsons (2001). Auxiliary devices (a water pump for circulating cooling water to the TE devices and a centrifugal fan to maintain appropriate back pressure on the Diesel engine) would consume approximately 80 kW. A net 91 kW increase in power could be generated for a 2 MW engine, a 5% increase. The estimated Cost of Electricity (COE) is $900/kW for this application.

Corrosive - Acidic [X] **Corrosive - Caustic** [ ] **Reactive** [ ] **Condensable** [ ] **Particulates** [X]

Report A01

Broad Applications of TE Devices by Location of Application

Non-Facility

(34) Application: Portable generators, coolant
Temperature Range: 250 - 300 °F

Application Type: Field Support, Internal Combustion
Type of Process: Continuous

Description: A Diesel engine can be connected to an electrical generator for producing electricity. The overall efficiency of a Diesel engine in converting the energy of the fuel into electricity is approximately 36%. As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using thermoelectric (TE) devices. The engine jacket normally rejects heat through the radiator while additional energy is available in the hot engine exhaust.
The coolant from the engine jacket can contain approximately 24% of the energy of the fuel. The coolant can range from 165°F (75°C) hot water to 250°F (120C) steam depending on the design of the cooling system. According to Parsons (2001), a Diesel generator producing 2 Megawatt (MW) of electrical power, the engine jacket can produce approximately 1.4 lb/s (5000 lb/hr) of 250°F (120°C) steam, a net 200 kilowatts (kW) of electricity can be generated by routing the steam through a heat exchanger/condenser with TE devices integrated into it. This represents a 10% increase in electricity produced from the engine. The estimated Cost of Electricity (COE) is $900/kW for this application (Munson 2001 Annex D).

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

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(35) Application: Radar and radio, transmitter
Temperature Range: 100 - 300 °F

Application Type: Field Support, Other
Type of Process: Varying

Description: Radar and radio transmitters can reach temperatures of 100°F to 300°F. Thermoelectric devices could be installed either directly on the transmitter element or on the hot side of the equipement's cooling system.

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

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(36) Application: Radar and radio, receivers
Temperature Range: 100 - 300 °F

Application Type: Field Support, Other
Type of Process: Varying

Description: Radar and radio transmitters can reach temperatures of 100°F to 300°F. Thermoelectric devices could be installed either directly

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

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(37) Application: Water distilling/purification unit
Temperature Range: 212 - 350 °F

Application Type: Field Support, Other
Type of Process: Continuous

Description: Water distilling units normally involve vaporizing water in order to separate it from contaminants, generating temperatures of at least 212°F. Thermoelectric devices could be installed nearly anywhere on these units. As well, other distilling and purification units that do not involve water vaporization, such as reverse osmosis, also raise the temperature of the water. Although the operating temperature of these units is not as high as vaporization units, thermoelectric devices coould find applications here as well.

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

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(38) Application: Refrigerators, portable
Temperature Range: 100 - 250 °F

Application Type: Field Support, Other
Type of Process: Continuous

Description: Portable refrigeration units are used for space conditioning and food storage in field operations. The waste heat from these units could be used to operate TE devices installed on the waste heat stream.

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

Report A01

Broad Applications of TE Devices by Location of Application

Non-Facility

(39) Application: Catalytic combustor **Temperature Range:** 300 - 700 °F

Application Type: Other, N/A **Type of Process:** Continuous

Description: Some applications where electricity is required may also require a highly reliable, lightweight, low noise source. For applications such as backpacking and military applications, a small catalytic combustor burning available fuels (i.e., propane, Diesel) could provide the heat source for a thermoelectric (TE) device.

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates [ ]**

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(40) Application: Guns, hot surfaces **Temperature Range:** 100 - 500 °F

Application Type: Other, N/A **Type of Process:** Varying

Description: Guns and weapons systems generate tremendous amounts of waste heat which is normally dispersed to ambient. For applications requiring non-continuous electrcity, installation of TE devices to the hot surfaces of these pieces of equipment could yield significant amounts of electrcity.

Corrosive - Acidic [X] **Corrosive - Caustic** [X] **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

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(41) Application: Jet Blast Deflector, Aircraft Carrier **Temperature Range:** 400 - 800 °F

Application Type: Ships, N/A **Type of Process:** Varying

Description: Jet blast deflectors shield personnel and aircraft on the flight deck of an aircraft carrier from the heat of a jet taking off from the deck. Presently, this heat is dispersed via a seawater cooling system. Installation of TE devices could capture a large amount of this heat that is normally wasted.

Corrosive - Acidic [X] **Corrosive - Caustic** [X] **Reactive [ ]** **Condensable [ ]** **Particulates [ ]**

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(42) Application: Ships: fuel oil and diesel **Temperature Range:** 200 - 800 °F

Application Type: Ships, Internal Combustion **Type of Process:** Varying

Description: A Diesel engine or fuel oil burning system can be connected to an electrical generator for producing electricity and can produce the propulsion power for a ship. The overall efficiency of a Diesel engine in converting the energy of the fuel into electricity is approximately 36% (Munson 2001). As a result, the engine produces two sources of waste heat that may be utilized for generating electricity using thermoelectric (TE) devices. The engine jacket normally rejects heat through the radiator while additional energy is available in the hot engine exhaust.

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

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(43) Application: Ships: gas turbine **Temperature Range:** 200 - 800 °F

Application Type: Ships, Gas Turbine **Type of Process:** Varying

Description: Gas turbines can be connected to an electrical generator for producing electricity and can be coupled with a ship propulsion system. At smaller electricity generating facilities, the system is many times not optimized with the use of a steam cycle or cogeneration. In one such case analyzed in the Parsons (2000) report, a 28.2 kilowatt (kW) microturbine that has been optimized with a recuperator produces 260 lb/hr of exhaust at 520ºF. By routing the turbine exhaust through a heat exchanger with thermoelectric (TE) devices integrated into it, an estimated 1.1 kW of additional electricity (4%) could be generated. The Cost of Electricity (COE) for this exhaust heat exchanger is $900/kW.

Corrosive - Acidic [ ] **Corrosive - Caustic [ ]** **Reactive [ ]** **Condensable [ ]** **Particulates** [X]

Report A02
Broad Applications of TE Devices Sorted by Application ID Number

Application ID	Application	Type of Application	Temperature Range
1	Closed Feedwater Heaters	Facility, Electricity Generation: Steam Turbine	250 - 450 °F
2	Hot Surfaces	Facility, Electricity Generation: Steam Turbine	100 - 1,000 °F
3	Flue Gases	Facility, Electricity Generation: Steam Turbine	212 - 400 °F
4	Hot Surfaces	Facility, Electricity Generation: Gas Turbine	500 - 700 °F
5	Exhaust	Facility, Electricity Generation: Gas Turbine	500 - 700 °F
6	Condenser Cooling Water	Facility, Electricity Generation: Combined Cycle	77 - 104 °F
7	Closed Feedwater Heaters	Facility, Electricity Generation: Combined Cycle	250 - 450 °F
8	Hot Surfaces	Facility, Electricity Generation: Combined Cycle	100 - 1,000 °F
9	Flue Gases	Facility, Electricity Generation: Combined Cycle	212 - 400 °F
10	Deisel Generators, cooling	Facility, Electricity Generation: Internal Combustion	250 °F
11	Deisel Generators, exhaust	Facility, Electricity Generation: Internal Combustion	800 °F
12	Condenser Cooling Water	Facility, Electricity Generation: Geothermal	77 - 104 °F
13	Closed Feedwater Heaters	Facility, Electricity Generation: Geothermal	250 - 400 °F
14	Hot Surfaces	Facility, Electricity Generation: Geothermal	100 - 1,000 °F
15	Condenser Cooling Water	Facility, Electricity Generation: Solar	77 - 104 °F
16	Closed Feedwater Heaters	Facility, Electricity Generation: Solar	250 - 450 °F
17	Hot Surfaces	Facility, Electricity Generation: Solar	100 - 1,000 °F
18	Fuel Cells	Facility, Electricity Generation: Other	150 - 1,800 °F
19	Waste-fueled Generators	Facility, Electricity Generation: Other	200 - 500 °F
20	Steam Boilers	Facility, Heating & Cooling: Steam Turbine	200 - 300 °F
21	Incinerators	Facility, Industrial Processes: Other	200 - 500 °F
22	Welding	Facility, Industrial Processes: Other	300 - 1,400 °F
23	Metal Heating & Melting	Facility, Industrial Processes: Other	300 - 2,400 °F
24	Compressed Air	Facility, Industrial Processes: Other	200 - 500 °F
25	Drying	Facility, Industrial Processes: Other	250 - 600 °F
26	Nuclear Material Storage	Facility, Industrial Processes: Other	600 - 700 °F
27	Transformers	Facility, Heating & Cooling: Other	200 - 300 °F
28	Condenser Cooling Water	Facility, Electricity Generation: Steam Turbine	77 - 104 °F
29	Engine exhaust	Non-Facility, Land Vehicles: Internal Combustion	200 - 800 °F
30	Engine coolant	Non-Facility, Land Vehicles: Internal Combustion	200 - 300 °F
31	Fuel Cells	Non-Facility, Land Vehicles: Other	150 - 1,800 °F
32	Ships: nuclear	Non-Facility, Ships: Nuclear	200 - 800 °F
33	Portable generators, exhaust	Non-Facility, Field Support: Internal Combustion	200 - 800 °F
34	Portable generators, coolant	Non-Facility, Field Support: Internal Combustion	250 - 300 °F
35	Radar and radio, transmitter	Non-Facility, Field Support: Other	100 - 300 °F
36	Radar and radio, receivers	Non-Facility, Field Support: Other	100 - 300 °F

