# Thermoelectric Power Generation Assessment

**1009453**

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Technical Update, February 2004

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This document was prepared by

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This document describes research sponsored by EPRI and PSE&G.

The publication is a corporate document that should be cited in the literature in the following manner:

*Thermoelectric Power Generation Assessment,* EPRI, Palo Alto, CA, and PSE&G, 2004.1009453.

# EXECUTIVE SUMMARY

The objective of this report is to evaluate the technical and economic feasibility of thermoelectric power generation technology for utility applications. The report focuses on the development efforts of seven thermoelectric power-generator companies:

- D.T.S. GmbH
- Global Thermoelectric Inc.
- Hi-Z Technology, Inc.
- Beijing Huimao Cooling Equipment Co., Ltd.
- Leonardo Technologies, Inc.
- Taihuaxing Trading Co., Ltd.
- Tellurex Corporation

Most companies have focused on products with less than 1-kW power output. Thermoelectric power generator manufacturers do not plan to pursue systems larger than 1 kW until the energy conversion efficiency is high enough to make the system economical for the required application.

## Company Comparison

Most of the thermoelectric generator developers have commercial products producing less than 1 kW. The efficiency achieved by conventional technologies ranges from 2% to 5%, with a high of 8%. New materials research and product development has shown efficiencies as high as 14% in the testing facility; see Table ES-1 for the selected performance characteristics.

**Table ES-1**
**Thermoelectric Power Generation Performance Characteristics**

| Company | Power Output (watts) | Energy Conversion Efficiency %, HHV | Near-Term Target Efficiency %, HHV |
|---|---|---|---|
| DTS GmbH | $10 – 40 * 10^{-6}$ | n/a | n/a |
| Global Thermoelectric | 15 – 550 | 2.1 – 3.2 | n/a |
| Hi-Z Technology, Inc. | 2 – 19 | 4.5 | 14 |
| Beijing Huimao Cooling Equipment Co., Ltd. | n/a | n/a | n/a |
| Leonardo Technologies, Inc. | 8 – 800 | 12 – 14 | Leonardo does not have a product available at 12 – 14% at this time. |
| Taihuaxing Trading Co., Ltd. | 2.6 – 14.7 | n/a | n/a |
| Tellurex Corporation | 2 – 12 | 3 – 5 | n/a |

Thermoelectric generators are being developed for use in combination with distributed power generators to utilize the waste heat for additional power generation, increasing the overall system efficiency. Table ES-2 lists those compatible DG systems with existing power generation devices.

Thermoelectric generation systems can significantly increase the power output of a distributed-generation power system. For example a TEG system with 14% efficiency could add 5 percentage points to the overall efficiency of a DG power system (assuming 40% electrical efficiency and 40% recoverable exhaust heat), with a corresponding decrease in fuel costs. This approach is probably not economically feasible at present, but could be when the thermoelectric system cost drops much below $500/kW.

**Table ES-2**
**Thermoelectric Generators Using Waste Heat from DG Power Generators**

| | DG Technologies | | | | | | |
|---|---|---|---|---|---|---|---|
| **Companies** | Reciprocating Engine | Combustion Turbine | Microturbine | PAFC | PEMFC | MCFC | SOFC |
| DTS GmbH | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Global Thermoelectric | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Hi-Z Technology, Inc. | ● | ❍ | ● | ● | ● | ❍ | --- |
| Beijing Huimao Cooling Equipment Co., Ltd. | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Leonardo Technologies, Inc. | ● | ● | ● | ● | ● | --- | --- |
| Taihuaxing Trading Co., Ltd. | ● | ❍ | ● | ● | ● | --- | --- |
| Tellurex Corporation | ● | --- | --- | ● | ● | --- | --- |

● = Continuous operation
❍ = Intermittent operation
--- = Applicable with exhaust temperature reduction
n/a = Information not available for DTS, Global Thermoelectric, and Beijing Huimao.

## Thermoelectric Power Generation Outlook

Several thermoelectric power generator developers have achieved energy conversion efficiencies of roughly 14% in testing situations. These developers are confident their products could achieve even higher efficiencies through further development, but the 14% efficiency is already three times higher than is available with conventional thermoelectric generators (2-5%).

Developers are continuing to seek funding for the development and commercialization of their products. Hi-Z Technology suggests they are ready to move forward and purchase the equipment required to manufacture thermoelectric generators based on quantum-wells materials.

Once developers are able to achieve higher efficiencies, they plan to begin looking toward systems capable of producing a higher power output at that time. Until then, the high power systems are not economical.

Table ES-3 outlines the current research and development activities at five of the thermoelectric companies.

**Table ES-3**
**Thermoelectric Power Generation Research and Development Activity**

| Company | Research and Development Activity |
|---|---|
| D.T.S. GmbH | D.T.S. continues to focus on the micro-scale thermoelectric power generation market, geared toward self-powered digital displays and recharging mobile electronics. |
| Global Thermoelectric | Global is focused on developing products for niche applications, i.e., TE generator rated for hazardous operation. |
| Hi-Z | Testing new materials, $B_4C$-$B_9C$-SiGe. Has achieved efficiency in the lab of 14% at roughly 250°C. Hi-Z hopes to achieve 20-30% efficiency and develop larger systems (>1kW).<br><br>Hi-Z currently has a 1kW power generation system built for use in diesel trucks using waste heat from the engine. |
| Leonardo Technologies | Currently funded by the U.S. Army (ERDC/CERL) to demonstrate their generator in combination with fuel cells and other sources of waste heat. |
| Tellurex Corporation | Tellurex continues to work with Michigan State University, who is developing new materials. |

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# 1
# INTRODUCTION

The objective of this report is to evaluate the technical and economic feasibility of thermoelectric power generation technology for utility applications. This report provides a worldwide assessment of thermoelectric power generation systems covering technical trends, commercialization status, and economic feasibility. The study initially looked for those technologies and products that may be configured to provide greater than 5 kW of AC electric power. However, current thermoelectric manufacturers do not have products over 500 watts. The assessment includes thermoelectric power generation designs of commercially available and emerging technologies for utility applications.

## Motivation for the Report

This report supports EPRI’s goal of providing utility members with information about emerging technologies that may offer new business opportunities and customer solutions.

High manufacturing costs and very low power generation efficiencies (2% - 5%) of thermoelectric power generators have prohibited the economical, large-scale production and use of these devices as a viable alternative energy source. However, recent progress in materials and manufacturing has demonstrated the potential to lower costs and increase the power generation efficiency. Therefore, thermoelectric devices may have the potential to cost effectively use waste heat from distributed generation technologies (i.e., fuel cells, reciprocating engines) or other heat sources for supplemental power generation.

## Organization for the Report

The information presented in this report was obtained through secondary research consisting of literature and web-based searches, and telephone interviews with seven vendors that are involved in the development and/or sales of thermoelectric power generation technology.

Section 2 - *Technology Overview* section summarizes the various types and configurations of thermoelectric power generations, describes how thermoelectric power generations work, and explains the basic theory behind thermoelectric power generation operation.

Section 3 - *Technology Trends* section introduces the thermoelectric power generation vendors and compares the various design approaches that are being taken. Technical obstacles are also addressed in this section.

Section 4 – *Technology Characteristics and Costs* section covers the performance characteristics of existing thermoelectric power generation products and the different cost components associated with technology, including capital cost, installation cost, and operation and maintenance (O&M) cost.

Section 5 - contains *Conclusions*.

A detailed profile of each vendor, including contact information, is contained in Appendix A of this report. Each profile contains company background, a description of the technology, and a discussion of the product status.

# 2
# TECHNOLOGY OVERVIEW

In a thermoelectric device, electric power is generated by a voltage difference that appears across an electrical loop formed by two dissimilar metals or semiconductors, when the two junctions between them are kept at different temperatures. Like a Stirling engine, thermoelectric devices can be configured to operated  as power producers (the Seebeck effect) or as heat pumps (the Peltier effect). Thermoelectric devices are highly reliable, but offer very low energy conversion efficiency (2%-5%).

Thermoelectric research is primarily materials science research, since the energy conversion efficiency is set by the properties of the materials used, including the electrical conductivity, Seebeck coefficient, and thermal conductivity. The thermoelectric figure of merit that combines these material properties is ZT (equal to the electrical conductivity times the Seebeck coefficient squared divided by the thermal conductivity). A ZT of one corresponds to an energy conversion efficiency of about 8%. Current materials research objectives are to achieve a ZT of 4, which corresponds to an efficiency of about 23% (for a cold source temperature equal to half the hot source temperature on an absolute scale).

## Principles of Operation

Thermoelectric power generators exploit the Seebeck effect. The Seebeck effect is an induced voltage in the presence of a temperature gradient. (The familiar thermocouple indicates temperature by correlating this voltage with the temperature difference between the hot and cold junctions..) The voltage and associated current flow can be used for power generation. A thermoelectric power generation module is composed of individual thermocouples (ranging from a single thermocouple to hundreds). Each thermocouple junction contains two different materials, joined together. A simplified diagram of a single thermocouple is shown in Figure 2-1. The thermocouple conductors are materials denoted X and Y. When heat is applied to junction B and junction A is kept cool, a voltage occurs across terminals $T_1$ and $T_2$.

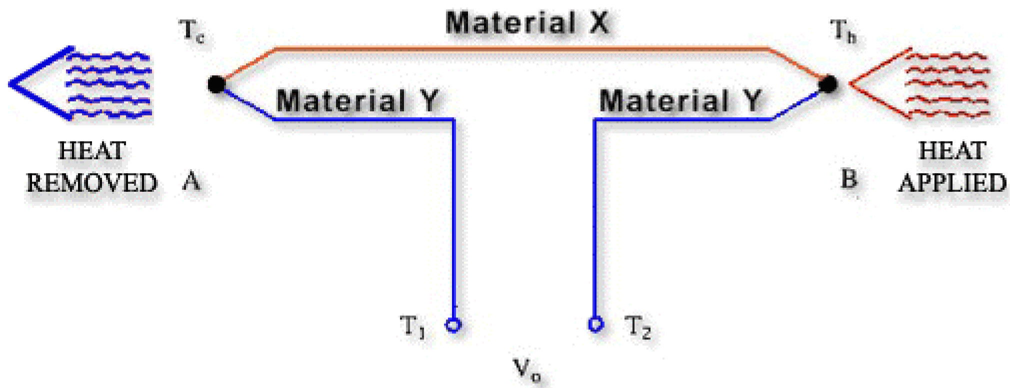



**Figure 2-1**
**Diagram of the Seebeck Effect**

The Seebeck voltage in Figure 2-1 can be expressed as:

$$V_0 = S_{xy}\left(T_h - T_c\right)$$

Where: $V_0$ = Voltage across the thermocouple (volts)
$S_{xy}$ = Differential Seebeck coefficient between the two materials, x and y (volts/$^o$K)
$T_h$ = Hot thermocouple temperature ($^o$K)
$T_c$ = Cold thermocouple temperature ($^o$K)

The Peltier effect results in cooling/heating occurring at the junctions of dissimilar materials in the presence of an electrical current. The Peltier effect is the reverse of the Seebeck effect and acts as a heat pump. In Figure 2-2, this is illustrated by applying a voltage across terminals $T_1$ and $T_2$. As a result of the current flow, I, cooling (heat absorption) will occur at the junction A and heating will occur at junction B.

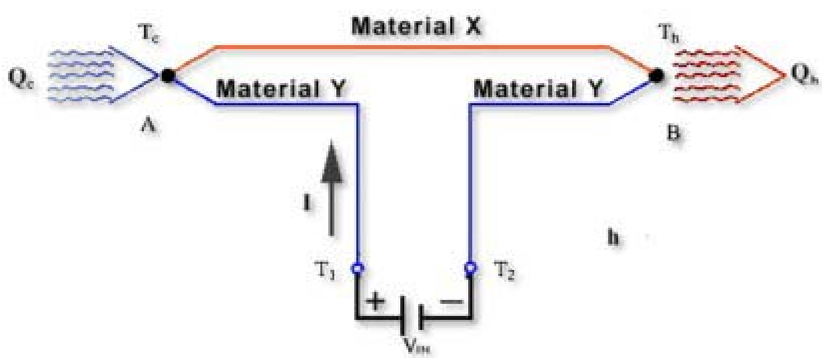



**Figure 2-2**
**Diagram of the Peltier Effect**

The rate of cooling or heating ($Q_c$ or $Q_h$) can be expressed as follows:

$$Q = p_{xy} I$$

Where: $Q$ = Heat absorbed or released (watts)
$p_{xy}$ = Differential Peltier coefficient between two materials, x and y (volts)
$I$ = Electric current flow (amperes)

The performance of a thermoelectric module can be predicted by the properties of the materials used in the device. The material-based figure-of-merit used for this purpose is defined as:

$$ZT = \frac{S^2 \sigma}{\lambda} T$$

Where: $ZT$ = Figure-of-merit
$S$ = Seebeck coefficient of the material (microvolts/K)
= Electrical conductivity of the material (1/ohm-meter)
= Thermal conductivity of the material (W/m-K)
$T$ = Absolute temperature (K)

In current commercial practices, a ZT of one is considered a high value and corresponds to an efficiency of approximately 8%. The efficiency is calculated with the following equation.

$$\eta = \left( \frac{T_h - T_c}{T_h} \right) \left( \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_c}{T_h}} \right)$$

Where: = Electrical efficiency, yield (kWe/kWth)
$T_h$ = Hot junction temperature (K)
$T_c$ = Cold junction temperature (K)
$ZT$ = Figure of merit

The efficiency of a thermoelectric module with a Tc/Th = 0.5 (e.g. Th=524 K and Tc=262K) is illustrated in Figure 2-3.

