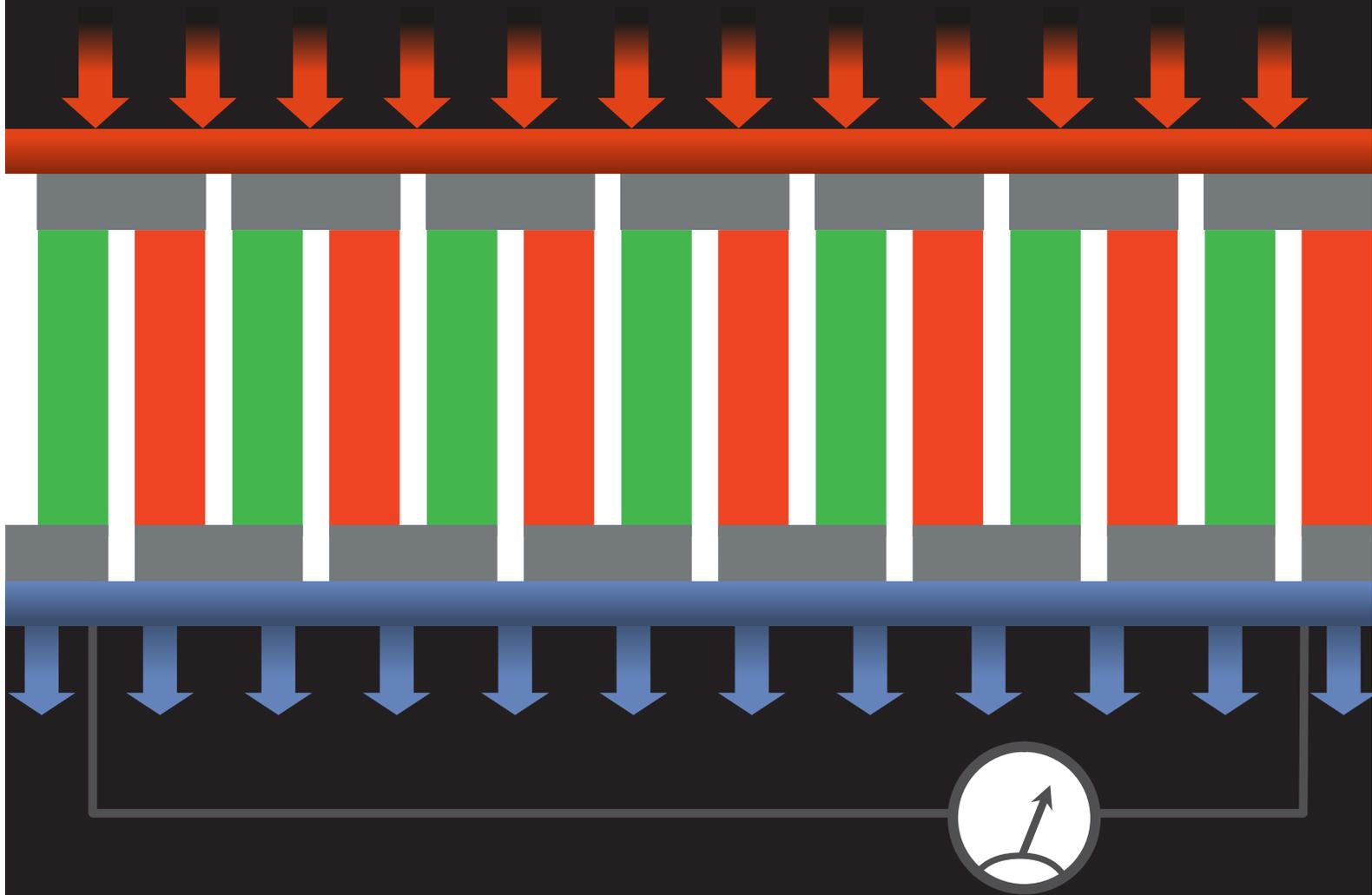


Engineering Scoping Study of Thermoelectric Generator Systems for Industrial Waste Heat Recovery