Report A02
Broad Applications of TE Devices Sorted by Application ID Number

Application ID	Application	Type of Application	Temperature Range
37	Water distilling/purification unit	Non-Facility, Field Support: Other	212 - 350 °F
38	Refrigerators, portable	Non-Facility, Field Support: Other	100 - 250 °F
39	Catalytic combustor	Non-Facility, Other: N/A	300 - 700 °F
40	Guns, hot surfaces	Non-Facility, Other: N/A	100 - 500 °F
41	Jet Blast Deflector, Aircraft Carrier	Non-Facility, Ships: N/A	400 - 800 °F
42	Ships: fuel oil and diesel	Non-Facility, Ships: Internal Combustion	200 - 800 °F
43	Ships: gas turbine	Non-Facility, Ships: Gas Turbine	200 - 800 °F

Report A03
Broad Applications of TE Devices Sorted by Type of Application

Facility

ID	Application	Temperature Range
	Electricity Generation	
1	Closed Feedwater Heaters, Steam Turbine	250 - 450 °F
2	Hot Surfaces, Steam Turbine	100 - 1,000 °F
3	Flue Gases, Steam Turbine	212 - 400 °F
4	Hot Surfaces, Gas Turbine	500 - 700 °F
5	Exhaust, Gas Turbine	500 - 700 °F
6	Condenser Cooling Water, Combined Cycle	77 - 104 °F
7	Closed Feedwater Heaters, Combined Cycle	250 - 450 °F
8	Hot Surfaces, Combined Cycle	100 - 1,000 °F
9	Flue Gases, Combined Cycle	212 - 400 °F
10	Deisel Generators, cooling, Internal Combustion	250 °F
11	Deisel Generators, exhaust, Internal Combustion	800 °F
12	Condenser Cooling Water, Geothermal	77 - 104 °F
13	Closed Feedwater Heaters, Geothermal	250 - 400 °F
14	Hot Surfaces, Geothermal	100 - 1,000 °F
15	Condenser Cooling Water, Solar	77 - 104 °F
16	Closed Feedwater Heaters, Solar	250 - 450 °F
17	Hot Surfaces, Solar	100 - 1,000 °F
18	Fuel Cells, Other	150 - 1,800 °F
19	Waste-fueled Generators, Other	200 - 500 °F
28	Condenser Cooling Water, Steam Turbine	77 - 104 °F
	Heating & Cooling	
20	Steam Boilers, Steam Turbine	200 - 300 °F
27	Transformers, Other	200 - 300 °F
	Industrial Processes	
21	Incinerators, Other	200 - 500 °F
22	Welding, Other	300 - 1,400 °F
23	Metal Heating & Melting, Other	300 - 2,400 °F
24	Compressed Air, Other	200 - 500 °F

Report A03
Broad Applications of TE Devices Sorted by Type of Application

Facility

ID	Application	Temperature Range
25	Drying, Other	250 - 600 °F
26	Nuclear Material Storage, Other	600 - 700 °F

Report A03
Broad Applications of TE Devices Sorted by Type of Application

Non-Facility

ID	Application	Temperature Range
	Field Support	
33	Portable generators, exhaust, Internal Combustion	200 - 800 °F
34	Portable generators, coolant, Internal Combustion	250 - 300 °F
35	Radar and radio, transmitter, Other	100 - 300 °F
36	Radar and radio, receivers, Other	100 - 300 °F
37	Water distilling/purification unit, Other	212 - 350 °F
38	Refrigerators, portable, Other	100 - 250 °F
	Land Vehicles	
29	Engine exhaust, Internal Combustion	200 - 800 °F
30	Engine coolant, Internal Combustion	200 - 300 °F
31	Fuel Cells, Other	150 - 1,800 °F
	Other	
39	Catalytic combustor, N/A	300 - 700 °F
40	Guns, hot surfaces, N/A	100 - 500 °F
	Ships	
32	Ships: nuclear, Nuclear	200 - 800 °F
41	Jet Blast Deflector, Aircraft Carrier, N/A	400 - 800 °F
42	Ships: fuel oil and diesel, Internal Combustion	200 - 800 °F
43	Ships: gas turbine, Gas Turbine	200 - 800 °F

Report A04
Broad Applications of TE Devices Sorted by Maximum Temperature

Application ID	Application	Type of Application	Temperature Range
23	Metal Heating & Melting	Facility, Industrial Processes: Other	300 - 2,400 °F
18	Fuel Cells	Facility, Electricity Generation: Other	150 - 1,800 °F
31	Fuel Cells	Non-Facility, Land Vehicles: Other	150 - 1,800 °F
22	Welding	Facility, Industrial Processes: Other	300 - 1,400 °F
2	Hot Surfaces	Facility, Electricity Generation: Steam Turbine	100 - 1,000 °F
8	Hot Surfaces	Facility, Electricity Generation: Combined Cycle	100 - 1,000 °F
14	Hot Surfaces	Facility, Electricity Generation: Geothermal	100 - 1,000 °F
17	Hot Surfaces	Facility, Electricity Generation: Solar	100 - 1,000 °F
11	Deisel Generators, exhaust	Facility, Electricity Generation: Internal Combustion	800 °F
29	Engine exhaust	Non-Facility, Land Vehicles: Internal Combustion	200 - 800 °F
32	Ships: nuclear	Non-Facility, Ships: Nuclear	200 - 800 °F
33	Portable generators, exhaust	Non-Facility, Field Support: Internal Combustion	200 - 800 °F
41	Jet Blast Deflector, Aircraft Carrier	Non-Facility, Ships: N/A	400 - 800 °F
42	Ships: fuel oil and diesel	Non-Facility, Ships: Internal Combustion	200 - 800 °F
43	Ships: gas turbine	Non-Facility, Ships: Gas Turbine	200 - 800 °F
4	Hot Surfaces	Facility, Electricity Generation: Gas Turbine	500 - 700 °F
5	Exhaust	Facility, Electricity Generation: Gas Turbine	500 - 700 °F
26	Nuclear Material Storage	Facility, Industrial Processes: Other	600 - 700 °F
39	Catalytic combustor	Non-Facility, Other: N/A	300 - 700 °F
25	Drying	Facility, Industrial Processes: Other	250 - 600 °F
19	Waste-fueled Generators	Facility, Electricity Generation: Other	200 - 500 °F
21	Incinerators	Facility, Industrial Processes: Other	200 - 500 °F
24	Compressed Air	Facility, Industrial Processes: Other	200 - 500 °F
40	Guns, hot surfaces	Non-Facility, Other: N/A	100 - 500 °F
1	Closed Feedwater Heaters	Facility, Electricity Generation: Steam Turbine	250 - 450 °F
7	Closed Feedwater Heaters	Facility, Electricity Generation: Combined Cycle	250 - 450 °F
16	Closed Feedwater Heaters	Facility, Electricity Generation: Solar	250 - 450 °F
3	Flue Gases	Facility, Electricity Generation: Steam Turbine	212 - 400 °F
9	Flue Gases	Facility, Electricity Generation: Combined Cycle	212 - 400 °F
13	Closed Feedwater Heaters	Facility, Electricity Generation: Geothermal	250 - 400 °F
37	Water distilling/purification unit	Non-Facility, Field Support: Other	212 - 350 °F
20	Steam Boilers	Facility, Heating & Cooling: Steam Turbine	200 - 300 °F
27	Transformers	Facility, Heating & Cooling: Other	200 - 300 °F
30	Engine coolant	Non-Facility, Land Vehicles: Internal Combustion	200 - 300 °F
34	Portable generators, coolant	Non-Facility, Field Support: Internal Combustion	250 - 300 °F
35	Radar and radio, transmitter	Non-Facility, Field Support: Other	100 - 300 °F
36	Radar and radio, receivers	Non-Facility, Field Support: Other	100 - 300 °F
10	Deisel Generators, cooling	Facility, Electricity Generation: Internal Combustion	250 °F
38	Refrigerators, portable	Non-Facility, Field Support: Other	100 - 250 °F
6	Condenser Cooling Water	Facility, Electricity Generation: Combined Cycle	77 - 104 °F
12	Condenser Cooling Water	Facility, Electricity Generation: Geothermal	77 - 104 °F
15	Condenser Cooling Water	Facility, Electricity Generation: Solar	77 - 104 °F
28	Condenser Cooling Water	Facility, Electricity Generation: Steam Turbine	77 - 104 °F