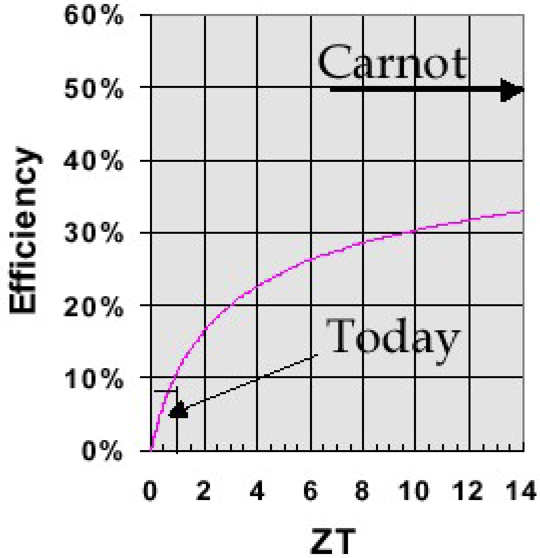



**Figure 2-3**
**Efficiency as a Function of the Figure of Merit, ZT (Tc/Th = 0.5)**

## Thermoelectric Materials

Initially, metals were the primary material used for thermoelectric power generation. Although the properties favored for good thermoelectric materials were known, the advantages of semiconductors as thermoelectric materials were neglected and research continued to focus on metals and metal alloys. These materials, however, have a constant ratio of electrical conductivity ( ) to thermal conductivity ( ) (Widemann-Franz-Lorenz law), so it is not possible to increase one without increasing the other. Metals best suited to thermoelectric applications should, therefore, possess a high Seebeck coefficient (S). Unfortunately, most possess Seebeck coefficients on the order of 10 microvolts/K, resulting in generating efficiencies of only fractions of a percent.

It was during the 1920's that the development of synthetic semiconductors with Seebeck coefficients in excess of 100 microvolts/K rekindled interest in thermoelectricity. At this time, it was not apparent that semiconductors were superior thermoelectric materials due to their higher ratio of electrical conductivity to thermal conductivity when compared to metals. Figure 2-4 illustrates experimental ZT values for several thermoelectric material combinations. Research and development of the higher temperature material combinations is primarily located at NASA's Jet Propulsion Laboratories, and universities.

Hi-Z Technology, Inc. is known to have put some effort into testing high temperature materials such as SiGe. These might eventually be employed for "topping cycles" in moderate temperature fuel burners.

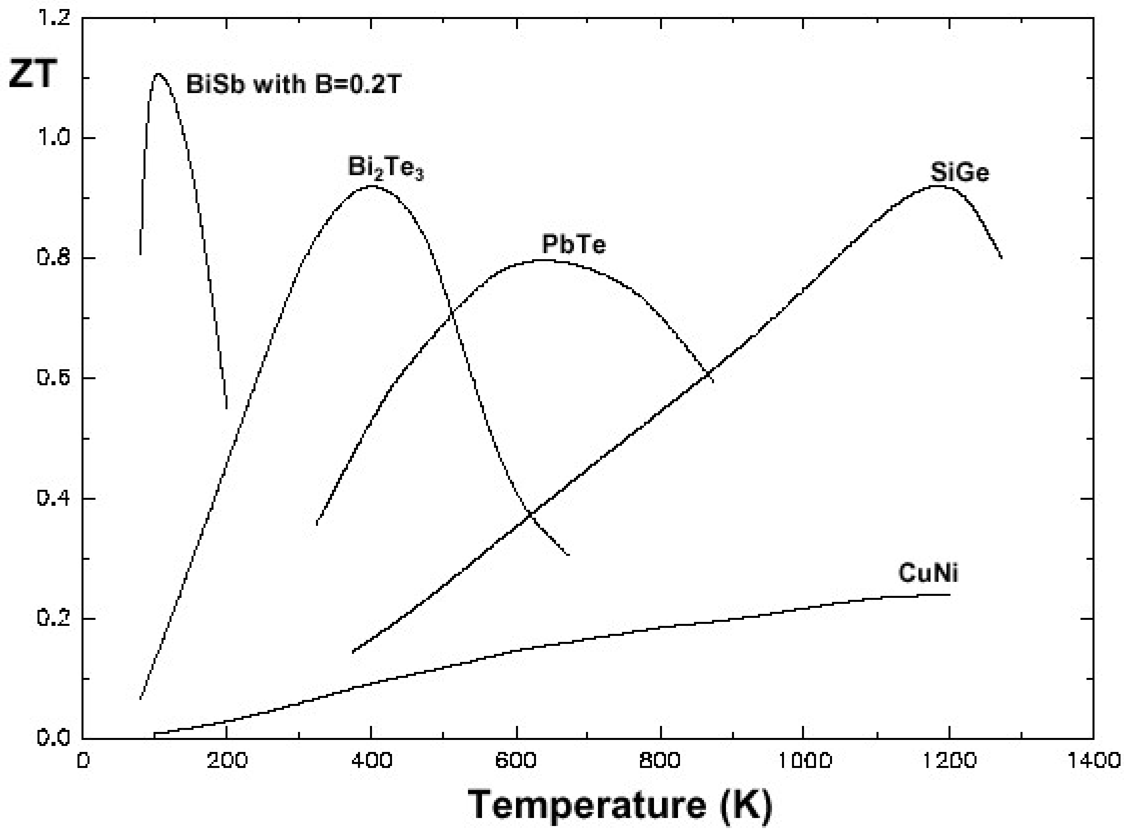



**Figure 2-4**
**Experimental ZT Results for Various Thermoelectric Materials**

Developers are now looking to quantum-well materials for higher efficiencies. A quantum-well material is a two dimensional material sandwiched between two barrier layers. Some of these materials include $B_4C/B_9C$ and$Si/Si_{0.8}Ge_{0.2}$. Hi-Z has performed tests in the laboratory achieving 14% energy conversion efficiency, and maintains a goal of 20-30%. The 14% efficiency was obtained at a temperature (250°C) compared to that used with conventional materials (such as Bismuth-Telluride). The newly tested quantum-well materials are currently under development and require further testing prior to commercialization.

# 3
# TECHNOLOGY TRENDS

The technology trends section reviews the history of thermoelectric research and development (R&D). The leading companies involved in thermoelectric power generation today are introduced and the strengths and weaknesses of the technology are discussed. In addition, the markets and applications for thermoelectric power generators are identified. This section also provides the research and development activities of the leading thermoelectric power generation companies.

## Research and Development History

In 1821, Thomas Johann Seebeck discovered that a compass needle deflects when placed in the vicinity of a closed loop formed from two dissimilar metal conductors if the junctions were maintained at different temperatures. He also observed that the magnitude of the deflection was proportional to the temperature difference. The deflection was also dependent on the type of conducting material and did not depend on the temperature distribution along the conductors.

In 1834, Jean Peltier discovered that the reverse phenomenon occurred where thermal energy is absorbed at one junction and discharged at a second junction in the presence of an electrical current flowing in the closed circuit. Twenty years later, William Thomson (Lord Kelvin) issued a comprehensive explanation of the Seebeck and Peltier Effects and described their interrelationship.

- The Seebeck Effect is an induced voltage in the presence of a temperature gradient used for power generation.
- The Peltier Effect results in pumping heat from a cool junction to a hot junction of dissimilar materials in the presence of an electrical current.

In the 1930's, Russian scientists began studying some of the earlier thermoelectric work in an effort to construct power generators for use at remote locations. This Russian interest in thermoelectricity eventually spread to the rest of the world.

Thermoelectric generators have traditionally been used in highly specialized applications such as power systems for operations in the polar regions and in outer space due to simplicity of the cycle design, as well as compact size with no moving parts. In these applications, the high costs and low power generation efficiencies were not primary concerns. However, with the increasing importance of energy conservation issues and decreasing costs, thermoelectric development has seen an effort to design efficient, low-cost products for commercial power generation markets.

Today's thermoelectric devices make use of modern semiconductor technology -- doped semiconductor material takes the place of the dissimilar metals used in early thermoelectric experiments.

## Thermoelectric Power Generation Technology Developers

The research phase of this project identified 7 companies worldwide that are involved in the development and/or sales of thermoelectric generators and/or thermoelectric power generation components.

Most of the companies in this report offer thermoelectric components. Only two of the seven developers offer commercial thermoelectric power generator modules as turnkey systems. Table 3-1 lists the seven thermoelectric generator (TEG) companies and their product offerings.

**Table 3-1**
**Thermoelectric Power Generation Technology and Product Developers**

| Company | Country | TEG Components | TEG Modules |
|---|---|---|---|
| DTS GmbH | Germany | ✓ | |
| Global Thermoelectric | Canada | ✓ | ✓ |
| Hi-Z Technology, Inc. | US | ✓ | ✓ |
| Beijing Huimao Cooling Equipment Co., Ltd. | China | ✓ | |
| Leonardo Technologies, Inc. | US | ✓ | |
| Taihuaxing Trading Co., Ltd. | China | ✓ | |
| Tellurex Corporation | US | ✓ | |

## Markets and Applications

The most common applications of thermoelectric devices are:

- Space power - Seebeck
    - Radioisotope power sources for deep space probes
    - 250,000,000 device-hours without a single failure
- Remote power (oil pipelines, sea buoys) - Seebeck
- Thermometry - Seebeck
- Refrigeration - Peltier

Recent research has also focused on the development of economic thermoelectric generators for waste heat recovery, e.g., using the thermal energy in vehicle tailpipe exhaust for electric power generation (primarily for military applications), or using the waste heat from central heating systems. Generators can operate off waste warm water as cool as 200° F. Recent advances in thermoelectric generation include high-power-density thermoelectric generating modules, heat-and-power cogeneration systems, heat-recirculating thermoelectric-combustion systems, and micro-scale thermoelectric converters.

Another application of thermoelectric generation is to prevent corrosion in producing oil and gas wells and pipelines fueled by the gas or oil in the pipeline. TEG offers unattended, continuous power for impressed-current cathodic protection systems in pipelines and well casings. With high reliability, low-maintenance requirements and minimal gas consumption, such generators also have comparatively negligible operating costs. Other continuous, low-power applications are for power remote telemetry units, gas analyzers and metering equipment, as well as for routine operating functions and emergency shutdown and to provide primary power for unmanned platforms and backup power on manned platforms for critical communications and emergency shutdown systems.

With the initiation of major waste-heat recovery programs in Japan, thermoelectric devices may have higher potential even with a higher capital cost to avoid high electric energy costs. Thermoelectric generators are well suited for waste heat recovery from distributed generation equipment. Table 3-2 includes the typical exhaust temperatures for several DG technologies. Table 3-3 lists the acceptable high side temperatures of the thermoelectric generators discussed in this report. Table 3-4 compares the different TEG developers and the potential of their products to generate supplemental electricity from DG waste heat. It is clear that most thermoelectric generation equipment is compatible with many DG technologies.

**Table 3-2**
**Thermal Characteristics of DG Technologies**

| Distributed Generation Technology | | Exhaust Temperature | | Heat Form |
|---|---|---|---|---|
| | | °F | °C | |
| Reciprocating Engine | | 180-900 | 82-482 | hot water, LP and HP steam |
| Combustion Turbine | | 500-1,100 | 260-593 | hot water, LP and HP steam |
| Microturbine | | 400-650 | 204-343 | hot water, LP steam |
| Fuel Cells | PAFC | 140-250 | 60-121 | hot water |
| | PEMFC | 120-170 | 49-77 | hot water |
| | MCFC | 700-800 | 371-427 | hot water, LP and HP steam |
| | SOFC | 1,400-1,800 | 760-982 | hot water, LP and HP steam |

**Table 3-3**
**Thermal Requirements of TEG Devices**

| Company | Maximum Continuous High Temperature | | Maximum Intermittent High Temperature | |
|---|---|---|---|---|
| | °F | °C | °F | °C |
| DTS GmbH | n/a | n/a | n/a | n/a |
| Global Thermoelectric | n/a | n/a | n/a | n/a |
| Hi-Z Technology, Inc. | 480 | 250 | 750 | 400 |
| Beijing Huimao Cooling Equipment Co., Ltd. | n/a | n/a | n/a | n/a |
| Leonardo Technologies, Inc. | 572 | 300 | n/a | n/a |
| Taihuaxing Trading Co., Ltd. | 500 | 260 | 680 | 380 |
| Tellurex Corporation | 329-365 | 165-185 | n/a | n/a |

n/a – information not available

The maximum high temperature is the maximum allowable temperature without degrading the thermoelectric device. Intermittent temperatures can be somewhat higher than continuous operating temperature without unacceptable degradation. Higher temperatures raise the vaporization rate, causing the thermoelectric generator to begin losing semiconductor material. Degradation occurs at high temperatures, increasing resistivity, causing a reduction in electrical conductivity, a corresponding reduction in the figure of merit and electrical efficiency, and decreasing the life of the module.