November 2006



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November 2006

*Dr. Terry Hendricks
Pacific Northwest National Laboratory*

*William T. Choate
BCS, Incorporated*

Acknowledgments

We gratefully acknowledge the support of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program (ITP). This study was carried out by Pacific Northwest National Laboratory (PNNL) and BCS, Incorporated under contract with DOE. We especially want to thank Dr. Sara Dillich (ITP) for her valuable input and direction, Rajita Majumdar (BCS, Incorporated) for handling the many edits and changes, and the reviewers who provided their insights and suggestions: Dr. Wayne Hayden (MMPACT, Inc.), Dr. Emory Ford (Materials Technology Institute), Dr. Drew Ronneberg (ITP) and Dr. Arvind Thekdi (E3M, Inc.) . We would also like to thank Dr. Adam Polcyn (PPG, Inc.) for his valuable technical data on glass furnaces and Elwin Rooy (Rooy Associates) for aid with the primary and secondary aluminum details.

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Executive Summary

Roughly a third of the energy consumed by the U.S. manufacturing industry is discharged as thermal losses to the atmosphere or to cooling systems. These discharges are the result of process inefficiencies and the inability of the manufacturing plants to utilize the excess energy. This lost or waste energy (heat) is estimated to be over 10 quads/yr (1 quad = 10^{15} Btu), an amount equivalent to more than 1.72 billion barrels of oil or 127 days worth of imported crude oil supply. Most of this lost energy is "low quality" and not practical or economical to recover. A portion of the waste heat, as much as 1.8 quads/yr,¹ is considered to be an opportunity for waste heat recovery.

Various technologies, including thermoelectric technologies, are being considered to recover and convert the industrial process waste energy to useful electrical energy. Thermoelectric (TE) materials, discovered in 1821, are semiconductor solids that produce an electric current when joined together and subjected to a temperature difference across the junction. This property makes it possible to produce direct current electricity by applying waste heat on one side of a TE material, while exposing the other side to lower or ambient temperature surroundings. TE materials available prior to about 1995 produced thermal-to-electric conversion efficiencies in the 2% to 5% range and were only used in small niche applications. However, recent significant advances in the scientific understanding of quantum well and nanostructure effects on TE properties and modern thin layer and nano-scale manufacturing technologies have combined to create the opportunity of advanced TE materials with potential conversion efficiencies of over 15%. The advent of these advanced TE materials offers new opportunities to recover waste heat more efficiently and economically with highly reliable and relatively passive systems that produce no noise and vibration.

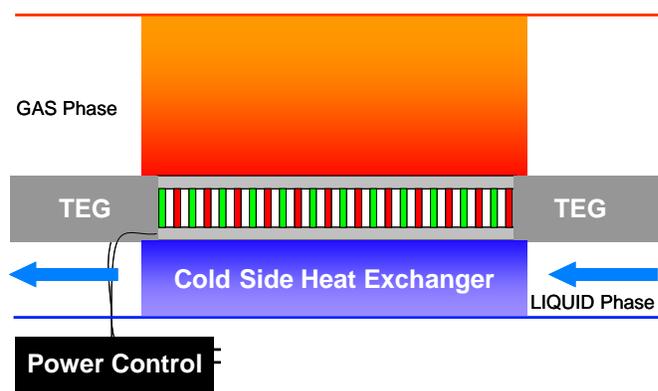


Figure A: Simplified TEG package block diagram

Useful thermoelectric power generation is achieved by combining four unit operations into one thermoelectric generator (TEG) system: a TE module consisting of an array of several or hundreds of TE material junctions; a hot-side heat exchanger; a cold-side heat exchanger; and a power electronic module to provide the desired volt and ampere output (Figure A). The interdependent design of each of these operations is critical to determining and realizing the anticipated TEG

performance in industrial waste energy recovery. Successfully moving from TE materials science to commercialization of waste heat TEG systems requires integrating these four components together, identifying large-volume applications where the market size is of commercial interest, and clearly and accurately identifying the engineering and performance challenges and limitations to entering these markets.