Annex B: Application Scoring

Report B01
Broad Applications of TE Devices Listed by Score

Application ID Number	Application	Location of Application	Score
4	**Hot Surfaces:** Electricity Generation, Gas Turbine	Facility	90
39	**Catalytic combustor:** Other, N/A	Non-Facility	90
2	**Hot Surfaces:** Electricity Generation, Steam Turbine	Facility	89
8	**Hot Surfaces:** Electricity Generation, Combined Cycle	Facility	88
26	**Nuclear Material Storage:** Industrial Processes, Other	Facility	83
14	**Hot Surfaces:** Electricity Generation, Geothermal	Facility	81
32	**Ships: nuclear:** Ships, Nuclear	Non-Facility	75
5	**Exhaust:** Electricity Generation, Gas Turbine	Facility	73
7	**Closed Feedwater Heaters:** Electricity Generation, Combined Cycle	Facility	72
43	**Ships: gas turbine:** Ships, Gas Turbine	Non-Facility	72
1	**Closed Feedwater Heaters:** Electricity Generation, Steam Turbine	Facility	70
42	**Ships: fuel oil and diesel:** Ships, Internal Combustion	Non-Facility	70
41	**Jet Blast Deflector, Aircraft Carrier:** Ships, N/A	Non-Facility	70
9	**Flue Gases:** Electricity Generation, Combined Cycle	Facility	69
18	**Fuel Cells:** Electricity Generation, Other	Facility	69
19	**Waste-fueled Generators:** Electricity Generation, Other	Facility	68
3	**Flue Gases:** Electricity Generation, Steam Turbine	Facility	68
17	**Hot Surfaces:** Electricity Generation, Solar	Facility	68
23	**Metal Heating & Melting:** Industrial Processes, Other	Facility	67
25	**Drying:** Industrial Processes, Other	Facility	67
20	**Steam Boilers:** Heating & Cooling, Steam Turbine	Facility	65
11	**Deisel Generators, exhaust:** Electricity Generation, Internal Combustion	Facility	65
10	**Deisel Generators, cooling:** Electricity Generation, Internal Combustion	Facility	61
33	**Portable generators, exhaust:** Field Support, Internal Combustion	Non-Facility	60
40	**Guns, hot surfaces:** Other, N/A	Non-Facility	58
27	**Transformers:** Heating & Cooling, Other	Facility	57
21	**Incinerators:** Industrial Processes, Other	Facility	57

Report B01

Broad Applications of TE Devices Listed by Score

Application ID Number	Application	Location of Application	Score
22	**Welding:** Industrial Processes, Other	Facility	57
24	**Compressed Air:** Industrial Processes, Other	Facility	56
16	**Closed Feedwater Heaters:** Electricity Generation, Solar	Facility	52
29	**Engine exhaust:** Land Vehicles, Internal Combustion	Non-Facility	52
30	**Engine coolant:** Land Vehicles, Internal Combustion	Non-Facility	49
31	**Fuel Cells:** Land Vehicles, Other	Non-Facility	49
34	**Portable generators, coolant:** Field Support, Internal Combustion	Non-Facility	48
35	**Radar and radio, transmitter:** Field Support, Other	Non-Facility	47
36	**Radar and radio, receivers:** Field Support, Other	Non-Facility	47
13	**Closed Feedwater Heaters:** Electricity Generation, Geothermal	Facility	45
37	**Water distilling/purification unit:** Field Support, Other	Non-Facility	33
38	**Refrigerators, portable:** Field Support, Other	Non-Facility	33
28	**Condenser Cooling Water:** Electricity Generation, Steam Turbine	Facility	29
6	**Condenser Cooling Water:** Electricity Generation, Combined Cycle	Facility	23
12	**Condenser Cooling Water:** Electricity Generation, Geothermal	Facility	23
15	**Condenser Cooling Water:** Electricity Generation, Solar	Facility	23

Annex C: Contact List

Contact List

- John Huston/Dave Shario – Wright Patterson contacts
    - Reza Salavani - 850-283-3715 – Talked with Reza on 5/30/2002. He indicated that his involvelement at Wright Patterson is in technology miniaturization (i.e. fuel cells). He indicated that a more appropriate contact at WPAFB would be Joe Sellner (937-255-7770) or Tom Reitz (no phone number given). They both work on turbines at WPAFB. Reza said that Major Lynn Borland is now Lt. Colonel Borland and her area of expertise is environmental.
    - Major Lynn Borland - 850-283-2989
- Mike Knapp – Army contacts may include Bill Hamilton (Garrison's Commander course) and Ed Davis (USACE GS-15). Called Mike on 5/28/02 to follow up . . . he said he would provide info by the end of the week.
- Dean Bensley – Additional information from Portsmouth NS. Talked with Dean on 5/30/2002 (9:15 a.m.). We will send an electronic copy of both DOE TE application study reports to Dean.(Sent afternoon 5/30) He indicated that Sharon Parshley (x-4632) is more involved in this area as an electrical/energy engineer. Another potential contact is Tim Dunn (x-3831). He is an environmental engineer.
- Brad Wroolie – Contacts on west coast
- Larry Strothers – (850) 283-6354, Air Force Civil Engineering Service Agency - Tyndall AFB Oklahoma. Talked with Larry on 5/24/2002. He helps develop energy policy for the Air Force. Sent him a fact sheet and questionnaire. Contact provided by J. Huston. We followed up with Larry Strothers on 5/30/2002. He gave us contact information for Dave Perkins (937-904-2370), an energy engineer/manager at WPAFB. Larry indicated that WPAFB is a good site with technologies representative of the AF overall. WPAFB has boilers, generator sets, etc. He also mentioned other representative Air Logistics Centers: Tinker, Hill and Robbbins AFBs. They all have significant industrial processes. He didn't have their contact info, but may e-mail us at a later date if found.(Have filled in a questionnaire form for him)
- Sharon Parshley – Called Sharon (Portsmouth NS) on 5/30/2002 (10:00 a.m.) as a follow up to conversation with Dean Bensley. Sharon is in charge of ESPC and DSM upgrades at Portsmouth. The DSM is out of the Huntsville region and the ESPC is a regional contract. Upgrades at Portsmouth have includes gas and package boilers, as well as upgrades to the underground steam distribution. The upgrades also involve plant hot water, white lighting and compressed air systems. One particular energy conservation measure (ECM) involved replacement of a 7.5 MW steam turbine with a 5.2 MW boiler (?)

  Sharon indicated that several energy audits have been performed at Portsmouth and information in the REEP database is dated based on plant upgrades. She wants us to take a tour and, at that time, she will provide the data. She asked that we get Dean Bensley to arrange the tour – in mid-late June. A complete site audit was performed by NAVSEA. Sharon indicated that mortgages on the ESPC and DSM at Portsmouth are about $43 Million ($11 M and $32M projects). She also indicated that some of the data may be available on the DoD Privatization site for Region A, Northeast Atlantic Fleet. Although, the upgrades have been performed, Portsmouth is on the BRAC list.

Sharon's e-mail is parshleysv@nail.ports.navy.mil. We will send her a fact sheet and questionnaire on the TE technology. She will also be attending Energy 2002 as a presenter on M&V (June 4 afternoon). We asked that she stop by the NETL conference booth.

On another note, Portsmouth contributes wastewater to a local POTW that treats ~500 million gallons per year. Portmouth contributes about 35-40 % of this stream. The BAMF Super ESPC may be another potential vehicle for site upgrades.

- Gene Crank – (805) 982-5589, Naval Support Agency, Port Hueneme. Contact provided by J. Huston.
- Russ Dominy – (805) 982-5177 NAVFAC, Port Hueneme, ESPC and Energy & Utilities Team. Wyatt met him at Energy 2002. Have contacted, sent fact sheet and questionnaire.
- Peter Fanning – (805) 982-5388, NAVFAC, Port Hueneme, Utilites team fanningpk@nfecs.navy.mil. Contacted us after receiving information about TE project from his boss. We sent a fact sheet to him. Original source of contact unknown, but this is probably a contact that Billy Lewis (CTC) made with Andy Del Collo, (202) 685-9173 NAVFAC Environmental RDT&E Program Manager.
- Alan Miller – Port Hueneme contact contact from Nichols' Internet searchs
- Germany POCs – Contact Juergen Baller – e-mail: bsbdpw.heidelberg.army.mil, Contact Kenneth Wunsche – e-mail: asgdpw.heidelberg.army.mil
- Contact Alvin Day – 850-283-6357, Air Force Civil Engineering Support Agency (AFCESA). Left a message ~ 5/10/2002. No return call was received. This was a contact provided by J. Cornette – cold call as he had no previous relationship to A. Day.
- Energy 2002 Potential Contacts per Steve Sain:
  - Mark Stepz (DOE M&V) Representative for FEMP
  - Jim Haywood (Army M&V) representative from the USACE
  - Russ Dominy (Navy M&V) NAVFAC ESPC technical lead for the Navy
  - Quinn Hart (Air Force)
- Steve Sain indicated that the USACE has a program called REEP (developed at CERL) for tracking Buildings, etc. – he said he would check out and let us know more info/contact. Followed up and downloaded the database program.
- Steve Sain provided another waste heat contact at the Army – Dick Faith (309-782-6485). He is a civilian energy manager for major concerns and industrial work for the Army mission. He is located at the Rock Island Arsenal –

Iowa/Illinois. Talked to Dick on 5/29/2002 and sent a copy of the fact sheet and questionnaire. He will be attending Energy 2002.