**Table 3-4**
**Thermoelectric Generators Using Waste Heat from DG Power Generators**

| | DG Technologies | | | | | | |
|---|---|---|---|---|---|---|---|
| **Companies** | Reciprocating Engine | Combustion Turbine | Microturbine | PAFC | PEMFC | MCFC | SOFC |
| DTS GmbH | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Global Thermoelectric | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Hi-Z Technology, Inc. | ● | ❍ | ● | ● | ● | ❍ | --- |
| Beijing Huimao Cooling Equipment Co., Ltd. | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| Leonardo Technologies, Inc. | ● | ● | ● | ● | ● | --- | --- |
| Taihuaxing Trading Co., Ltd. | ● | ❍ | ● | ● | ● | --- | --- |
| Tellurex Corporation | ● | --- | --- | ● | ● | --- | --- |

● = Continuous operation
❍ = Intermittent operation
--- = Applicable with exhaust temperature reduction
n/a = Information unavailable for DTS, Global Thermoelectric and Beijing Huimao

## Technical Obstacles

The major technological hurdle faced by thermoelectric power generation has been increasing the efficiency of converting heat into electricity. Conventional efficiencies of 2-5% are inadequate for most potential applications. Research has focused on evaluating new materials, designating the most important material traits to increase the efficiency, and altering existing materials.

Several companies active in thermoelectric research and development have identified new materials and demonstrated efficiencies of roughly 14% in the lab operating at the same high temperature as conventional (bismuth-telluride) thermoelectric generators (250° C).

## Strengths and Weaknesses

Commercial stand alone thermoelectric generators have a wide range of strengths that are important for many market applications. Strengths of the thermoelectric power generator include:

- High reliability (>250,000 hours)

- Low noise
- No vibrations
- Small size
- Lightweight
- Decreased life cycle costs
- No compressed gases or chemicals
- Environmentally benign

The main disadvantages of thermoelectric power generators are the low electrical efficiency and the high initial cost. The low efficiency does not make the TE generator economical for most commercial applications. Specialized niche market applications will continue to benefit from the strengths of thermoelectric generators until the efficiency can be increased enough to make the TE generator prove economical.

## Development Issues

Developers are focused on two primary issues, both aimed at reducing costs of manufacturing and operating a thermoelectric device. They are:

- Improving manufacturing processes
- Increasing efficiency

The first issue, improving manufacturing processes, is intended to decreasing production costs to manufacture thermoelectric devices. Computer component manufacturers produce high volumes of products using semiconductor materials. Many of these manufacturing techniques carry over to thermoelectric device production, lowering costs.

The second development issue, increasing efficiency, is pushing research and development groups to explore material properties to find ways to increase the figure of merit (ZT). A higher ZT corresponds to higher energy conversion efficiency. Currently, 8% energy conversion is possible with conventional materials and some companies are claiming to have achieved 14% with new material research.

Table 3-5 outlines the research and development work several companies are pursuing to address the development issues discussed above.

**Table 3-5**
**Thermoelectric Power Generation Research and Development Activity**

| Company | Research and Development Activity |
|---|---|
| D.T.S. GmbH | D.T.S. continues to focus on the micro-scale thermoelectric power generation market, geared toward self-powered digital displays and recharging mobile electronics. |
| Global Thermoelectric | Global is testing larger systems specifically for offshore drilling applications. |
| Hi-Z | Testing new materials, $B_4C$-$B_9C$-SiGe. Has achieved efficiency in the lab of 14% at roughly 250°C. Hi-Z hopes to achieve 20-30% efficiency and develop larger systems (>1kW).<br><br>Hi-Z currently has a 1kW power generation system built for use in diesel trucks using waste heat from the engine. |
| Leonardo Technologies | Currently funded by the U.S. Army (ERDC/CERL) to demonstrate their generator in combination with fuel cells and other sources of waste heat. |
| Tellurex Corporation | Tellurex continues to work with Michigan State University, who is developing new materials. |

# 4

# TECHNOLOGY CHARACTERISTICS AND COSTS

This section of the report highlights some of the performance characteristics of today's thermoelectric power generators. It also addresses the economic concerns and goals of the developer companies.

## Performance Characteristics

Developers have taken a variety of approaches in order to increase the appeal of thermoelectric power generations to customers. Some of the approaches include:

- Improving efficiency
- Extending overall product lifetime
- Decreasing cost through less expensive materials

Thermoelectric power generators are capable of using waste heat from a variety of sources to generate electric power, e.g., thermal energy from heating systems in the form of warm water, and waste heat off truck engines, distributed power generation equipment, or any other source capable of providing the appropriate heat requirement. Other sources of thermal energy include any gas or liquid combustible fuel and solar heat (typically in space applications).

There are several size classes of thermoelectric devices. Small systems are typically used for small-scale power electronics and space applications in the micro-watt range. Mid-size thermoelectric systems are roughly 1-500 watts. Large thermoelectric systems are greater than 1 kW and would be useful for utilities if they had adequate efficiencies. Currently, the small scale products are used for niche applications where the low efficiency is not a concern. The mid-size products are commercially available with an efficiency range of 2% to 5%. Products with higher efficiencies and large power output are in the development stage. Table 4-1 includes the performance characteristics of the different thermoelectric power generators available. Leonardo reports the highest efficiency, but this product is not currently available and has been demonstrated only in a laboratory setting.

**Table 4-1**
**Thermoelectric Power Generation Performance Characteristics**

| Company | Power Output (watts) | Energy Conversion Efficiency %, HHV |
|---|---|---|
| DTS GmbH | 10 – 40 * 10-6 | n/a |
| Global Thermoelectric | 15 – 550 | 2.1 – 3.2 |
| Hi-Z Technology, Inc. | 2 – 19 | 4.5 |
| Beijing Huimao Cooling Equipment Co., Ltd. | n/a | n/a |
| Leonardo Technologies, Inc. | 8 – 800 | 12 – 14 |
| Taihuaxing Trading Co., Ltd. | 2.6 – 14.7 | n/a |
| Tellurex Corporation | 2 – 12 | 3 – 5 |

Current technology commercially available can achieve efficiencies ranging from 2% to 5%. Higher efficiencies have been reported by conventional technologies up to roughly 8%. Several companies, through lab research, development, and testing have achieved even higher efficiencies, ranging from 12% to 14%. These systems utilize new materials and require additional work to move to full-scale commercial production.

The thermoelectric generator itself does not produce any emissions, but if a fuel is combusted to create the heat to operate the thermoelectric generator, emissions will be produced from that process. Thermoelectric generators do not emit any vibration, and the low amounts of noise are only related to the heat source.

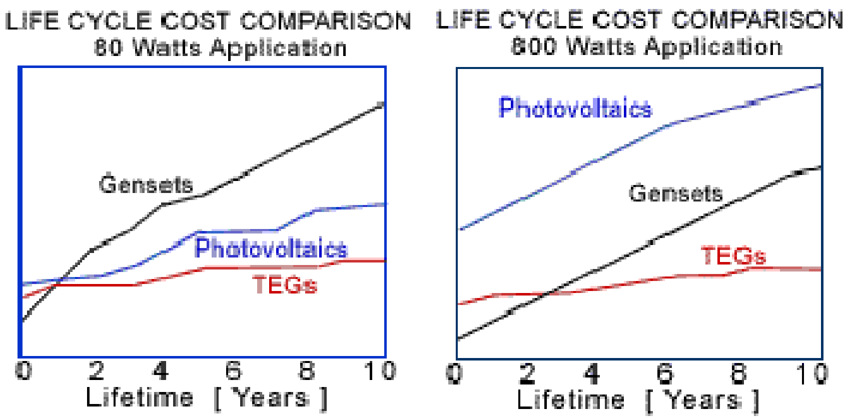
Thermoelectric generators have operated more than 250,000,000 device-hours without a single failure in space applications. The generators are highly reliable with no moving parts. Maintenance requirements are typically a couple hours a year. The generators also have a long life, up to 20 years, according to Global Thermoelectric.

## Costs

Hi-Z Technology offers four products (2.5, 9, 14, and 19 watts). The price per unit varies based on the quantity purchased. The largest unit, HZ-20, has a power output of 19 watts and costs per unit vary from $4,470/kW to $8,100/kW. This is comparable to the prototype cost of the Leonardo system of $5,000/kW.

Hi-Z Technology suggests that a system with an efficiency of 20-30% and output power greater than 1 kW could be produced for $100-150/kW. EI views this as very optimistic and unlikely to be achieved in the near future.

In Figure 4-1, Global Thermoelectric compares the life cycle costs of a photovoltaic system, ICE generator set, and thermoelectric generator for an 80 and 800-Watt applications as a function of lifetime. Although ICE has the lower cost for short-term installations, the figure shows that thermoelectric generators are favorable for installation lifetimes over three years for the 800 watt system (over one year for the 80 W system). The photovoltaic system in this example assumes a southern U.S. state with high light intensity. Fuel costs are included and the discount rate is 10%.




(Courtesy of Global Thermoelectric)

**Figure 4-1**
**Life Cycle Cost Comparison for 80 and 800 Watt Remote Power Applications**

While the capital and fuel costs of diesel and natural gas internal combustion engine (ICE) generator sets are typically lower than that of thermoelectric generators, ICE generator sets require a skilled technician to perform regular maintenance. Since thermoelectric generators require almost no maintenance, ICE generator sets have higher operational costs, more downtime, and lower overall reliability. When the complete life-cycle costs are compared, thermoelectric generators can have lower life-cycle cost. In addition, the greater inherent reliability of thermoelectric generators over ICE generator sets provides an important advantage in remote locations.

In contrast, photovoltaic systems have higher capital costs than thermoelectric generators, lower fuel costs, and similar maintenance requirements. Although properly sized photovoltaic systems have shown promise in providing low-power solutions in areas with high solar insolation, solar users often turn to thermoelectric generators because of problems with reliability, short battery life, and theft. Thermoelectric generators have a 20-year design life and require minimal maintenance over the life of the system. An equivalent photovoltaic system would require 20-year life batteries—the cost of batteries alone can be as much as the thermoelectric generator. Studies have shown that when the capital cost of a photovoltaic system is based on medium-life batteries (i.e., 10 years), the true life-cycle cost of the solar system is much higher than that of a thermoelectric generator due to the high cost of battery replacement and higher maintenance costs. In contrast to solar systems, theft and vandalism are not a concern with thermoelectric generator systems, which are small and unobtrusive and can be mounted inside security shelters, if required.

# 5
# CONCLUSIONS

The objective of this report is to evaluate the technical and economic feasibility of thermoelectric power generation technology for utility applications. The report focuses on the developments of seven thermoelectric power-generator companies:

- D.T.S. GmbH
- Global Thermoelectric Inc.
- Hi-Z Technology, Inc.
- Beijing Huimao Cooling Equipment Co., Ltd.
- Leonardo Technologies, Inc.
- Taihuaxing Trading Co., Ltd.
- Tellurex Corporation

The analysis of the above manufacturers and their thermoelectric power generation products resulted in the following conclusions:

- The stated objective of this project was to investigate products greater than 5 kW; however, most companies have focused on products with less than 1-kW power output. Thermoelectric power generator manufacturers do not plan to pursue systems larger than 1 kW until the energy conversion efficiency is high enough to make the system economical for the required application.
- The efficiency achieved by conventional technology types ranges from 2% to 5%, with a high of 8%.
- New materials research and product development has shown efficiencies as high as 14% in the testing facility.
- Thermoelectric generators are being developed for use in combination with distributed power generators to utilize the waste heat for additional power generation, increasing the overall system efficiency.
- The research and development activities of five of the above companies that will determine the future of thermoelectric products are outlined in Table 5-1.