This report evaluates the TEG system with the intent to

- examine industrial processes in order to identify and quantify industrial waste heat sources that could potentially use TEGs;
- describe the operating environment that a TEG would encounter in selected industrial processes and quantify the anticipated TEG system performance;
- identify cost, design and/or engineering performance requirements that will be needed for TEGs to operate in the selected industrial processes; and
- identify the research, development and deployment needed to overcome the limitations that discourage the development and use of TEGs for recovery of industrial waste heat..

Waste Heat Recovery and Selected Opportunities

Recovering waste heat is financially sound when practical and economic recovery technologies are available and an identifiable use for the recovered energy is readily available. Waste heat can be recovered either by exchanging the energy with other materials/fluids (such as in heat exchangers and recuperators) or by converting to another form of energy (e.g., thermal to electric). New opportunities for efficiently recovering waste heat have been created because of advances in micro- and nano-technologies. The key to identifying TEG waste heat recovery applications is to determine when thermal exchange between existing process fluids is not an available option or provides no useful technical or economic benefit.

The quality of waste heat (i.e., temperature, composition, energy content, and accessibility) varies significantly and depends on the industrial process emanating it. A large portion of industrial waste heat is contained in gases which are discharged at $\sim 300^{\circ}\text{F}$. This temperature range represents very low-quality heat and currently no commercially viable means to recover this energy is available (Section 3.3 briefly discusses a future technology, piezoelectric generation, which may be applicable at these temperatures). This temperature range is also too low for the efficient operation of a TEG. New TE materials potentially provide conversion efficiencies of 15% to 25% when operating at hot-side temperatures of 450°C to 750°C . These efficiencies are needed to make the TEG economically viable.

Three industrial waste heat processes were selected to investigate applicability of TEGs: glass furnaces (485°C to $1,400^{\circ}\text{C}$), aluminum Hall-Hèroult cells ($\sim 960^{\circ}\text{C}$), and reverberatory furnaces ($\sim 760^{\circ}\text{C}$). These processes are large scale, have high-temperature discharges and offer significant commercial potential to a TEG developer. The quality of heat (i.e., high temperature) at the discharge of the process equipment is suitable for TEG and these processes typically have situations that are not suited for standard fluid-to-fluid heat exchange operations that would increase process efficiency. Further, these process plants can use TEG electricity onsite. Ethylene furnaces were also examined since the reaction temperature is over 850°C . However, in this application, the hot flue gas energy is routinely recovered by transferring heat to make steam used to drive the large compressors needed for gas handling and distillation. The final flue gas temperature is low quality (i.e., 300°F) and not suitable for TEG energy recovery. Similarly, industrial and commercial boilers were selected for examination because of their enormous amount of waste energy, but were found unsuitable for TEG application owing to the low temperature of their waste heat ($\sim 300^{\circ}\text{F}$).

The temperature, composition, heat capacity and thermal conductivity of the waste heat gas discharge from the selected processes were calculated for a typical plant. These data provided the basis for quantifying the anticipated performance of TEG systems using advanced, high-performance TE materials.

Thermoelectric Generator Performance in Selected Opportunities

The performance of TE materials is expressed through “figure-of-merit” or ZT , a dimensionless value related to the efficiency of conversion of thermal energy to electric energy. TE materials discovered in the early mid-1900s demonstrated limited conversion efficiencies with ZT of only ~ 1 . However, recently discovered advanced TE materials (nano-structured, thin-film superlattice, and quantum well materials) have been characterized with ZT above 2; scientists further believe that $ZT \sim 4$ is achievable in the near future. ZT has no known theoretical upper limit. TE materials with $ZT \sim 2$ and above can provide thermal to electric conversion efficiencies of over 15%.