- Steve Sain said to call Lesha Thomas at AEE Atlanta and reference his name for more information on the application/testing process. Her e-mail is cert@aeecenter.org. Often, the application can be submitted less some of the pieces.
- John Vavrin – (800) 872-2375, x-7570, coordinator for AMC/CERL actions, performs Process Optimization Analyses, also suggested looking at CERL website for energy data about the installations listed below, especially Watervillet, email: john.vavrin@erdc.usace.army.mil:
  - Picatinny Arsenal: currently decentralizing heating plant
    - Rich Sloboda – (973) 724-4561, Energy Manager
    - Rich Havrisko – (973) 724-5520, Sloboda's boss
  - Watervillet Arsenal: 1999 Optimization Audit performed – still has centralized heating
    - Vanessa Duens – (518) 266-3672
  - Tobyhanna Arsenal: heating plant already decentralized
    - Jim Brandle – (570) 895-7097
  - Rock Island Arsenal: still has central heating
    - Dave Osbourn – (309) 782-2393
- Gary Hein – (850) 283-6329 TRW employee, Air Force Energy manager, works at Tyndall AFB, thinks Wright/Patterson AFB would be best for our needs, said that DUERS data would accessible by energy managers for their bases.
- Dave Perkins (937) 904-2370 Received from Gary Hein. Made contact on 6/22/02 and sent a factsheet to him. He replied that he did not have the data we were seeking but gave referred us to:
    - Sam G Williams (937) 787-6722 Energy Program Managers for AF Materiel Command
    - Mike Saywer (937) 904-1513 Energy Program Managers for AF Materiel Command
- Bruce Frizell– (703) 784-4030, POC for Marines at Quantico provided by Jim Marsh. Bruce indicated that at Quantico and many other USMC bases, PPV (privatization) of family housing was occurring. He provided the following people who may be able to help:
  - CDR Jeffrey Hoel – (703) 784-5409 Director of PWC Quantico and in charge of privitazation of housing. Followed up with commander Hoel. He directed us to contact Mike Herlan.
  - John Dorsey – (703) 784-5442, Deputy Director of PWC-will be in charge of facilities when an upcoming reorganization happens
  - Mike Herlan – (703) 784-5102, Utilities Manager at Quantico. Sent Mike a fact sheet and questionnaire and requested a site meeting to obtain energy data. On 8/15/02, met with him to discuss required data. We presented the UCAR data

given to us by Sharon Parshley as data that was especially helpful to generate the report. He later sent the applicable data from Quantico's UCAR via email.

– Craig Sakai – (703) 695-8302/8517, Head of Environmental Group @ HQ USMC, the POC that Bruce and Jim Marsh used to know at HQ is now gone, but this person should be able to direct our call.

Annex D: REEP Data

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr) Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
AIR FORCE				
AF ACADEMY	0	652	0	100,254
ALTUS AFB	0	96	0	0
ANDREWS AFB	0	0	4,352	0
ARNOLD	0	329	2	0
BARKSDALE AFB	0	184	0	0
BEALE AFB	0	57	102	0
BOLLING AFB	0	78	8	0
BROOKS	0	104	0	0
BUCKLEY ANG BASE	0	0	0	0
CANON AFB	0	119	0	0
CARSWELL	0	28	6	6,779
CHARLESTON AFB	0	13	184	0
COLUMBUS AFB	0	12	78	0
DAVIS MONTHAN AFB	0	3	0	0
DOBBINS	0	0	0	0
DOVER AFB	0	0	49	0
DYESS AFB	0	1	0	0
EDWARDS	0	227	22	0
EGLIN	0	255	0	0
ELLSWORTH AFB	0	5,643	83	0
F E WARREN AFB	0	0	0	0
FAIRCHILD AFB	0	553	1	0
GOODFELLOW AFB	0	40	0	0
GRAND FORKS AFB	0	141	62	0
GRISSOM ARB	0	17	0	0
GUNTER AFB	0	43	0	0
HANSCOM	0	152	11	0
HICKAM	0	0	0	0
HILL	0	124	22	0
HOLLOMAN AFB	0	195	0	0
HOMESTEAD	0	0	0	22
HURLBURT FIELD	0	0	0	0
KEESLER AFB	0	416	0	0
KELLY	0	1,641	0	0
KIRTLAND	0	408	0	0
LACKLAND AFB	0	119	198	0
LANGLEY AFB	0	180	23	0
LAUGHLIN AFB	0	58	0	0
LITTLE ROCK AFB	0	178	0	0
LOS ANGELES	0	105	0	0
LUKE AFB	0	81	0	0
MALMSTROM AFB	0	391	41	0
MARCH ARB	0	0	0	27,200
MAXWELL AFB	0	158	0	0
MCCHORD AFB	0	276	43	0
MCCLELLAN	0	378	0	0
MCCONNELL AFB	0	365	0	0
MCGUIRE AFB	0	494	74	0
MINOT AFB	0	148	125	88,167
MOODY AFB	0	57	14	0
MOUNTAIN HOME	175	4	18	0
NELLIS AFB	0	97	3	0

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr) Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
OFFUTT AFB	0	39	19	0
ONIZUKA AFS	0	10	0	0
PATRICK AFB	0	57	20	0
PETERSON AFB	0	177	0	0
POPE AFB	0	172	16	0
RANDOLPH AFB	0	70	0	0
REESE AFB	0	70	0	0
ROBINS	0	654	14	0
SCHRIEVER AFB	0	1	39	0
SCOTT AFB	0	384	22	0
SEYMOUR JOHNSON AFB	0	1	0	0
SHAW AFB	0	97	21	0
SHEPPARD AFB	0	242	1	0
TINKER	0	1,669	0	0
TRAVIS AFB	0	250	0	0
TYNDALL AFB	0	46	0	0
VANCE AFB	0	70	0	0
VANDENBERG AFB	0	4,598	418	0
WESTOVER ARB	0	20	131	0
WHITEMAN	0	0	0	0
WRIGHT-PATTERSON	840	277	33	0
Subtotals for AIR FORCE:	**1,015**	**23,524**	**6,255**	**222,422**

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr): Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
ARMY				
ABERDEEN PROVING GROUND	0	18	439	0
ANNISTON ARMY DEPOT	177	6	151	0
BLUE GRASS ARMY DEPOT	120	1	34	0
CARLISLE BARRACKS	0	153	4	0
CORPUS CHRISTI ARMY DEPOT	0	0	0	0
DETROIT ARSENAL	0	267	0	0
DEVENS RES. FORCES TRNG	0	330	394	0
DUGWAY PROVING GROUND	0	0	181	0
FT A P HILL	0	1	0	0
FT BELVOIR	0	0	4,944	0
FT BENNING	0	1,284	58	0
FT BLISS	0	1,401	0	0
FT BRAGG	0	79	2,968	0
FT BUCHANAN	0	0	0	0
FT CARSON	0	260	326	0
FT DETRICK	0	439	451	0
FT DIX RESERVE FORCES TRNG	0	188	941	0
FT DRUM	68	401	269	0
FT EUSTIS	0	308	376	0
FT GORDON	0	302	104	0
FT GREELY	0	0	1,789	-5,952
FT HAMILTON	0	26	101	0
FT HOOD	0	4,106	0	0
FT HUACHUCA	0	282	0	0
FT IRWIN (and NTC)	0	0	0	0
FT JACKSON	0	818	42	0
FT KNOX	15	824	172	0
FT LEAVENWORTH	0	9	0	0
FT LEE	0	761	168	0
FT LEONARD WOOD	0	480	522	0
FT LEWIS	0	1,265	2,629	0
FT McCOY	423	445	53	0
FT McPHERSON	0	565	209	0
FT MEADE	0	0	15	0
FT MONMOUTH	0	192	244	0
FT MONROE	0	40	84	0
FT MYER	0	16	120	0
FT POLK	0	0	0	0
FT RICHARDSON	540	540	540	0
FT RILEY	0	1,200	0	0
FT RUCKER	0	300	56	0
FT SAM HOUSTON	0	53	0	0
FT SHAFTER	0	59	84	0
FT SILL	0	2,623	19	0
FT STEWART	0	0	151	0
FT WAINWRIGHT	2,128	0	116	1,027
HAWTHORNE ARMY DEPOT	0	0	174	0
HOLSTON AAP	166	2	0	0
HUNTER AAF	0	6	10	518
IOWA AAP	200	212	249	0
LAKE CITY AAP	0	253	0	0
LETTERKENNY ARMY DEPOT	0	1	324	0