**Table 5-1**
**Thermoelectric Power Generation Research and Development Activity**

| Company | Research and Development Activity |
|---|---|
| D.T.S. GmbH | D.T.S. continues to focus on the micro-scale thermoelectric power generation market, geared toward self-powered digital displays and recharging mobile electronics. |
| Global Thermoelectric | Global is focused on developing products for niche applications, i.e., TE generator rated for hazardous operation. |
| Hi-Z | Testing new materials, $B_4C$-$B_9C$-SiGe. Has achieved efficiency in the lab of 14% at roughly 250°C. Hi-Z hopes to achieve 20-30% efficiency and develop larger systems (>1kW).<br><br>Hi-Z currently has a 1kW power generation system built for use in diesel trucks using waste heat from the engine. |
| Leonardo Technologies | Currently funded by the U.S. Army (ERDC/CERL) to demonstrate their generator in combination with fuel cells and other sources of waste heat. |
| Tellurex Corporation | Tellurex continues to work with Michigan State University, who is developing new materials. |

# A
# COMPANY PROFILES

Profiles of the following vendors that are involved in the development and/or sales of thermoelectric power generation technology are included here:

- D.T.S. GmbH
- Global Thermoelectric Inc.
- Hi-Z Technology, Inc.
- Huimao Cooling Equipment
- Leonardo Technologies Inc.
- Taihuaxing Trading/Thermonamic Electronics
- Tellurex Corporation

The profiles for each developer include the following information:

- Company history
- Financial status of the company
- Description of the technology
- Planned or existing products
- Physical and performance specifications
- Commercialization plans and status
- Present cost and future projections
- Competitive advantages
- Technical, manufacturing, and/or commercialization obstacles

## D.T.S. GmbH (Thin Film Thermoelectric Generator Systems GmbH)

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Fax: +49 (0) 345 52 44 292
E-mail: dts@dts-generator.com
Web: http://www.dts-generator.com
Contact: Dr. rer. nat. habil. M. Stordeur (chief executive manager)
E-mail: stordeur@dts-generator.com

D.T.S. is developing end-use applications for thin-thermoelectric films.

### *Company Background*

D.T.S., located in Halle, Germany, manufactures low power (10-40µW) thin film thermoelectric power generators in micro-electronic or micro-systemic modules. D.T.S also manufactures sensor systems in the small performance range and IR-radiation detectors.

D.T.S. has developed a thin-film thermoelectric generator which converts thermal energy into electrical energy directly and whose output is compatible to the requirements of recent micro electronic and micro-matched system loads. Low Power Thermo Generators (LPTGs) are self-sufficient energy sources for the electrical small performance range which are harmless to the environment.

D.T.S. can also develop LPTGs with customized thermal and electrical design parameters.

D.T.S. uses up-to-date high-vacuum deposition equipment to prepare thin thermoelectric films and to solve many different deposition tasks.

### *Technology Overview*

The LPTG is an application of the thermoelectric principle and converts thermal energy directly into electrical energy. Using an available temperature difference (i.e., waste heat from an electronic device) as an energy source, the LPTG has a potential output of 10-40 µW with an output voltage of a few volts.

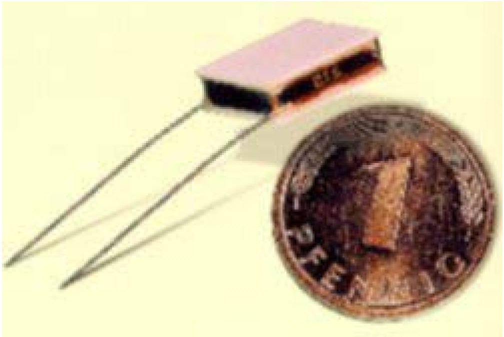

**Figure A-1**
**DTS Thermoelectric Generator**

Because of the thin-film technology, a miniaturized construction with a volume of 0.2 $cm^3$ can be achieved (see Figure A-1) and its electrical data are compatible with the requirements of recent micro systems.

The LPTG can be a self-sufficient energy source for micro and sensor systems in consumer and industrial applications, such as:

- Electronic heat cost allocators
- Electronic wrist watches
- Active transponders
- Self-sufficiently powered temperature displays
- Self-sufficiently powered temperature warning systems
- Recharging of mobile electronics

### *Technology Status and Products*

The design of the thermoelectric generator and its electrical and thermal parameters are adjustable for specific applications. General specifications for the D.T.S. products are in Table A-1.

**Table A-1**
**D.T.S. Product Specifications**

| Characteristic | Units | Value | Error |
|---|---|---|---|
| Power Output | µW | 10-40 | --- |
| Length | mm | 9.0 | ±0.05 |
| Width | mm | 7.5 | ±0.05 |
| Height | mm | 2.8 | ±0.1 |
| Connector Length | mm | 2 x 80 | --- |
| Connector Diameter | mm | 0.2 | --- |
| Mass | mg | 390 | --- |

A demonstration appliance is available to visualize the mode of operation and performance of the LPTG. The principle assembly consists of the following parts:

- Temperature control
- Temperature displays
- Low-power management with load and displays for the electrical consumption of the load

**Figure A-2**
**LPTG Demonstration Device Powering a Wristwatch**

The demonstration appliance creates a fixed temperature difference between the warm and cold side, i.e., between the heat-couple plates of the LPTG. As a result, a thermoelectric voltage is generated and, in the closed circuit, an electric current flows. The load (e.g., a wristwatch) and the low-power management are directly supplied by only the LPTG. The four-digit displays of the demonstration appliance show the technical working status of the electrically separate temperature control circuit (warm side and cold side temperature) and load (wristwatch) circuit (electrical voltage and current of the load).

### *EPRI Perspective*

The thermoelectric power generation equipment manufactured by D.T.S. produces an extremely small power output (10-40µW). This equipment is geared toward small-scale applications such as self-powered digital displays and recharging mobile electronics. There is no indication that they will be developing bulk power modules in the near future.

## Global Thermoelectric, Inc.

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E-mail: globalhq@globalte.com; tegsales@globalte.com

### *Global Thermoelectric Corp. (U.S.)*

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E-mail: tegs@globalteusa.com

*On August 4, 2003, Global Thermoelectric and FuelCell Energy announced that the two companies have entered into an agreement for FuelCell Energy to acquire Global Thermoelectric. Global's previous agreement with Quantum Fuel Systems Technologies Worldwide, Inc. was terminated as a result of the proposed combination with FuelCell Energy.*

Founded in 1975, Global Thermoelectric, Inc. (Global) is based in Calgary, Alberta, Canada, and is the world's largest supplier of thermoelectric generators.

Global thermoelectric generators are operating in remote areas in over 45 countries around the world. In 2001, Global generated total revenues of C$15.4 million (about US$10 million), all in the thermoelectric generator division.

Global manufactures lead tin-telluride thermoelectric power generators that range in output size from 15 to 550 watts, and are available for applications up to 5 kW. Current applications include power for remote control and monitoring of oil or gas pipelines and production facilities, as well as power for navigational aids, telecommunications systems, and cathodic protection of pipelines and well casings. The thermal conversion efficiency using natural gas or propane ranges from 2.1% to 3.2% (electrical, HHV).

### *Company Background*

Global Thermoelectric (Global), based in Calgary, Alberta, was established in 1975 to commercialize 3M’s thermoelectric generator technology that was originally developed for the Apollo space program. Global now has 95% of the market share for thermoelectric generators, which they sell in over 45 countries for a variety of remote applications up to 5 kW, including pipeline cathodic protection, instrumentation power, and telecommunications. Thermoelectric products are manufactured in the Generator Manufacturing Plant in Bassano, Alberta.

Global also has a fuel cell division, opened in 1997, to develop and commercialize planar solid oxide fuel cell systems that utilize cogeneration.

The thermoelectric generator division has about 40 employees, while the fuel cell division has over 100 employees.

## Financial Status

Global is a publicly held company listed on The Toronto Stock Exchange under the symbol GLE. As shown in Table A-2, Global generated total revenues of C$15.4 million (about US$10 million) in 2001, with a gross margin of C$4.9 million (about US$3.2 million). Sales of thermoelectric generators decreased in 2001 when compared to the previous year as a result of the completion in 2001 of a large contract (exceeding C$19 million) with the Gas Authority of India. In addition, Enbridge invested $25 million dollars (preferred stock) into Global in July of 2000 for fuel cell research and development. Global has liquid assets of $100 million in the bank, dedicated to fuel cell development efforts.

**Table A-2**
**Global Thermoelectric Financial Data (Canadian $)**

| Financial Data (000s) | 2001 | 2000 |
|---|---|---|
| Revenue | $ 15,357 | $ 25,392 |
| Gross margin | 4,883 | 7,006 |
| Investment income | 5,911 | 3,894 |
| Research, engineering and development – net | 15,087 | 5,870 |
| Net loss from continuing operations | (12,968) | (445) |
| Net earnings (loss) from discontinued operations | 1,177 | (233) |
| Net loss | (11,791) | (678) |
| Dividends on preferred shares | 500 | 482 |
| Capital expenditures | $ 9,007 | $ 5,765 |
| Financial Position (000s) | | |
| Cash and short-term investments | $ 121,064 | |
| Capital assets - net | 15,286 | |
| Total assets | 146,849 | |
| Share capital | 158,821 | |
| Accumulated deficit | $ (20,274) | |

Source: Global Thermoelectric Inc. Annual Report 2001

## *Technology Overview*

As illustrated in Figure A-3, the three main parts of Global's solid-state thermoelectric generator are a burner, the thermopile, and cooling fins. As heat moves from the gas burner through the thermoelectric module, it causes an electrical current to flow. The heart of Global’s thermoelectric generator is a hermetically sealed thermoelectric module (thermopile), which contains an array of lead-tin-telluride semiconductor elements. Global's generators range in output size from 15 to 550 watts, and can be paralleled for applications up to 5,000 watts.

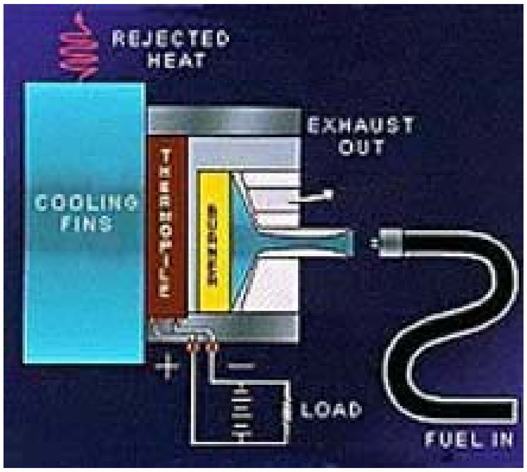


**Figure A-3**
**The Main Parts of Global's Thermoelectric Generators are a Burner, Thermopile, and Cooling Fins (Drawing Courtesy of Global Thermoelectric)**

According to Global, the competitive advantages of their thermoelectric generators include:

- High Reliability: The solid-state design (with no moving parts) provides trouble-free operation
- Low Maintenance: Requires one to two hours a year
- Competitive Price: Low capital and operating costs for systems up to 5,000 watts (as compared to photovoltaic and other thermoelectric systems)
- Long Life: Hermetically sealed thermopile has a 20-year life
- Easy Installation: Typically requires less than a day to install and commission
- Continuous Operation: Field proven, they operate unsheltered in all climates and weather conditions and are not affected by salt spray, bird droppings, or airborne contaminants

The most advantageous applications of thermoelectric generators are situations with the following characteristics:

- Load requirements from 15 to 5,000 watts
- Critical application requiring highly reliable power
- Low maintenance is required
- Long life is important
- Extreme climatic conditions (hot, cold, wet, dry) exist
- Remote or unattended location

## Commercialization Obstacles

Global has found that customer demand for thermoelectric generators has historically been contingent on regional natural gas development drilling and pipeline activity, which in turn has been affected by the relative strength in natural gas prices. The prospect of continued gas exploration and development in such areas as the Mackenzie Delta in northern Canada also provides additional longer-term opportunities for Global's products. The market for Global's thermoelectric generators is expected to expand as other countries around the world develop their natural gas infrastructure. The construction of natural gas and liquids pipelines in developing countries has typically provided sales opportunities for Global’s generators.

Global Thermoelectric Inc. received a Letter of Intent from the Gas Authority of India Ltd. (GAIL) for a US$3.6 million order of thermoelectric power systems for GAIL's Vizag-Secunderabad LPG Pipeline Project. Global will be responsible for the supply, installation, and commissioning of turnkey thermoelectric generator systems at 26 sites along the pipeline. In addition, Global will supply fuel conditioning systems, system control panels, DC-DC converters and civil and mechanical works at pipeline sites. The contract award follows Global's recently completed successful collaboration with GAIL on a US$12.9 million contract for the supply of turnkey power systems to the 1,200 km Jamnagar-Loni Pipeline, the world's longest LPG pipeline.