One economic challenge to thermoelectrically recovering waste heat is to do it in a manner such that it is competitive with utility generated power. Although thermoelectric generators (TEGs) are commercially available today, their use has been limited to small-scale (<50,000 Btu/day of useful work) niche applications where the primary concerns are the reliability, low noise, low vibration or remote operation of the device, the cost and conversion efficiency being only of secondary concern. Today’s commercial TEGs cost about \$30 per watt and operate at roughly 3% efficiency. TEGs for waste heat recovery will need to cost about \$5 per watt or one-sixth the current costs in order to be competitive with readily available electricity. New TE materials (i.e., $ZT \sim 2$) and advanced heat transfer technologies can potentially produce conversion efficiencies four to five times higher than what is commercially produced today. Modules designed around $ZT \sim 2$ materials are very compact and can be retrofit into existing operations without major changes to process ductwork. If TEG modules with $ZT \sim 2$ materials can be built with costs similar to today’s $ZT \sim 1$ modules, then the efficiency increase can make TEGs commercially competitive with utility-generated power.

The ZT “figure-of-merit” is a combination of three material properties and the operating temperature (T). It is defined as:

$$ZT = (\alpha^2 \sigma / \lambda) T$$

where,

α is the Seebeck coefficient of the material (volt-kelvin⁻¹)

σ is the electrical conductivity of the material (ampere-volt⁻¹·meter⁻¹)

λ is the thermal conductivity of the material (watt-meter⁻¹·kelvin⁻¹)

The performance of TEG systems can be enhanced by

- increasing TE material ZT ;
- maintaining a large temperature differential across the TE module through efficient heat transfer; and
- providing efficient hot- and cold-side heat transfer that produces high thermal flows through the system.

While ZT improvement is limited by advances in TE material development, the hot-side and cold-side heat exchangers supplying heat to and dissipating heat from the device, respectively, play a critical role in determining the efficiency of a TEG system. A 100°C reduction in temperature differential in a $ZT \sim 2$ module can result in over a 20% loss in performance. This report has quantified how increasing hot-side heat exchanger performance, in particular, increases TEG system output dramatically and identifies the requirements that will create sufficient TEG power output to enable commercial viability of TEG technology technically and economically.

Achieving the required level of hot-side heat exchange performance is a significant engineering challenge requiring new heat exchange materials, designs and concepts that at the same time do

not add substantially to capital and operating costs. The new heat exchange materials/surfaces will need to provide heat exchanger performance two to five times greater than the best commonly available technologies. Adding to the challenge of hot-side exchanger design is the fact that most industrial waste heat gas streams have components that can foul and corrode heat exchange surfaces, thereby degrading TEG performance. Further, the streams are near atmospheric pressure, and therefore, may require energy-consuming blowers/compressors to reach the flows and heat fluxes desired. Finally, it was also established that increase in TE material performance is only important if an increase in hot-side heat transfer performance is simultaneously achieved. This again indicates the critical importance of hot-side heat exchange mechanism in the overall system design and performance.

The cold-side heat exchanger can be designed to operate with a liquid as the heat exchange medium. Liquids have thermal conductivities and capacities an order of magnitude higher than that of gases, which allows the cold-side heat exchanger to use proven technologies. The cold side also has a lower heat flux than the hot side since a portion of the energy throughput is being converted to electricity. Attention must be paid to optimizing the cold-side heat exchanger so that pumping power requirements do not consume a significant portion of the electricity produced.

The TEG electrical output will be direct current at relatively high voltage (Vdc), in order to reduce the ampere load within the generator. The high TEG power output can be used to run readily available DC motors, compressors, and other electrical equipment. In some cases, it will be necessary to use DC-AC power electronics to convert the output to AC signals required by some electrical equipment. Fortunately, the necessary DC power controls and converters are standard and have relatively low cost and high conversion efficiencies.

Conclusion

There are several significant opportunities for thermoelectric recovery of waste heat. TEG application in glass furnaces alone, which represent about 1% of industrial waste heat losses, would generate over \$25,000,000 in annual sales, assuming higher efficiency TEGs with $ZT \sim 2$ could be built for \$5/watt and 5% of the market buys TEGs per year. The magnitude of this opportunity, both in terms of recovered energy and potential sales, warrants continued research and development.