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr) Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
LIMA TANK PLANT	220	0	0	0
LONE STAR AAP	0	379	360	0
MCALESTER AAP	0	234	7	0
MILAN AAP	42	0	153	0
NEWPORT CHEMICAL DEPOT	0	623	90	0
PICATINNY ARSENAL	0	245	500	0
PINE BLUFF ARSENAL	0	124	0	0
PRESIDIO OF MONTEREY	0	62	0	0
PUEBLO CHEMICAL DEPOT	141	0	51	0
RADFORD AAP	1,374	1	0	0
RED RIVER ARMY DEPOT	151	168	1,000	0
REDSTONE ARSENAL	0	88	0	0
ROCK ISLAND ARSENAL	365	19	8	15,647
SIERRA ARMY DEPOT	0	14	91	0
SOLDIERS SYSTEMS CENTER-NATICK	0	0	162	0
SUNNY POINT MILITARY OCEAN TER	0	0	8	0
TOBYHANNA ARMY DEPOT	283	0	24	0
TOOELE ARMY DEPOT	12	3	333	0
UMATILLA CHEMICAL DEPOT	0	0	76	0
WALTER REED	0	148	184	0
WATERVLIET ARSENAL	0	0	157	0
WEST POINT MIL ACAD	0	103	756	0
WHITE SANDS MISSILE RANGE	0	667	0	0
YUMA PROVING GROUND	0	4	19	0
Subtotals for ARMY:	**6,425**	**23,398**	**23,490**	**11,240**

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr) Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
MARINES				
BARSTOW	0	440	0	32,575
CAMP LEJEUNE	7,099	1,466	2,466	332,733
CAMP PENDLETON	0	3,010	364	175,199
QUANTICO	0	533	1,745	139,902
TWENTYNINE PALMS	0	696	309	82,103
YUMA	0	229	331	61,078
Subtotals for MARINES:	**7,099**	**6,374**	**5,215**	**823,590**

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr): Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
NAVY				
ADAK	0	0	1,165	23,000
ALAMEDA NARF	0	559	0	149,267
ALBANY	0	646	0	73,854
ANNAPOLIS	0	244	298	108,138
BEAUFORT/PARRIS IS	0	1,124	389	108,491
BETHPAGE	0	120	670	73,840
BRUNSWICK	0	0	292	33,783
CHARLESTON	143	880	852	487,216
CHERRY POINT	6,938	764	488	221,542
CHINA LAKE	0	686	0	87,394
COLTS NECK	0	123	124	29,321
CORPUS CHRISTI	0	506	0	142,536
CRANE NWSC	0	570	186	76,848
DAHLGREN	0	0	0	82,479
DALLAS	0	802	0	23,623
FALLON	0	65	75	27,440
GREAT LAKES	0	2,118	0	126,018
GULFPORT	0	396	0	34,252
INDIAN HEAD	3,056	0	2,893	25,768
INDIANAPOLIS	0	186	0	41,924
JACKSONVILLE	0	1,465	501	393,304
KEY WEST	0	0	246	83,001
KINGS BAY	2,438	43	896	220,194
LAKEHURST	0	179	493	24,786
LEMOORE	0	432	184	79,279
LOS ANGELES AREA	0	92	1,409	630,379
LOUISVILLE	0	302	0	37,776
MARE ISLAND	0	921	0	138,852
MECHANICSBURG	0	539	130	67,352
MEMPHIS	0	806	133	114,131
MERIDIAN NAS	0	298	0	32,914
MIRAMAR	0	351	134	53,986
MOFFETT FIELD	0	258	0	47,698
N.ORLEANS	0	478	0	84,311
N.Y.CITY	0	193	75	34,812
NEW LONDON	0	344	1,889	187,682
NEWPORT	0	530	953	125,798
NORFOLK	3,096	681	8,466	1,233,548
OAKLAND	0	1,174	0	287,421
OAKLAND HOSPITAL	0	61	0	19,455
ORLANDO	0	596	455	133,241
PATUXENT RIVER	0	338	891	121,710
PEARL HARBOR	0	1,206	654	632,402
PENSACOLA	0	1,508	382	307,972
PHILADELPHIA	0	1,825	369	258,801
PORT HUENEME/PT.MA	0	718	211	126,810
SAN DIEGO	0	1,276	1,346	1,008,226
SAN FRANCISCO	0	273	0	11,038
SEATTLE	0	1,630	2	450,883
TRENTON	0	0	170	35,606
WARMINSTER	0	226	96	64,377
WASHINGTON D.C.	0	151	949	442,621

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr) Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
WHIDBEY IS.	2,290	0	3,816	86,703
YORKTOWN	0	0	748	46,234
Subtotals for NAVY:	**17,961**	**28,683**	**33,030**	**9,600,037**

Report D01
REEP Database Summary Report by Service Branch

Installation Name	Heating Equipment Capacities (in MBTU/Hr) Coal Fired	Gas Fired	Oil Fired	Electricity Generated On-site (MWh/yr)
Subtotals for AIR FORCE:	**1,015**	**23,524**	**6,255**	**222,422**
Subtotals for ARMY:	**6,425**	**23,398**	**23,490**	**11,240**
Subtotals for MARINES:	**7,099**	**6,374**	**5,215**	**823,590**
Subtotals for NAVY:	**17,961**	**28,683**	**33,030**	**9,600,037**
Grand Totals :	**32,500**	**81,979**	**67,990**	**10,657,289**

379,536 **total yearly heating capacity (B BTU)**	**268,176** **total yearly electricity generation capacity (B BTU)**

Annex E: Case Studies

Watervliet Arsenal
Case Study of Thermolelectric Benefits

Equipment	Total Heat Generated	Percent of total heat available to TE devices	Waste heat available to TE devices	Potential Electricity produced
Heating Plant (Oil-fired)	326,560 MBTU	10%	32,656 MBTU	1531 MW hr
Industrial Processes				
• Induction Heating	785 MBTU	35%	275 MBTU	12.7 MW hr
• Metal Plating	853 MBTU	33%	282 MBTU	13.1 MW hr
• Air Compressors	2288 MBTU	5%	1143 MBTU	5.3 MW hr
				31 MW hr
		Total		1562 MW hr
Savings of $162,448 per year (with 10.04 cents per kW hr in NY)				
Current Energy expenditures: $2,561,000				

Data sources:
Process Energy and Pollution Review, U.S. Army Corps of Engineers, 1999.
REEP database

Portsmouth Naval Shipyard
Case Study of Thermolelectric Benefits

Equipment	Total Heat Generated	Percent of total heat available to TE devices	Waste heat available to TE devices	Potential Electricity produced
Heating Plant (Natural Gas & Oil fired)	867,675 MBTU	10%	86,768 MBTU	4069 MW hr
On-site Electricity Generation	104,916 MBTU	5%	5,246 MBTU	246 MW hr
		Total		4315 MW hr
Savings of $507,012 per year (with 11.75 cents per kW hr in NH)				
Current Energy expenditures: $4,271,000				

Data sources:
Unified Cost Accounting Report (UCAR) for PNSY, 1999.
REEP database

Marine Corps Base Quantico
Case Study of Thermolelectric Benefits

Equipment	Total Heat Generated	Percent of total heat available to TE devices	Waste heat available to TE devices	Potential Electricity produced
Heating Plant (Natural Gas-fired)	515,946 MBTU	10%	51,595 MBTU	2419 MW hr
		Total		2419 MW hr
Savings of $141,753 (with 5.86 cents per kW hr in VA)				

Data sources:
Unified Cost Accounting Report (UCAR) for MCBQ, 1999.
REEP database

Hill Air Force Base
Case Study of Thermolelectric Benefits

Equipment	Total Heat Generated	Percent of total heat available to TE devices	Waste heat available to TE devices	Potential Electricity produced
Heating Plant (Natural Gas & Oil fired)	510,000 MBTU	10%	51,000 MBTU	2392 MW hr
Industrial Processes	20,000 MBTU	5%	5,246 MBTU	47 MW hr
		Total		2439 MW hr
Savings of $130,974 per year (with 5.37 cents per kW hr in UT)				
Current Energy expenditures: appx $3,500,000				

Data sources:
Air Force Civil Engineers Support Agency data collected for boiler inspections.
REEP database

Appendix B: European Case Study Report

European Case Study

Background

This report follows the previous study, *Evaluate & Demonstrate Broad Applications for Thermoelectric Devices for Department of Defense*, submitted by *CTC* and LTI. This prior report outlined general military applications of TE Devices based on sources of low-grade waste heat that is otherwise being discarded. TE Devices offer a wide range of possibilities within the U.S. military to improve overall power generation efficiency without increasing emissions. Based on the general applications evaluated and the overall potential to increase power output, it was recommended that a site be identified for a field-scale demonstration at a U.S. military installation. The objective of this demonstration is to generate specific operation data under real operating conditions. This demonstration will also help refine current estimates of cost/benefit economics and return on investment.

Energy Efficiency and Environmental Management at U.S. Military Bases

TE Devices offer the potential to improve the energy efficiency and environmental performance of power production throughout the U.S. military. TE Devices can specifically assist in helping the U.S. military comply with Executive Order 13123, which requires that all DOD facilities reduce their energy consumption by 1.25% per year. This reduction is determined from a baseline of 1985 energy consumption. DOD must also comply with Executive Orders 12759 and 12902, which require that Federal agencies reduce the energy consumption at all federal facilities by 30% from 1985 levels by 2005.

In general, military installations and activities must comply with all federal, state, and any applicable local or host-country regulations. Additional specific military regulations that encourage the introduction of energy efficiency and environmental performance improvements include those found under the Office of the Deputy Under Secretary of Defense Environmental Security Program, the Army Environmental Program in Foreign Countries that falls under regulations defined in AR 200-1, Environmental Protection and Enhancement (February 1997), and the Commander's Guide to Environmental Management (March 1998).