Global also competes with alternative electrical generating technologies for remote power applications. Although Global asserts that its thermoelectric generators have significant reliability advantages over other competing products, the emergence of new technologies, such as fuel cells, may influence Global’s ability to compete in remote power applications.

### ***Technology Status and Products***

Global Thermoelectric offers a line of thermoelectric generators (TEGs) with electric output power ranging from 15 to 550 W. Each is a complete standalone system requiring only a gas supply (natural gas or propane) and an electric load.

The following are the primary features of Global's thermoelectric generators:

- Operate on natural gas, propane or butane
- Hermetically sealed power unit has 20-year design life
- Burner system is constructed from high-temperature nickel alloys
- Stainless steel cabinets
- Automatic spark ignition
- Automatic safety shutoff

Global’s current TEG product line consists of the seven models listed in Table A-3. One model, the 1120, is approved for operating in hazardous conditions. For applications requiring greater electric power output that is provided by the Model 8550, Global will design a system using multiple units connected in parallel. All models are available in 12-V or 24-V versions, and some are available in 6.7-V and 48-V versions.

**Table A-3**
**Power Rating, Efficiency, and Size of Global Thermoelectric's Thermoelectric Generator (TEG) Products**

| Model Number | Electric Output Power (W)[1] | Thermal Conversion Efficiency[2] | LxWxH (inches) |
|---|---|---|---|
| 5015 | 15 | 2.3% | 20x11x19 |
| 5030 | 21 | 2.3% | 14x14x18 |
| 5060 | 54 | 2.8% | 25x15x39 |
| 1120 (Hazardous Approved) | 100 | 2.6% | 32x21x46 |
| 5120 | 108 | 2.8% | 30x15x39 |
| 5220 | 176 | 2.1% | 32x17x48 |
| 8550 | 550 | 2.7% | 61x61x40 |

## Physical and Performance Specifications

Standard features of Global's thermoelectric generators:

- Contain no moving parts
- Reliable
- Low maintenance source of DC electrical power
- All applications where regular utilities are unavailable or unreliable
- Electric features include reverse current protection
- Accept natural gas or propane fuel
- Cabinet 304 stainless steel construction
- Natural convection cooling type
- Thermopile is hermetically sealed lead tin-telluride
- Burner is Meeker type Inconel 600
- Fuel system is brass, aluminum, and stainless steel

[1] Rated at 24 Volts output voltage, 20°C ambient temperature, and 750 meters elevation
[2] Electric power output divided by thermal energy input when fueled by natural gas

- Ambient operating temperatures ranges is -55 to 55°C (-67 to 130 °F)
- Automatic spark ignition with low-voltage alarm contacts
- Optional features include volt and amp meters, automatic fuel shut-off, fuel filter, and pole mount or bench stand, corrosive environment fuel system, flame arrestor, cathodic protection interface panel

Additional features for the thermoelectric generators for hazardous areas:

- Class 1, Div. 2 or Class 1, Div. 1 hazardous area ratings
- CSA Certification for hazardous areas (Class 1, Div. 2, Group D, Temp T3)
- FM Certification for hazardous areas (Class 1, Div. 2, Temp T3)

The specifications for three of Global's thermoelectric generators are listed in Table A-4. These three illustrate the range from lowest to highest power and include the hazardous approved TEG (1120).

Figure A-4 shows the Global Thermoelectric Model 8550, their unit with the highest output power.

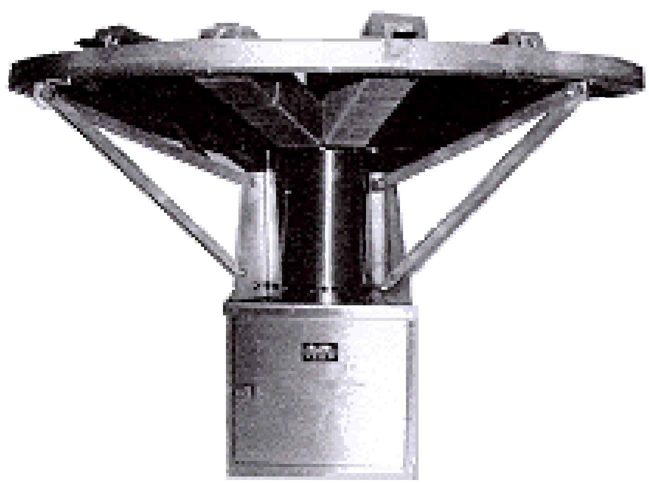

**Figure A-4**
**Global Thermoelectric Model 8550**

**Table A-4**
**Specifications for Selected Global Thermoelectric Generators (TEGs)**

| Characteristic | Units | TEG with Lowest Power | Hazardous Approved TEG | TEG with Highest Power |
|---|---|---|---|---|
| Model number | | 5,015 | 1,120 | 8,550 |
| Thermopile | | PbSnTe | PbSnTe | PbSnTe |
| **Power Specification (@ 20°C and 750 m elevation)** | | | | |
| | Watts @ 6.7V | | 110 | |
| | Watts @ 12V | 15 | 100 | 480 |
| | Watts @ 24V | 15 | 100 | 550 |
| | Watts @ 48V | | 100 | 480 |
| **Fuel Consumption** | | | | |
| Natural Gas (1,000 Btu HHV/scf) | $m^3$/day | 1.5 | 8.8 | 48.0 |
| | scf/day | 53 | 311 | 1,694 |
| Propane (92,000 Btu HHV/gal) | Liters/day | 2.1 | 11.4 | 76.0 |
| | gal/day | 0.55 | 3.0 | 20.1 |
| **Supply Pressure** | | | | |
| Minimum Supply Pressure | kPa | 103 | 103 | 207 |
| | psi | 15 | 15 | 30 |
| Maximum Supply Pressure | kPa | 1,724 | 1,724 | 1,724 |
| | psi | 250 | 250 | 250 |
| **Heat Rate (HHV)** | | | | |
| Natural Gas | Btu/kWh @ 24V @ 20°C | 147,031 | 129,388 | 128,318 |

| Characteristic | Units | TEG with Lowest Power | Hazardous Approved TEG | TEG with Highest Power |
|---|---|---|---|---|
| Propane | Btu/kWh @ 24V @ 20°C | 141,788 | 115,456 | 139,946 |
| **Thermal Conversion Efficiency (HHV)** | | | | |
| Natural Gas | % HHV @ 24V @ 20°C | 2.3 | 2.6 | 2.7 |
| Propane | % HHV @ 24V @ 20°C | 2.4 | 3.0 | 2.4 |
| **Physical Dimensions** | | | | |
| Length | mm | 508 | 813 | 1,549 |
| | inch | 20 | 32 | 61 |
| Width | mm | 279 | 533 | 1,549 |
| | inch | 11 | 21 | 61 |
| Height | mm | 483 | 1,168 | 1,016 |
| | inch | 19 | 46 | 40 |
| Footprint | square foot/kW @ 24V @ 20°C | 102 | 47 | 47 |
| Shipping Weight (dry) | kg | 20 | 128 | 102 |
| | lb | 44.1 | 282 | 225 |

Figure A-5 shows the configuration and dimensions of the Global Thermoelectric Model 8550, their unit with the highest output power. Note that for 500 W output power, the size of the heat exchanger exceeds five feet.

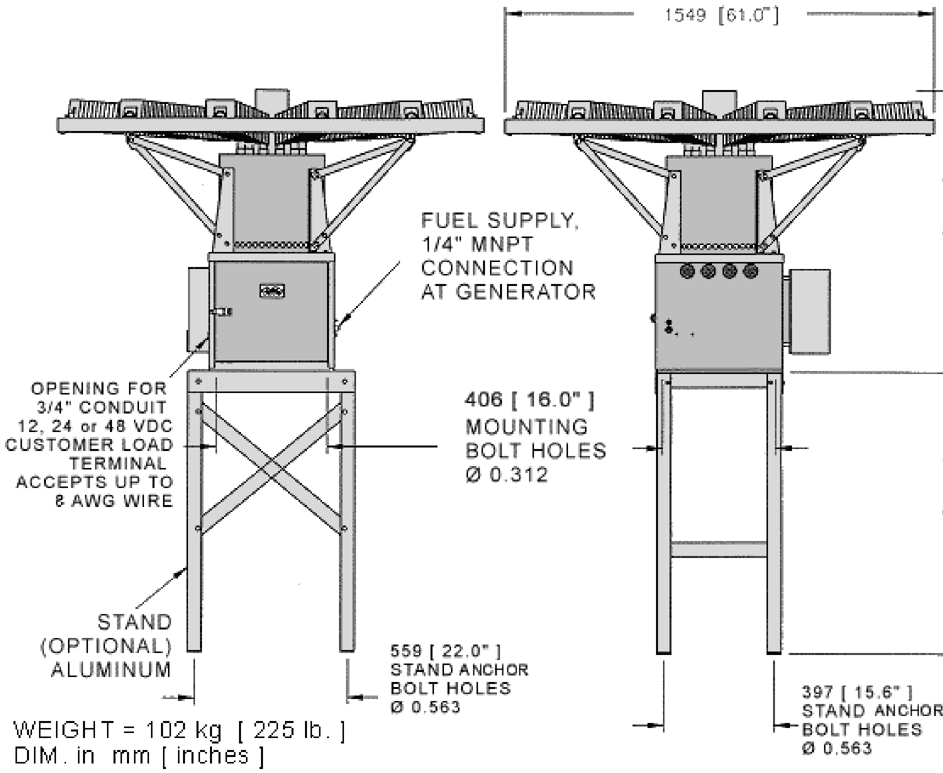


**Figure A-5**
**Global Thermoelectric Model 8550 Configuration and Dimensions**

## Commercial Applications

Common applications of Global's TEG systems include power for remote control and monitoring of oil or gas pipelines and production facilities, as well as power for navigational aids, telecommunications systems and cathodic protection of pipelines and well casings.

For oil and gas use, the TEGs are used to provide electrical current to prevent corrosion in producing oil and gas wells and pipelines. Unattended, continuous power is required for impressed-current cathodic-protection systems in pipelines and well casings.

For supervisory control and data acquisition (SCADA) applications, the TEGs are used for remote instrumentation, automation, and communication. The left photograph in Figure A-6 shows a TEG being used to provide 5,000-W for SCADA, communications, and cathodic protection of a gas pipeline in India. Pipeline operators and oil and gas producers are increasingly using SCADA systems for monitoring, measuring, and controlling equipment in the field. TEGs are being used to power remote telemetry units, gas analyzers and metering equipment, as well as for routine operating functions and emergency shutdown.

For offshore oil and gas operations, TEGs are used to provide primary power for unmanned platforms and backup power on manned platforms for critical communications and emergency shutdown systems. The center photograph in Figure A-6 shows a TEG being used to provide 200-W for communications and safety equipment in Thailand. For offshore oil and gas operators, the biggest operational concern is the harsh and highly corrosive offshore environment. The polar regions offer harsh remote operational environments, long winter nights and snow, which mitigate against photovoltaics. The photograph in Figure A-6 shows a TEG system which has operated since 1985 to provide 100 watts for navigational aids in the Yukon, Canada.

**Figure A-6**
**Global TEG systems providing power for different applications (from left to right: 5,000-W for SCADA, communications and cathodic protection of gas pipeline in India, 200-W TEG for communications and safety equipment in Thailand, and a 100-W unit operated since 1985 for navigational aids in the Yukon, Canada)**

As the telecom industry's reliability requirements approach 100%, thermoelectric generators are becoming the reliable and cost-effective power supply solution of choice. Also, as many telecom applications involve remote sites, the low maintenance requirements of TEG's are a distinct advantage as site visits can be reduced to coincide with the annual preventive maintenance cycle of telecom equipment. Additional applications of Global generators in the telecommunications industry include:

- VSAT terminals
- Point to point microwave links
- Point to multi-point systems
- Cellular and PCS
- Radio/television rebroadcasting systems
- Military communication systems
- Fiber optic links
- Mobile radio repeaters
- Emergency services communication.

## Operation and Maintenance Costs

The key operational feature of Global thermoelectric generators is the minimal maintenance requirement associated with the product's solid state design. Recommended maintenance of one to two hours per year is all that is required to check the power output and ensure a clean fuel supply by cleaning and/or changing the orifice and fuel filter. Consumables for recommended maintenance are typically less than one percent of the capital cost per year.

## Life Cycle Costs

In Figure A-7, Global compares the life cycle costs of a photovoltaic system, ICE generator set, and thermoelectric generator for an 80 and 800-Watt applications as a function of lifetime. Although ICE has the lower cost for short-term installations, the figure shows that thermoelectric generators are favorable for installation lifetimes over three years for the 800 watt system (over one year for the 80 W system). The photovoltaic system in this example assumes a southern U.S. state with high light intensity. Fuel costs are included and the discount rate is 10%.

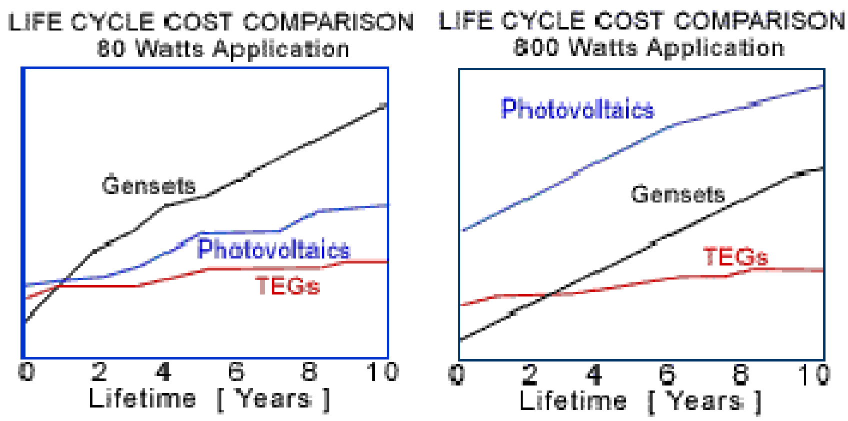


**Figure A-7**
**Life Cycle Cost Comparison for 80 and 800 Watt Remote Power Applications (Courtesy of Global Thermoelectric)**

While the capital and fuel costs of diesel and natural gas internal combustion engine (ICE) generator sets are typically lower than that of thermoelectric generators, ICE generator sets require a skilled technician to perform regular maintenance. Since thermoelectric generators require almost no maintenance, ICE generator sets have higher operational costs, more downtime, and lower overall reliability. When the complete life cycle costs are compared, thermoelectric generators can have lower life cycle cost. In addition, the greater inherent reliability of thermoelectric generators over ICE generator sets provides an important advantage in remote locations.

In contrast, photovoltaic systems have higher capital costs than thermoelectric generators, lower fuel costs, and similar maintenance requirements. Although properly sized photovoltaic systems have shown promise in providing low power solutions in areas with high solar insolation, solar users often turn to thermoelectric generators because of problems with reliability, short battery life, and theft. Thermoelectric generators have a 20-year design life and require minimal maintenance over the life of the system. An equivalent photovoltaic system would require 20-year life batteries—the cost of batteries alone can be as much as the thermoelectric generator. Studies have shown that when the capital cost of a photovoltaic system is based on medium life batteries (i.e., 10 years), the true life cycle cost of the solar system is much higher than that of a thermoelectric generator due to the high cost of battery replacement and higher maintenance costs. Theft and vandalism are a minimal concern with thermoelectric generator systems, due to their small size and the ability to mount them inside security shelters, if required.

## EPRI Perspective

Global Thermoelectric is clearly the market leader in thermoelectric generator sales, having 95% of the market share. This is particularly true for those generators that might be used in higher power applications. In 2002, Global began testing a larger thermoelectric generator specifically designed to meet the challenging needs of offshore drilling platforms. The test results of this larger system will directly impact the use of TEGs for utility-scale applications.

In the third quarter of 2003, Quantum Fuel System Technologies Worldwide Inc. is expected to complete the purchase of Global. Quantum, based in Irvine, California, currently makes systems for alternative-fuel vehicles and fuel cell applications. Global’s operation in Alberta, Canada is expected to continue following the completion of the sale, with all head office functions consolidated into Quantum’s California headquarters.

## Hi-Z Technology, Inc.

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Web: www.hi-z.com

Hi-Z Technology, Inc. is actively involved in research and development of thermoelectric power generation devices and continues to pursue niche market applications for their products. Hi-Z has established thermoelectric power generation products commercially available.

### *Company Background*

Hi-Z Technology, Inc., based in San Diego, California, is actively involved in the research and development of thermoelectric power generation devices. Hi-Z has written and presented numerous papers related to thermoelectric generator performance and niche applications.

Hi-Z is developing thermoelectric generators with combustion heat sources for the U. S. Army, TACOM-ARDEC for battery replacement in the field and for powering lightweight portable battery chargers (paper presented at the 40th Power Sources Conference, 10 - 13 June 2002, Cherry Hill NJ). These small generators range in output power from 0.3 watts to 20 watts. The main thrust of the development work is to demonstrate utilization of diesel or other military logistics fuel as the heat source. The thermoelectric generating modules being used operate at relatively low hot side temperatures and with modest power conversion efficiencies. Nevertheless, the concept shows potential advantage over batteries in watts per pound and watt-hours per pound, thus addressing the "battery problem" and the need for lightening the soldier's battery burden, and doing so at reasonable costs. Hi-Z is continuing to develop new thermoelectric materials and devices that promise significantly improved performance in the future.

Hi-Z is pursuing niche end-use applications as well as advanced materials research.

### *Technology Overview*

The thermoelectric module consists of multiple thermocouples arranged electrically in series and thermally in parallel. The thermocouple consists of “Hot Pressed” bismuth-telluride-base semiconductors to provide higher efficiencies at most waste heat temperatures. This material also has a high strength, capable of enduring rugged applications. The bonded metal conductors enable the thermoelectric module to operate continuously at temperatures as high as 480°F (250°C) and intermittently as high as 750°F (400°C) without degrading the module. Above this temperature, the thermoelectric module vaporization rate increases and loss of the semiconductor materials occurs. In addition, the resistivity increases lowering the life of the system.

The Hi-Z thermoelectric modules are suited for waste-heat recovery.

In most applications insulating wafers are required on both sides of the module. It is also recommended to use a heat transfer paste with these wafers. The thermal paste fills any gaps between the thermoelectric module surface and the wafer surface to maximize the heat transfer. Too much grease, however, will diminish the heat transfer by reducing the metal to metal contact.

An additional accessory module available at Hi-Z Technology includes the DC/DC converter, Model HZ-12-24 rel. 2. It is designed for use with two HZ-14 or two HZ-20 modules. The DC/DC converter is 3.25 inches by 4.5 inches in size and weighs 5 ounces. It can handle input voltages between 1.8 and 9 volts and output currents up to 2.5 amperes at voltages up to 15 volts. The output current at a particular output voltage depends on the input voltage, and can be estimated from the input power, taking into account an efficiency of about 87%. The converter can be used as a battery charger or as a fixed output voltage device.

### *Technology Status and Products*

Hi-Z Technology offers four thermoelectric power generation modules:

- HZ-2 – 2.5 watt output
- HZ-9 – 9 watt output
- HZ-14 – 14 watt output
- HZ-20 – 19 watt output

Table A-5 through Table A-8 details the physical, performance, and cost specifications for Hi-Z's thermoelectric power generators. These generators, however, are individual components and can be connected together to create a larger power generation system.

**Table A-5**
**HZ-2 Specifications**

| HZ-2 Specifications | Units | Value | Tolerance |
|---|---|---|---|
| Physical Properties | | | |
| Width and Length | in (cm) | 1.15 (2.9) | ±0.01 (0.25) |
| Thickness | in (cm) | 0.2 (0.508) | ±0.01 (0.25) |
| Weight | grams | 13.5 | ±2 |
| Compressive Yield Stress | ksi (MPa) | 3 (20) | Minimum |
| Number of Active Couples | | 97 | --- |
| Thermal Properties | | | |
| Design Hot Side Temperature | C (F) | 230 (450) | ±10 (20) |

| | | | |
|---|---|---|---|
| Design Cold Side Temperature | C (F) | 30 (85) | ±5 (10) |
| Maximum Continuous Temperature | C (F) | 250 (480) | --- |
| Minimum Continuous Temperature | C (F) | none | --- |
| Maximum Intermittent Temperature | C (F) | 400 (750) | --- |
| Thermal Conductivity 1 | W/cm*K | 0.024 | +0.001 |
| Heat Flux 1 | W/sqcm | 9.54 | ±0.5 |
| Electrical Properties (as a generator) 1 | | | |
| Power 2 | Watts | 2.5 | Minimum |
| Load Voltage | Volts | 3.3 | ±0.1 |
| Internal Resistance | Ohm | 4.0 | ±0.05 |
| Current | Amps | 0.8 | ±1 |
| Open Circuit Voltage | Volts | 6.53 | ±0.3 |
| Efficiency | % | 4.5 | Minimum |
| Costs 3 | | | |
| 1-199 units | $/unit | 46.00 | |
| 200-999 units | $/unit | 41.00 | |
| 1,000-4,999 units | $/unit | 31.00 | |
| 5,000-9,999 units | $/unit | 27.00 | |
| Ceramic insulating wafer (one) | $ | 3.00 | |
| Thermal Grease (20 grams) | $ | 45.00 | |

1 – At design temperatures
2 – At matched load (refer to the graphs for properties at various operating temperatures and conditions)
3 – In U.S. dollars (August 2002)

**Table A-6**
**HZ-9 Specifications**

| HZ-9 Specifications | Units | Value | Tolerance |
|---|---|---|---|
| Physical Properties | | | |
| Width and Length | in (cm) | 2.47 (6.27) | ±0.01 (0.25) |
| Thickness | in (cm) | 0.261 (0.651) | ±0.01 (0.25) |

| | | | |
|---|---|---|---|
| | | | (0.25) |
| Weight | grams | 105 | ±3 |
| Compressive Yield Stress | ksi (MPa) | 10 (70) | Minimum |
| Number of Active Couples | | 97 | --- |
| Thermal Properties | | | |
| Design Hot Side Temperature | C (F) | 230 (450) | ±10 (20) |
| Design Cold Side Temperature | C (F) | 30 (85) | ±5 (10) |
| Maximum Continuous Temperature | C (F) | 250 (480) | --- |
| Minimum Continuous Temperature | C (F) | none | --- |
| Maximum Intermittent Temperature | C (F) | 400 (750) | --- |
| Thermal Conductivity 1 | W/cm*K | 0.018 | +0.001 |
| Heat Flux 1 | W/sqcm | 5.52 | ±0.5 |
| Electrical Properties (as a generator) 1 | | | |
| Power 2 | Watts | 9 | Minimum |
| Load Voltage | Volts | 3.28 | ±0.1 |
| Internal Resistance | Ohm | 1.15 | ±0.05 |
| Current | Amps | 2.9 | ±1 |
| Open Circuit Voltage | Volts | 6.5 | ±0.3 |
| Efficiency | % | 4.5 | Minimum |
| Costs 3 | | | |
| 1-199 units | $/unit | 131.00 | |
| 200-999 units | $/unit | 118.00 | |
| 1,000-4,999 units | $/unit | 89.00 | |
| 5,000-9,999 units | $/unit | 77.00 | |
| Ceramic insulating wafer (one) | $ | 3.00 | |
| Thermal Grease (20 grams) | $ | 45.00 | |

1 – At design temperatures
2 – At matched load (refer to the graphs for properties at various operating temperatures and conditions)
3 – In U.S. dollars (August 2002)

**Table A-7**
**HZ-14 Specifications**

| HZ-14 Specifications | Units | Value | Tolerance |
|---|---|---|---|
| Physical Properties | | | |
| Width and Length | in (cm) | 2.47 (6.27) | ±0.01 (0.25) |
| Thickness | in (cm) | 0.2 (0.508) | ±0.01 (0.25) |
| Weight | grams | 82 | ±3 |
| Compressive Yield Stress | ksi (MPa) | 10 (70) | Minimum |
| Number of Active Couples | | 49 | --- |
| Thermal Properties | | | |
| Design Hot Side Temperature | C (F) | 230 (450) | ±10 (20) |
| Design Cold Side Temperature | C (F) | 30 (85) | ±5 (10) |
| Maximum Continuous Temperature | C (F) | 250 (480) | --- |
| Minimum Continuous Temperature | C (F) | none | --- |
| Maximum Intermittent Temperature | C (F) | 400 (750) | --- |
| Thermal Conductivity 1 | W/cm*K | 0.024 | +0.001 |
| Heat Flux 1 | W/sqcm | 9.54 | ±0.5 |
| Electrical Properties (as a generator) 1 | | | |
| Power 2 | Watts | 14 | Minimum |
| Load Voltage | Volts | 1.65 | ±0.1 |
| Internal Resistance | Ohm | 0.15 | ±0.05 |
| Current | Amps | 8 | ±1 |
| Open Circuit Voltage | Volts | 3.5 | ±0.3 |
| Efficiency | % | 4.5 | Minimum |
| Costs 3 | | | |
| 1-199 units | $/unit | 108.00 | |
| 200-999 units | $/unit | 97.00 | |
| 1,000-4,999 units | $/unit | 78.00 | |

| | | | |
|---|---|---|---|
| 5,000-9,999 units | $/unit | 63.00 | |
| Ceramic insulating wafer (one) | $ | 3.00 | |
| Thermal Grease (20 grams) | $ | 45.00 | |