The mission of the Environmental Security Program is to comply with all applicable laws; support the military readiness of the armed forces by ensuring continued access to the air, land, and water needed for training and testing; improve the quality of life of military personnel and their families by protecting them from environmental, safety, and health hazards, and maintaining quality military facilities; and contribute to weapon systems that have improved performance, lower cost, and better environmental characteristics.

Under the Army Environmental Program in Foreign Countries, the Army based abroad will comply with environmental standards defined by the following documents: applicable international agreements such as treaties, Status of Forces Agreements, supplementary or other bilateral and multilateral agreements; as well as country-specific Final Governing Standards or, in the absence of these, the Overseas Environmental Baseline Guidance Document

The Commander's Guide to Environmental Management assists Army commanders in developing and maintaining their environmental programs. Although primarily for Army installations and activities within the continental United States, this guide provides a basis for effective environmental management. The guide supports the implementation of cost-saving, innovative environmental technologies that may include equipment, changes to procedures, or modification to processes. A Technology Transfer Program administered by the U.S. Army Environmental Center encourages the demonstration of emerging environmental technologies to prove their capabilities and gather performance and cost information under actual working conditions at Army installations. Air emissions management in particular being in compliance with the Clean Air Act Amendments of 1190 (CAAA-90), are also a significant aspect of overall environmental management. Implementation of emission prevention measures is encouraged to reduce environmental compliance costs.

U.S. Military Planning for Worldwide Bases

The Pentagon is currently in the process of re-evaluating current basing of forces throughout the world. The new plans will see an increase in United States military presence in Eastern Europe, the Caucasus region, and Africa with a decrease in historically high areas of concentration such as Germany. The United States military expects to maintain approximately 8,000 troops in Poland and position approximately 15,000 troops in the Caucasus region. The largest bases in the Caucasus will be in Romania and Bulgaria due to their proximity to ports on the Black Sea. Additional forces will rotate through a series of smaller bases throughout the region. In Africa, the United States will rotate approximately 6,000 troops through up to a dozen small bases in Algeria, Morocco, Tunisia, Senegal, Ghana, Mali, and Kenya.

Current United States military forces in Germany number approximately 70,000 troops. The military is considering plans to redeploy army soldiers from large garrison bases in Heidelberg, Wiesbaden, Grafenwöhr, and Würzburg. These plans could result in a decrease of as many as 45,000 army soldiers in Germany. Some bases in Germany, however, are expected to remain. These include Ramstein Air Base and the United States European Command in Stuttgart. Crucial air hubs in Italy and Spain are also likely to remain. Camp Ederle in Vicenza, Italy is already experiencing a base expansion due to the redeployment of army soldiers from Germany.

Field-Scale Demonstration

Although the trend has recently been to replace on-site power production at U.S. military bases with grid purchased electricity, there remain on-site power plants at many installations. Additionally, emerging security threats and other considerations may influence a reverse of this trend or at least the maintenance of a minimum, base load amount of on-site power production. There is a clear security benefit to having full or at least partial on-site power generation at U.S. military bases abroad. On-site power generation allows the base to maintain full operation in the event of any local power outages or grid disruptions due to a variety of events including weather, accidents, fuel shortages, strikes, or intentional sabotage. The installation of TE Devices can enhance an installation's on-site power capability by increasing the power plant's output for a given amount of fuel. TE Devices can improve power plant efficiency, lessen emissions, reduce operating costs, and extend the operational capability of on-site fuel storage in the event of delivery disruptions.

U.S. Army Base in Heidelberg, Germany

The U.S. Army base in Heidelberg, Germany was originally identified as a potential site due to the presence of on-site power generation. The Heidelberg base currently receives almost all of its electricity from the local grid and district heat from the local municipal district heating loop (140 °C hot water supply), but has been planning to install a micro-turbine at the base hospital. The planned gas turbine is projected to have an output of 60 kWe, 120 kW heat (exhaust temperature 280 °C). The installation of this turbine, however, is currently on hold.

U.S. Army Base Camp Ederle In Vicenza, Italy

Since the installation of the new turbine at Heidelberg was placed on hold, other potential military installations were investigated, with the most promising being Caserma (Camp) Ederle in Vicenza, Italy. Camp Ederle is located in Vicenza, Italy about 25 miles west of Venice. The units stationed at base include the following: SETAF Infantry Brigade; 1/508th Infantry (ABCT); 509th Signal Battalion; 14th Transportation Battalion; 22D Area Support Group; USARHC-Vicenza; and the Armed Forces Network. The base offers the typical amenities such as post-exchange, commissary, theater, clubs, and recreation opportunities. The Vicenza Exchange is the largest Mall Complex (over 80,000 sq ft) in the area. The U.S. Army Health Clinic at Vicenza serves a population of approximately 8,000 personnel. Housing for personnel is primarily off-post. Camp Ederle is located on the east side of Vicenza, not far from the Vicenza East (EST) exit off Autostrada (A4) that runs from Venice to Milan. The city of Vicenza has a population of approximately 160,000. The area around Vicenza is in the foothills of the Alps and is comprised of vineyards, farmland, and industry. The area contains many historical sites including numerous churches and villas.

Potential Applications of Thermoelectrics at Camp Ederle

The planned power plant modifications call for the installation of a 1.2 MW steam turbine and the upgrade of the existing boiler set, which involves replacing the current set of three, 12 MBtu (6k kcal, i.e., 24x.252=6k kcal) boilers with three, 24 MBtu boilers. As mentioned in the previous report, the two biggest sources of heat lost in a fossil fuel driven steam cycle are in the condenser and in the hot flue gas.

One primary location is the placement of the TE Device in the condenser receiving the low-quality steam exhaust or into the closed feedwater heaters used to preheat incoming water to the boiler of the steam cycle. This would require the design of an integrated thermoelectric/condenser or thermoelectric/heat exchanger. This application would have to ensure that adequate heat transfer is maintained in the condenser or heat exchanger. The other primary location identified in the report and potentially viable for this application is to place the TE Device at the exhaust of the boiler. The TE Device would simply be placed on the surface at the top of the boiler or surrounding the exit stack. This application would have to ensure that an adequate draft remains in the stack.

The next step is to pursue an on-site demonstration of TE Devices at U.S. Army Camp Ederle in Vicenza, Italy. This demonstration is to be coordinated with base power plant modifications being conducted by Siemens Westinghouse.

Appendix C: TE Device Test Data

Thermoelectric Device Evaluation

LTI expected the operating specifications of the 12-in. square LTI TE Device to be 80-100 VDC and 10 amps output at a temperature differential of 100 °C. On receipt and visual inspection, a resistance test was conducted on each device. Table C1 demonstrates the results of these tests. This test verified that the TE Device was still a complete electrical circuit. The 27 TE Devices received were tested and eight devices had resistance measurements indicating that the electrical circuit was still complete. The remaining 19 devices were determined to be an “open circuit” and were not functional as received.

The eight devices were tested using the single device test stand documented in Task 3 discussion. The device was placed on the 12-in. square copper hot plate and connected to the facility chilled water supply and return. It was electrically connected to the test circuitry and resistive load. The device was then subjected to an increasing temperature differential until a 100 °C differential was reached.

The power graph (Figure C1) below was typical of the eight tested. This particular device had an approximate average voltage of 10 VDC (Figure C2) and average current of 22 milliamps resulting in an average power output of approximately 220 milliwatts. Most of the devices received had a serial number stamped into the copper bottom plate. This graph represents TE Device N9 power output.

Table C5. Resistance measurements of LTI TE devices as received.

Item No.	Serial Number	Resistance	Comments
1	N1	< 1.0k Ohms	
2	07/15/01 N2	< 1.2k Ohms	
3	07/15/01 N3	Open	Reworked -Solder melted during test
4	07/15/01 N4	200 Ohms	
5	09/14/01 N5	Open	
6	09/14/01 N6	Open	
7	09/14/01 N7	< 1M Ohm	
8	09/14/01 N8	< 1M Ohm	
9	09/14/01 N9	200 Ohms	
10	09/14/01 N10	Open	
11	09/14/01 N11	Open	
12	09/14/01 N12	Intermittent	Starts at 1k Ohm, then rises until open
13	09/14/01 N13	Open	
14	09/17/01 N14	Open	
15	09/17/01 N15	Open	
16	09/17/01 N16	Open	
17	09/17/01 N17	Open	
18	09/17/01 N18	Open	1 of 2 used to build low resistance unit
19	09/17/01 N19	Open	
20	09/17/01 N20	Open	2 of 2 used to build low resistance unit
21	09/17/01 N21	Open	
22	09/17/01 N22	Open	
23	09/17/01 N23	Open	
24	09/17/01 N24	Open	
25	09/17/01 N25	< 1.2k Ohm	
26	N26	up to 11 Meg	Resistance fluctuated significantly
27	25.01.2001 27	2.4 Ohm	No voltage output, complete device shorted