1 – At design temperatures
2 – At matched load (refer to the graphs for properties at various operating temperatures and conditions)
3 – In U.S. dollars (August 2002)

**Table A-8**
**HZ-20 Specifications**

| HZ-20 Specifications | Units | Value | Tolerance |
|---|---|---|---|
| Physical Properties | | | |
| Width and Length | in (cm) | 2.95 (7.5) | ±0.01 (0.25) |
| Thickness | in (cm) | 0.2 (0.508) | ±0.01 (0.25) |
| Weight | grams | 115 | ±3 |
| Compressive Yield Stress | ksi (MPa) | 10 (70) | Minimum |
| Number of Active Couples | | 71 | --- |
| Thermal Properties | | | |
| Design Hot Side Temperature | C (F) | 230 (450) | ±10 (20) |
| Design Cold Side Temperature | C (F) | 30 (85) | ±5 (10) |
| Maximum Continuous Temperature | C (F) | 250 (480) | --- |
| Minimum Continuous Temperature | C (F) | none | --- |
| Maximum Intermittent Temperature | C (F) | 400 (750) | --- |
| Thermal Conductivity 1 | W/cm*K | 0.024 | +0.001 |
| Heat Flux 1 | W/sqcm | 9.54 | ±0.5 |
| Electrical Properties (as a generator) 1 | | | |
| Power 2 | Watts | 19 | Minimum |
| Load Voltage | Volts | 2.38 | ±0.1 |
| Internal Resistance | Ohm | 0.3 | ±0.05 |
| Current | Amps | 8 | ±1 |
| Open Circuit Voltage | Volts | 5.0 | ±0.3 |

| | | | |
|---|---|---|---|
| Efficiency | % | 4.5 | Minimum |
| Costs 3 | | | |
| 1-199 units | $/unit | 154.00 | |
| 200-999 units | $/unit | 132.00 | |
| 1,000-4,999 units | $/unit | 103.00 | |
| 5,000-9,999 units | $/unit | 85.00 | |
| Ceramic insulating wafer (one) | $ | 5.00 | |
| Thermal Grease (20 grams) | $ | 45.00 | |

1 – At design temperatures
2 – At matched load (refer to the graphs for properties at various operating temperatures and conditions)
3 – In U.S. dollars (August 2002)

Hi-Z develops and manufactures products in the micro-watt range for space applications. Hi-Z has also developed a 1 kW thermoelectric generator specifically for large diesel trucks using waste heat from the truck exhaust system. Seventy-two HZ-14 modules compose the 1 kW generator, looking like the truck's vertical muffler, which it replaces. The generator is located in the exhaust gas line after the engine turbocharger. Heat from the cold side of the thermoelectric generator is removed by circulating water to a standard automotive radiator. This thermoelectric generator can be employed as a substitute for the truck engine alternator. Power to the driveshaft increases by three to five horsepower, which increases fuel efficiency and reduces emissions. Road tests have been performed, confirming greater than 1 kW power output. Development of this product was supported by the U.S. Department of Energy and by the California Energy Commission.

Hi-Z's research is focused on higher efficiency thermoelectric products using quantum-well materials such as $B_4C/B_9C$ and $Si/Si_{0.8}Ge_{0.2}$. Hi-Z has demonstrated an efficiency of 14% at 250 °C in the testing facility, and is currently looking for additional funding support to purchase manufacturing equipment to begin production of the new products. Hi-Z hopes to obtain efficiencies as high as 20-30% with the new materials. At that time, they will consider developing larger systems (1-20 kW). They anticipate costs to fall to $100-150/kW.

### *EPRI Perspective*

Hi-Z Technology is a leader in the thermoelectric power generator industry, second to Global Thermoelectric. Hi-Z is actively involved in research and development of thermoelectric power generation devices and continues to pursue niche market applications for their products. Hi-Z has developed a 1 kW unit for use with large diesel engine exhaust systems and continues to keep an eye on large-scale development opportunities. Hi-Z has established products commercially available, and their role in the research field, will ensure Hi-Z maintains their edge in the commercialization of new products.

## Beijing Huimao Cooling Equipment Co., Ltd.

Xi Zhuang Village, Huang Cun Town, Da Xing, Beijing 102609, People's Republic of China
Phone: 0086-10-68160581, 60275767 Fax: 0086-10-68189379, 60275767
Mobile Phone: +86 13501215859 (contact Mr. Zheng Xu)
Email: info@huimao.com, a_xu@163.net
Web: www.huimao.com

Beijing Huimao Cooling Equipment Co., Ltd. currently has available thermoelectric power generation modules. However, their primary focus is cooling applications. Huimao does not assemble or manufacture complete thermoelectric power generation systems.

### *Company Background*

Beijing Huimao Cooling Equipment Co., Ltd., located in Beijing, China, is a company specializing in the research, design, and manufacturing of thermoelectric cooling modules (TEC), as well as standard and custom multi-stage TEC modules configured to meet the needs of specific applications.

Huimao can also provide fully configured, custom designed assemblies incorporating TEC modules with heat sink, heat pipe, and customer supplied parts. Huimao supports all of its products with technical and design assistance.

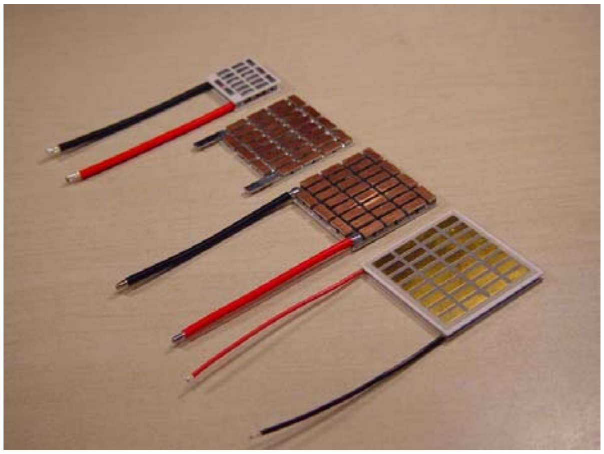

**Figure A-8**
**Huimao Thermoelectric Cooling Modules**

### *Technology Overview*

Huimao uses bismuth-telluride semiconductors for their thermoelectric modules. They use the same material for their cooling devices as they do in their power generation modules since the power generation modules are adapted from the cooling products.

The thermoelectric module is a kind of solid-state thermal energy pump, because of its light weight, small size and fast response. Because of its low noise, shatter proof, shock resistance, long life, and easy maintenance, it can also be used in a variety of applications such as military, aviation, aerospace, medical treatment, epidemic prevention, experimental apparatus, and consumer products.

Thermoelectric power modules offer the following benefits:

- **High reliability and long life** - The materials of the thermoelectric module are connected to the copper conductor tab by two shielding layers. Thus, they can effectively avoid the diffusion of copper and other harmful elements, which enable the modules to have longer use life. In addition, every module is tested and selected by instruments to guarantee its high quality. The life of the module can reach 300,000 hours and more (based on Huimao testing and tests by the National Special Test Center).
- **Operation under high temperature -** The thermoelectric module adopts a series of new soldering materials. The highest temperature of these soldering materials is as high as 125° C, 150° C, 200 °C and 300° C. In addition, Huimao is striving to improve the module's performance and enlarge its application range.
- **Perfect Moisture Protection -** Every thermoelectric module has been subjected to moisture protection treatment, which is made in a vacuum with a silicone coating. Thus, it can effectively prevent water and moisture from entering the inside of module.
- **Various specifications -** Huimao can produce various specifications of modules in groups. Huimao is now producing modules with a power density that is twice as high as common modules, and has successfully developed and manufactured the double-stage high-power modules with the temperature difference of more than 90°C, with the power of tens of watts. The modules have low internal resistance, ideal for thermoelectric power generation.

### *Technology Status and Products*

Selected Huimao's power generation thermoelectric module specifications are located in Table A-9.  Huimao's thermoelectric power generators have small internal resistance, long life, and are thermally stable.

**Table A-9**
**Selected Specifications of Huimao's Power Generation Modules**

| Product Number | Couples | Current (mA) | Voltage (V) | Qcmax T=0 (W) | Tmax Qcold= 0 (°C) | Dimensions (mm) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Thot=27°C | | L | W | H |
| TEC1-03130T125 | 31 | 30 | 3.5 | 64.5 | 63 | 35 | 35 | 5.0 |
| TEC1-03140T125 | | 40 | | 85.5 | 61 | 35 | 35 | 4.5 |
| TEC1-03150T125 | | 50 | | 106.9 | --- | 35 | 35 | 4.2 |
| TEC1-03160T125 | | 60 | | 64.2 | --- | 35 | 35 | 4.0 |
| TEC1-03180T125 | | 80 | | 85.5 | --- | 35 | 35 | 3.8 |

Quality and reliability are a major concern for Huimao engineers. The material has two shielding layers for guarding against the diffusion of harmful substances. The module passes through the moisture protection treatment twice, so as to prevent the degradation of the module's performance. It has more than ten quality control points in the module production process, followed by testing and selection, to ensure the quality and reliability of products.

## *EPRI Perspective*

Huimao currently manufactures and sells thermoelectric modules for power generation. However, their primary focus is cooling applications (office water coolers and portable coolers to keep food items cold). Huimao does not assemble or manufacture complete thermoelectric power generation systems nor do they offer assemblies at the kW-scale.

## Leonardo Technologies, Inc.

Bedford, New Hampshire
Phone: (724) 327-4789
Contact: Jack Adams

Leonardo has indicated their thermoelectric device promises a fuel-to-electricity conversion efficiency of 12-14%.

### *Company Background*

Leonardo Technologies was founded in 2000 by Craig Cassarino. Mr. Cassarino constructed and tested several prototype thermoelectric modules that convert waste heat into electrical energy and has sought funding for further development, assistance with more efficient production methods, and commercialization opportunities.

### *Technology Overview*

Leonardo is currently under contract by the U. S. Army Engineering Research and Development Center, Construction Engineering Research Laboratory (ERDC/CERL) to demonstrate their thermoelectric power generation systems. The objective of the ERDC/CERL-funded program is to provide demonstration and evaluations of the application of thermoelectric devices for supplemental electric power generation from fuel cells and other sources of waste heat generation, leading to increased electrical generation efficiency and reduced environmental impacts.

In this program, thermoelectric devices will be integrated into existing fuel-cell power plants and other sources of waste heat, such as boiler systems. The devices will utilize the waste heat to generate electrical energy during normal operation. This electrical energy will be fed back into the existing utility grid or to other system operations to supplement system operation or increase overall system efficiency.

Funding of this project will be used to conduct an initial study to identify and evaluate additional potential defense and other government applications for thermoelectric devices besides fuel cells; facilitate baseline and field demonstrations of thermoelectric devices; and perform an assessment and optimization of thermoelectric device manufacturing.

The data collected from these demonstration sites will be used to evaluate, among other criteria, the efficiency of power generation, quality of power generated and potential return on investment. The current manufacturing practices and raw material sources of the thermoelectric devices will be studied to evaluate potential cost savings, device flexibility and formability, and potential for use of recycled materials.

### *Technology Status and Products*

Leonardo has indicated their thermoelectric device promises a fuel-to-electricity conversion efficiency of 12-14%. The minimum temperature is 212 °F (100 °C) and the maximum hot-side temperature is 572 °F (300 °C). Modules produce 8-800 Watts and 8-80 volts DC. The modules are manufactured from bismuth and telluride, which are standard materials for thermoelectric modules. The high performance is achieved by using a unique manufacturing procedure which results in a proprietary composite material. The cost of the prototype (Figure A-9) is about $5,000/kW. Testing is expected to continue through 2004.

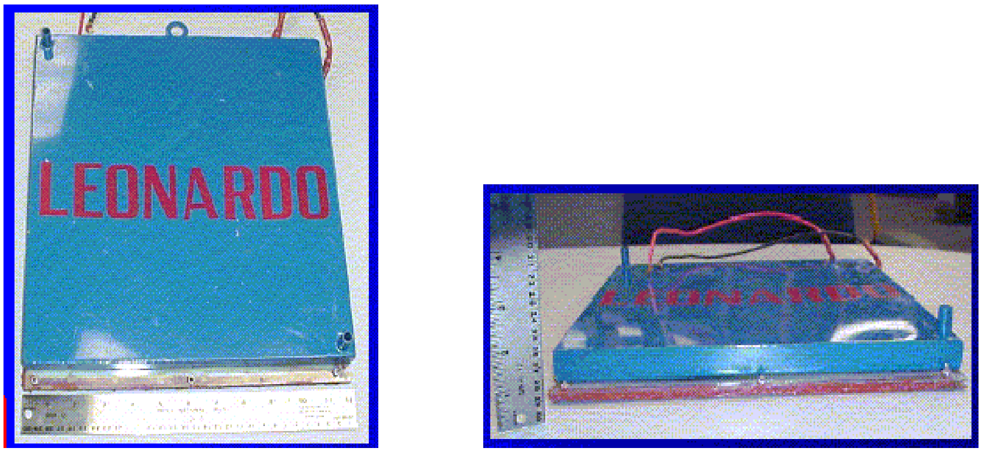


**Figure A-9**
**Leonardo Prototype Thermoelectric Power Generator**

### *EPRI Perspective*

Leonardo is still under contract to CERL for demonstration testing of their thermoelectric power generation system and anticipates additional funding for their research and demonstration efforts in FY 2004. Leonardo has indicated their thermoelectric device promises a fuel-to-electricity conversion efficiency of 12-14%, nearly three times that of other manufacturers. Should they be able to achieve this efficiency at kW- levels, their systems should be useful in utility applications. Their development program bears watching.