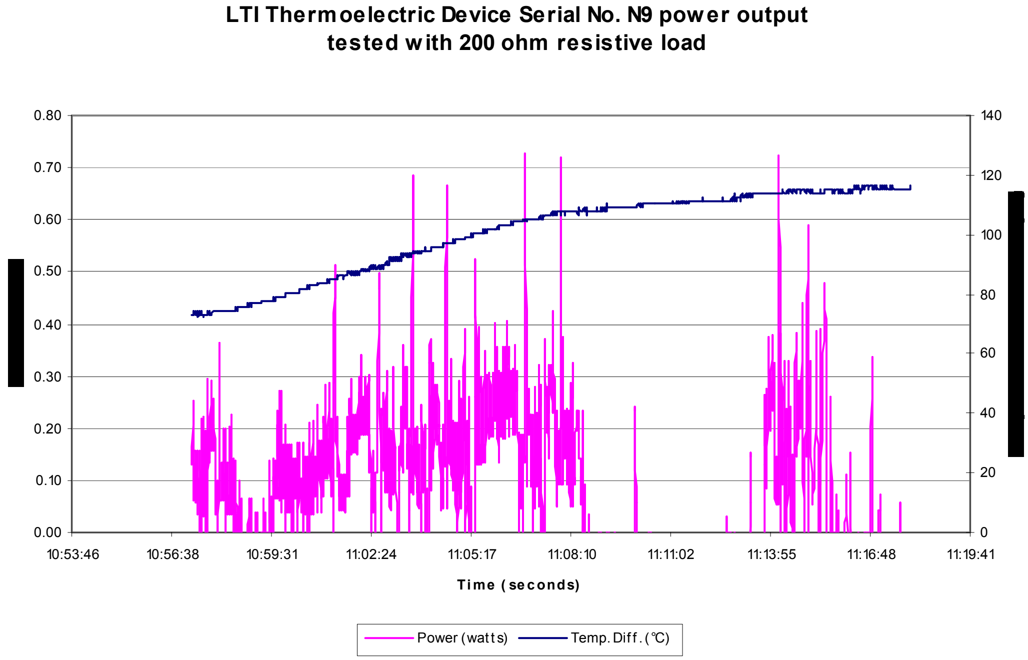

Figure C1. Power output chart of LTI device N9.

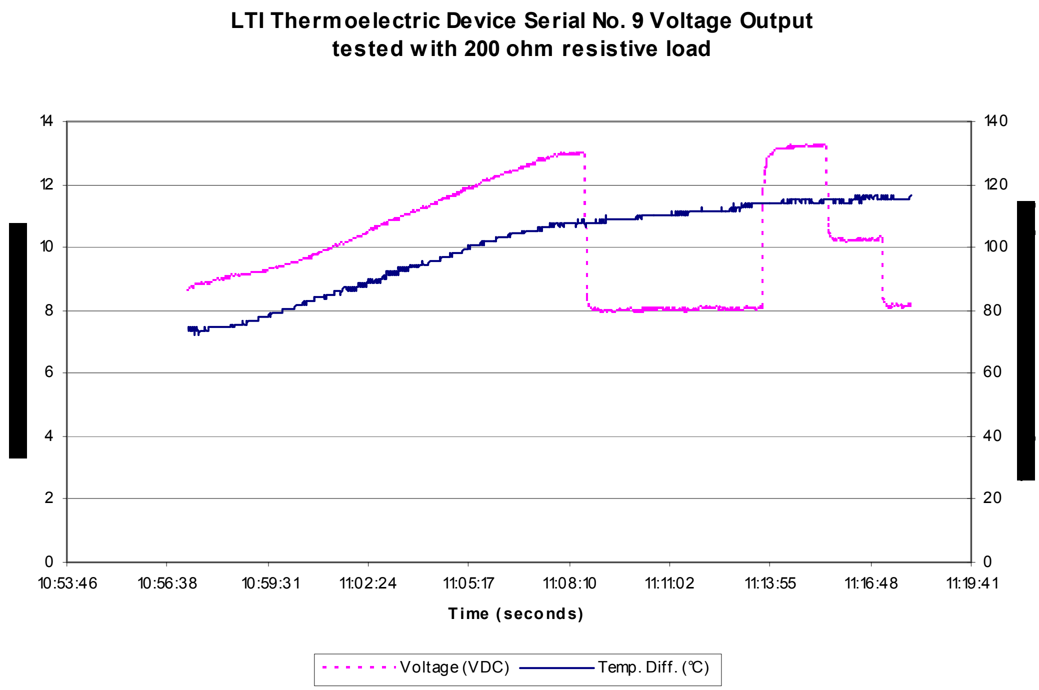

Figure C2. Voltage output chart of LTI device N9.

Appendix D: TE Wafer Test Information

TE Wafer Testing

Testing of the LTI TE wafers was conducted using the procedures described in Section 3.4. A datasheet was generated to standardize the data collected (Table D1). The following are samples of the data collected.

Table D6. LTI New Hampshire wafer pair 16—open circuit test data.

Thermoelectric Project Wafers Manufactured in: New Hampshire Received by CTC: 7/7/2003 Test Date: 7/15/2003								
Wafer Pair No.	**P+N 16**	**Load Resistance: Measured**		**Open Circuit**		**Wafer Room Temp. Resistance measurement:**		**0.197 Ohms**
Measurement No.	**Target Hot side Temp (°F)**	**Hot Side Temp (°F)**	**Cold Side Temp (°F)**	**Temp. Diff. (°F)**	**Temp. Diff. °C)**	**Measured Voltage (mV) with resistive load**	**Measured Current (mA)**	**Calculated Power (mW)**
1	Room Temp	79.5	80.9	-1.4	-18.6	0.03		0
2	100	102.0	81.0	21.0	-6.1	3.8		0
3	125	123.0	83.0	40.0	4.4	3.8		0
4	150	145.0	83.8	61.2	16.2	6.4		0
5	175	178.0	86.0	92.0	33.3	8.8		0
6	200	205.0	87.7	117.3	47.4	11.5		0
7	225	224.0	89.4	134.6	57.0	12.3		0
8	250	250.0	90.9	159.1	70.6	15.0		0
9	275	277.0	92.3	184.7	84.8	17.7		0
10	300	300.0	94.1	205.9	96.6	19.5		0
11	325	327.0	96.3	230.7	110.4	22.9		0
12	350	347.0	98.1	248.9	120.5	23.7		0
13	375	377.0	100.0	277.0	136.1	25.8		0
14	400	399.0	103.5	295.5	146.4	26.6		0

LTI Production and Testing Summary

Ingots of both P- and N-type semiconductor materials were manufactured and processed in the New Hampshire lab. Manufacturing and processing parameters were varied in order to increase the electrical output of the thermoelectric material. Ingots were sliced into P- and N-type wafers, and then tested. Results for the initial manufacturing runs were in the range of reasonable optimistic expectations (Figures D1 and D2).

Time and budget restraints prevented extensive manufacturing of ingots and testing of diode pairs. The initial testing procedures and results suggested a redesign of the testing procedure to allow for "bipolar" testing. Bipolar testing permits the testing of not only the diode pair, but also the individual N- and P-type legs. Our bipolar findings indicate that the majority of the power generation of the current LTI-NH TE material is a result of the N-leg. In some instances, the P-leg was found to be so weak that it produced a negative effect on the power generation provided by the N-leg. This finding indicates that changes are warranted in the manufacturing parameters to increase the population of "holes" in the P-type legs.

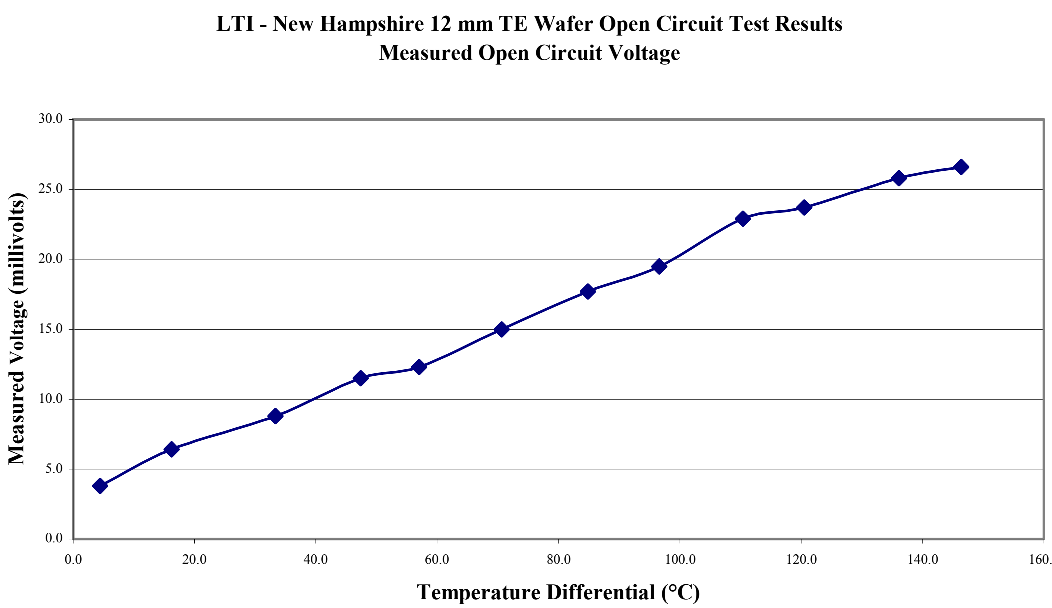

Figure D1. LTI New Hampshire wafer pair 16—open circuit test data.

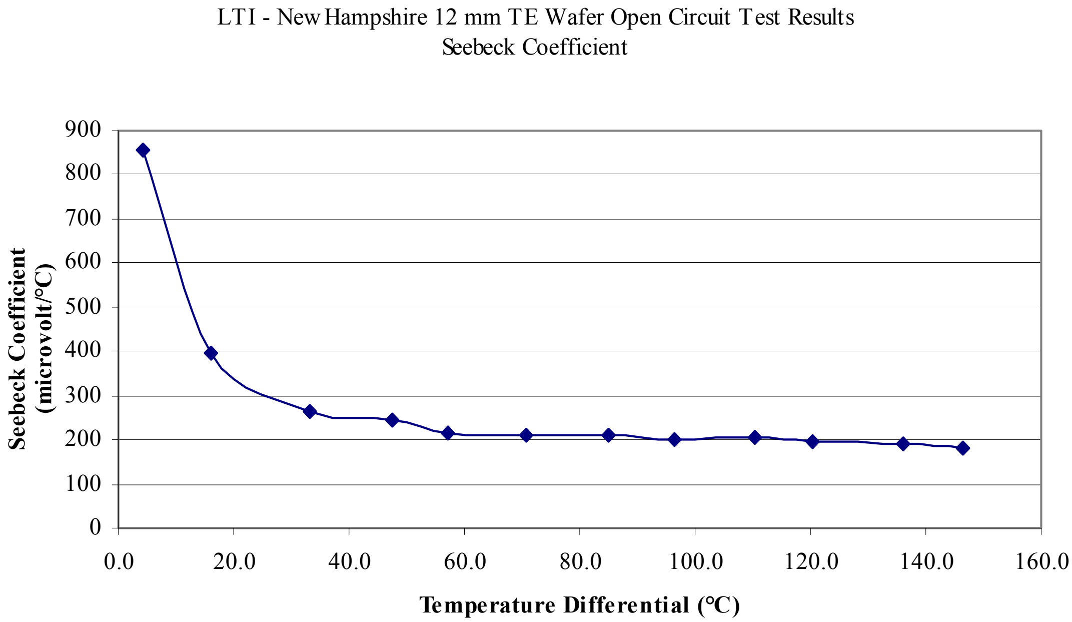

Figure D2. LTI New Hampshire wafer pair 16—open circuit Seebeck coefficient.

The greatest difficulty in testing the semiconductor pairs was establishing ohmic contact. The test setups, both at *CTC* and LTI-NH, were designed using dead-weights and electrically-conductive grease to create electrical contact in the test circuits. This method allowed repetitive testing of the same diode pairs, both in the New Hampshire lab and at *CTC* in Pennsylvania. These contacts do not provide as good an electrical connection as soldering could provide. This accounts for the variation of some of the test results.

LTI-NH Wafer Test Equipment

1. Hewlett Packard 3455A digital voltmeter
2. Wavetek digital multimeter
3. Solid state cooling systems low flow LC cold plate
4. OK industries SA-750 series hotplate (500 °F)
5. Lauda recirculating lab heater/chiller with ice bank and heater coils
6. Various thermometer probes
7. Laptop computer to record test results.

LTI-NH Test Procedure Specifics

Test wafers are inserted into a test apparatus similar to the *CTC* apparatus as shown in Figure D3. Data recorded by LTI is demonstrated in Figure D4.

Figure D3. LTI TE wafer test apparatus.

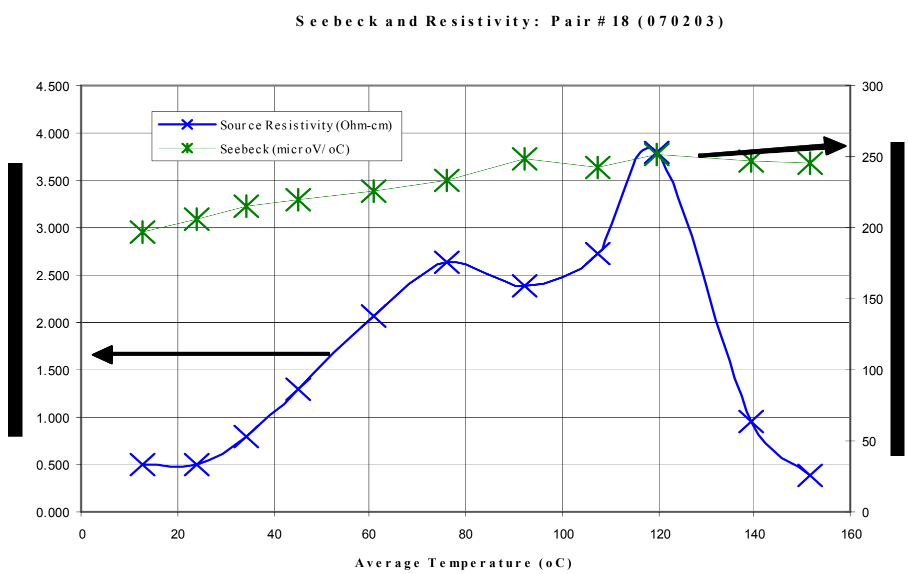

Figure D4. LTI test results—wafer pair 18 manufactured in New Hampshire.

Differences between the two testing devices are that the LTI-NH testing apparatus included:

- Four pairs of N- and P-type material, located under the four corners of the 6-in. square cooling plate.
- *CTC* copper sheet (placed top and bottom of the N- and P-type wafers) was replaced by (bottom) a single 2-in. long by 2-in. wide and 1/4-in. thick copper plate, and by (top) two 2-in. long by 3/4-in. wide and 1/4-in. thick copper straps.

- The bottom copper plate has a threaded 5-40 hole (on a corner) and a 4mm temperature probe hole (down the center) to accept a probe.
- The bottom copper plate was placed on top of a 2-in. square alumina plate which is placed on top of the hotplate. Between both the hotplate and the alumina, and the alumina and the copper plate, was a thin layer of heat sink compound to ensure good thermal contact from the hotplate up through to the copper plate.
- On top of the copper plate, two 12mm diameter, 2mm thick N- and P-type wafers (1 diode) were placed for testing.
- Between the wafers and copper plate, a thin layer of a silver containing electrically conductive grease increased conductivity and reduced electrical resistance. This same silver grease was used on top of the wafers.
- On top of the wafers, the two 2-in. long by 3/4-in. wide and 1/4-in. thick copper straps were placed.
- The top copper straps both had a threaded 5-40 hole (on a corner) and a 4mm temperature probe hole (down the center) to accept a probe.
- Temperature probes used on the cold sides were thermometers with a dial range of 0 to 220 °F.
- Temperature probes used on the hot sides provided digital readouts from 0 to 500 °F.
- Multiple probes were used to double check accuracy.
- Heat sink compound was placed on top of the copper straps, then another electrically insulating piece of two-in. square alumina, then heat sink compound, then the cooling plate was placed on top of the four pairs of wafers.
- Electrical connections between the copper plates and straps and the HP 3455A meter were accomplished using 20-gauge test wire leads, with a soldered connector on the copper end, through which was passed a 5-40 machine screw that filled tapped holes on the four bottom copper plates and the eight top straps.
- The eight primary test leads were located at the cold side of the diode pairs being tested (top straps).
- The four secondary leads were placed on the bottom hot side of the diode as common leads.
- The common leads enabled the bipolar testing of the individual N- and P-type legs.
- Bipolar testing was used both for measuring electrical resistance and generated voltage.
- Primary test leads terminated at four pairs of gold-plated audio banana plug connectors.
- Common test leads terminated at single banana plugs.
- Test leads provided data that was displayed by the HP 3455A Voltmeter.
- The Voltmeter provided both voltage and resistance values.

- Deadweights (48.50 lb.) set on top of the cooling plate helped increase ohmic contact.
- The cold plate heat exchanger was cooled by a pump that supplied ice water from a Lauda Recirculating Lab Heater/Chiller with ice bank and heater coils.

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14. ABSTRACT

The Department of Defense (DOD) is concerned with reliable and cost-effective power generation of on-site power generators as well as minimizing the environmental impact of these generators. Thermoelectric (TE) devices offer the opportunity to generate power without additional fuels, without moving parts, and with negligible environmental impact. An electrical energy conversion efficiency of approximately 15% would be required to obtain an acceptable return on investment for TE devices. A feasibility study to was performed to determine how, assuming a 16% efficiency, TE devices could impact the DOD's power generation capabilities.

Based on research indicating energy conversion efficiencies of 20%, TE devices were built and tested. Of 27 TE devices supplied, only 8 were functional; each device produced only 1 Watt of power. Current manufacturing processes and design parameters were assessed and recommendations made. Three locations were prepared as demonstration sites for TE devices, site evaluation criteria were outlined, and process results given. Control and Data Acquisition (CDAQ) Systems for single and multiple test stands were developed to gather all necessary data variables during the demonstrations, and a portable technology system was developed to enable personnel to demonstrate the technology in any location.

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