## Taihuaxing Trading Co., Ltd.
## Thermonamic Electronics (Xiamen)

Factory - West Unit 309, Guang Ye Building
Torch Hi-Tech Industrial Development Zone, Xiamen 361006, P.R. of China
Tel: +86-592-5714012, Fax: +86-592-5714010
E-mail: sales_taihuaxing@sitechina.com
Web: http://www.sitechina.com/thermoelectric/

Taihuaxing has been producing thermoelectric modules for heating, cooling, and power generation applications since 1986. Power output ranges from 2.6 to 14.7 Watts.

### *Company Background*

Taihuaxing Trading is a sales and marketing office of Thermonamic Electronics (Xiamen) Co., Ltd., who has been producing the thermoelectric module since 1986. Taihuaxing thermoelectric power generation modules contain no moving parts and are small and light-weight. The thermoelectric modules have been used in the military, medical, industrial, consumer, scientific/laboratory, electro-optic, and telecommunications industries for cooling, heating and electric power generation applications.

### *Technology Overview*

The thermoelectric modules use bismuth-telluride semiconductors between ceramic plates. They are solid-state, vibration-free, noise-free systems that convert heat to power. Advantages of Taihuaxing's thermoelectric power generation modules are that they:

- Use waste heat to produce electricity
- Have no moving parts
- Make no noise
- Are reliable and maintenance free (recommended for use at remote sites)
- Can use any fuel or heat source, flexible
- Are light and small (the module can be used to make a mini-power output generator)

### *Technology Status and Products*

The thermoelectric power module for converting heat source directly into electricity is designed and manufactured by Taihuaxing's unique technology. The bismuth-telluride-based thermoelectric module can operate at temperatures as high as 500°F (260°C) continuously and intermittently up to 680°F (380°C) without degrading. The thermoelectric module will generate DC electricity as long as there is a temperature difference across the module. The modules use a single ceramic plate or double ceramic plate pattern per the purchaser's request.

Currently, Taihuaxing has 126 couples in two standard sizes; 40mm x 40mm and 56mm x 56mm series modules for different applications (see Table A-10). Taihuaxing also offers 30mm x 30mm modules.

**Table A-10**
**Taihuaxing Thermoelectric Module Specifications**

| Characteristics at Th=446°F, Tc=122°F | Units | TEP1-1264-3.4 | TEP1-1264-1.5 | TEP1-12656-0.8 | TEP1-12656-0.6 |
|---|---|---|---|---|---|
| Size | mm | 40 x 40 | 40 x 40 | 56 x 56 | 56 x 56 |
| Open Circuit Voltage3 | Volts | 8.8 | 8.6 | 8.7 | 8.6 |
| Internal Resistance | Ohms | 7 | 3 | 1.7 | 1.2 |
| Matched Load Output4 Voltage | Volts | 4.3 | 4.2 | 4.2 | 4.2 |
| Matched Load Output Current | Amps | 0.6 | 1.4 | 2.5 | 3.5 |
| Matched Load Output Power | Watts | 2.6 | 5.9 | 10.5 | 14.7 |
| Heat Flux Across the Module | Watts | ~60 | ~140 | ~240 | ~350 |
| Heat Flux Density | Watts/cm 2 | ~3.75 | ~8.8 | ~8 | ~11 |

The output power based on the load resistance for the TEP1-1264-1.5 module is illustrated in Figure A-10. When the load resistance is equal to the internal resistance (3 ohms), the output power is at its maximum.

### *EPRI Perspective*

Taihuaxing produces power generation products with the output ranging from 2.6 to 14.7 Watts in a series of four thermoelectric products. There is no indication that they will be developing products soon in the kW output level.

[3] The open circuit voltage is the output voltage of the module with no load connected.
[4] The matched load output is the output of module when the load resistance is equal to the module's internal resistance. The output voltage or current will change with the load. Under matched load, the output power is at a maximum.

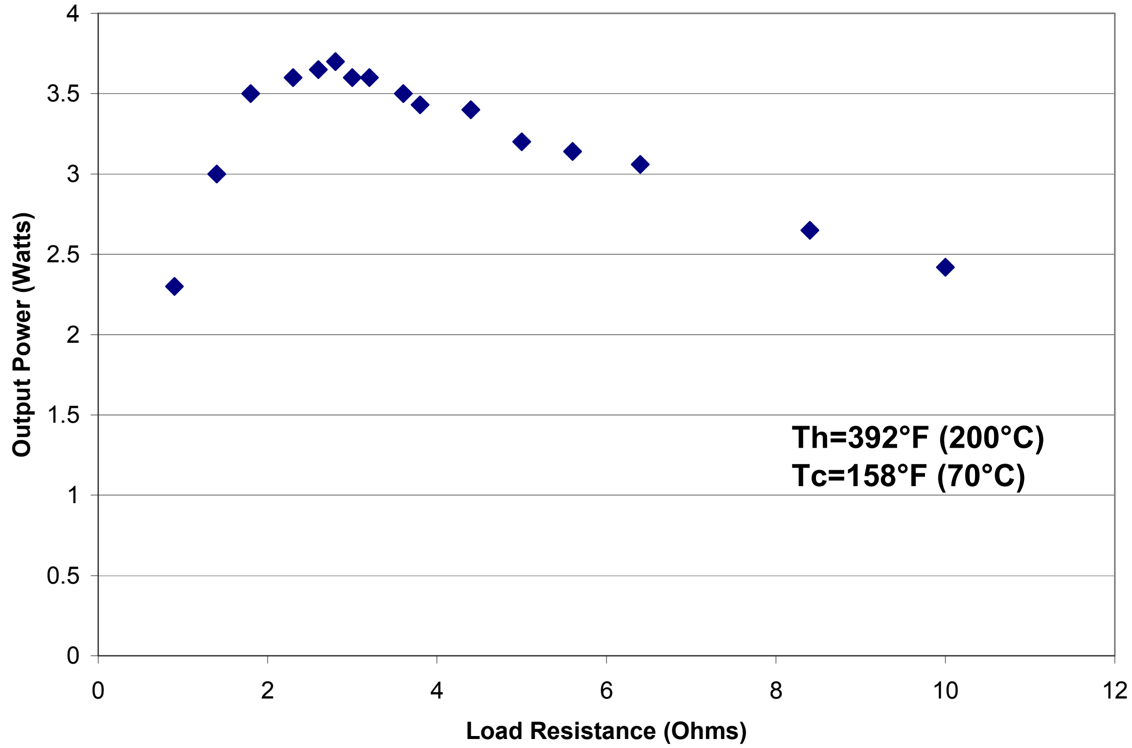


**Figure A-10**
**Output Power versus Load Resistance for the module TEP1-1264-1.5**

## Tellurex Corporation

1248 Hastings, Traverse City, MI 49686-4320, U.S.A.
Phone: 231-947-0110 Fax: 231-947-5821
E-mail:tellurex@tellurex.com, rmccreery@tellurex.com
Web: http://www.tellurex.com
Contact: Ronald McCreery - Tellurex Sales Manager

Tellurex, headquartered in Traverse City, Michigan, is a manufacturer of Zmax® thermoelectric modules and subassemblies for heating, cooling, and power generation applications. Tellurex does not currently manufacture complete power generation systems; however, they do manufacture and sell the thermoelectric module components of the system.

### *Company Background*

Tellurex works closely with Michigan State University to research and development thermoelectric devices. Michigan State University and Tellurex Corporation have signed research and exclusive licensing agreements for their work in the development of thermoelectric materials, stemming from the research of Dr. Mercouri Kanatzidis, a Professor of Chemistry at Michigan State University.

The agreements allow Dr. Kanatzidis to conduct his research with Tellurex providing the capacity for synthesizing new crystalline structures and fabricating working devices.

Under the agreements, the University will receive funding and other support over a three-year period, while Tellurex develops the commercial potential of the technology.

Tellurex's thermoelectric products are available directly through Tellurex or through their distributor, Allied Electronics.

### *Technology Overview*

Tellurex recently began manufacturing and selling thermoelectric modules that can be used for power generation. They are a component supplier, however, and do not sell complete turnkey power generation systems.

Tellurex uses bismuth-telluride (Bi-Te) semiconductors. For power generation, Tellurex has demonstrated energy conversion efficiencies of 3-5% for small scale products (approximately 2 watts).

### *Technology Status and Products*

Tellurex is focused on developing niche consumer items for end-use products, such as a fan used to convert heat to electricity on a wood stove. Mosquito machines, to trap and kill mosquitoes, are their most popular consumer product. Tellurex has investigated 1-2 kW thermoelectric generator (TEG) systems but has not pursued further development as they were not economically feasible.

**Table A-11**
**Tellurex TEG Specifications**

| Characteristic | Units | Value |
|---|---|---|
| Hot side temperature | ° F (°C) | 329-365 (165-185) |
| Cold side temperature | ° F (°C) | 122 (50) |
| Delta T | ° F (°C) | 257 (125) |
| Power Output | Watts | 2-125 |
| Energy Conversion Efficiency | % | 3-5 |

Tellurex's most popular generator module, operating at a hot side temperature of 347° F (175°C) and a cold side temperature of 122° F (50°C), has the power generating capabilities illustrated in Figure A-11.

[5] Single or multiple units to produce the range of 2 – 12 Watts.

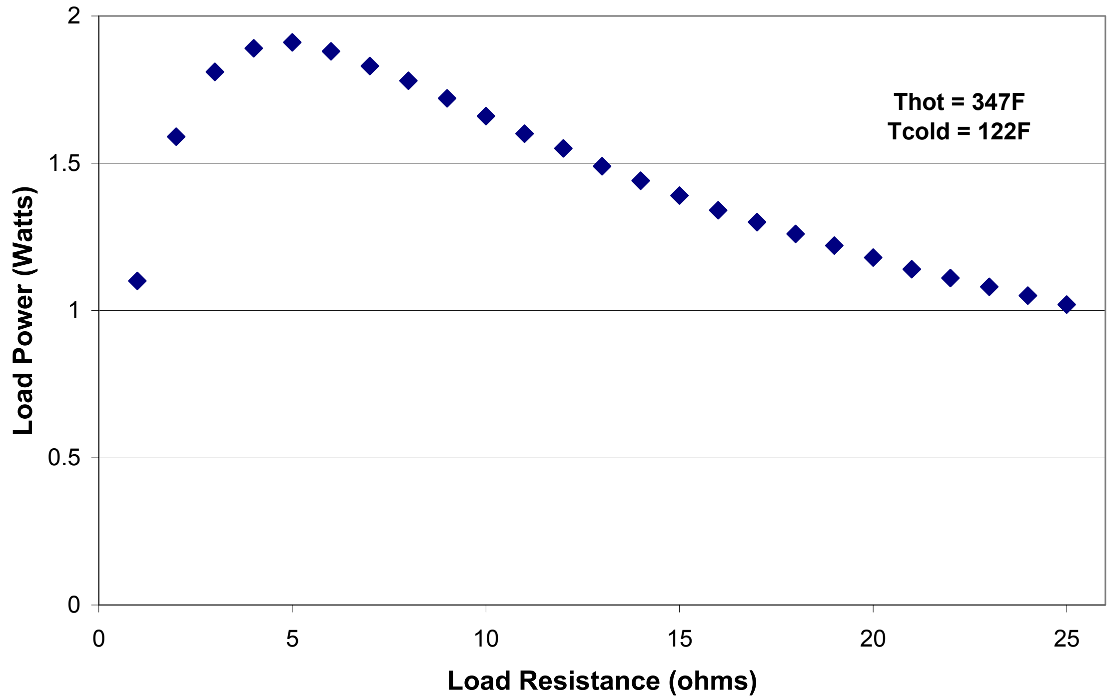


**Figure A-11**
**Load Power versus Load Resistance in Tellurex TEG Products**

## *EPRI Perspective*

Tellurex manufacturers and sells modules for power generation, but they do not offer any complete turnkey power generation systems. There is no indication that they will be developing products soon in the kW output level.

## About EPRI

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