The new demand for semiconductor materials (e.g., tellurium, germanium, and gallium) that would result from widespread use of TEGs with $ZT \sim 2$ would constitute about 2% to 4% of world production. This increase in demand would not significantly stress or disrupt world markets for these materials (section 4.2.3). Research on new TEG devices must consider manufacturing techniques to keep TE material demand low (> 4.9 W/gm) and TEG system costs low (\sim \$5/W).

Advanced TEG systems using $ZT \sim 2$ TE materials are pushing the limits of current thermal transfer technologies to provide the required TEG interface heat fluxes and hot-side heat transfer. Significant R&D work is required to demonstrate that hot side heat exchangers can be built for a cost and pressure drop that does not detract from the value provided by a $ZT \sim 2$ TEG system. It is possible that advanced TEG systems using $ZT \sim 4$ TE materials, depending on their exact formulation and TE properties, could far exceed current thermal transfer technologies and require exotic/ultra-advanced heat exchanger technologies that are not well defined or characterized at this point.

Current materials with a $ZT \sim 1$ are not cost effective for industrial waste heat recovery. However these materials offer the opportunity to perform systems R&D on industrial waste heat streams in order to build the knowledge base, achieve valuable lessons-learned, and gain practical experience with the design and operating parameters that will be determine the success of high heat flux $ZT \sim 2$ TEG systems. R&D and engineering studies on how to interface TEG systems with existing process equipment, as well as studies of possible exhaust system modification (duct length, residence times, etc.) could lead to greater opportunities for integrating TEG systems in more industrial applications.

While continued research in advanced TE materials and device fabrication is necessary and recommended, it is also critical that closely coordinated, parallel R&D projects be executed to research, develop, validate, and demonstrate advanced heat transfer materials, thermal interface materials, heat exchanger technologies, and protective coatings in order to enable successful commercialization of advanced TEG systems (i.e., $ZT \sim 2$). The importance of TEG system R&D being closely coordinated with advanced TE material R&D can not be over emphasized if this technology is to achieve its ultimate potential in industrial waste energy recovery.

1. Introduction

Thermoelectric (TE) materials use electricity to produce heating and cooling effects (temperature gradients) or conversely use temperature gradients to produce electricity. Older bulk TE materials, such as Bi_2Te_3 and PbTe , can provide only limited power generation efficiency, typically as low as 4-7%. Recently discovered advanced TE materials (nanostructured, thin-film superlattice, and quantum well materials) that have been characterized in the last 5-7 years and continue to be developed are projected to provide a much higher efficiency (typically 12-20%). TE energy efficiency in cooling is generally characterized by the Coefficient of Performance or COP (i.e., the ratio of the heat removed to the input power). The older bulk TE materials in most cooling applications offer COP ~ 1 , while a COP of >2 is required for TE materials to be considered as viable alternatives in refrigeration applications.

TE commercial device and systems, to date, have been limited to small-scale ($<50,000$ Btu/day of useful work) applications in niche markets where energy efficiency is not a concern. In the past, it has been technically and economically more energy efficient for large-scale industrial settings to employ traditional heating and cooling systems (e.g., heat exchangers and recuperators) rather than thermoelectric ones (particularly, when older TE materials only provide 4-7% conversion efficiency). Likewise, in most past cases, it was always more efficient to produce electricity using traditional generators rather than a thermoelectric generator (TEG). With the advent of the newly discovered advanced TE materials, this situation appears to be changing rapidly.

There is at least one significant opportunity for improved TEG systems in large-scale industrial applications: the large quantities of thermal energy (i.e., waste heat) discharged in emissions. This “waste” energy, estimated at 1,800 trillion Btu per year (TBtu/year),¹ has no economic value or in some cases a negative value (i.e., requires additional processing) and is discharged to the environment. Although industry has numerous options for utilizing waste heat, there are some large applications where it is not practical to capture the waste heat energy using traditional energy recovery or conversion technologies. These typically include applications where the plant does not have use for the recovered wasted energy, for example to preheat water, raw materials, or combustion air. In such cases, TEGs offer a potential means to add value to the industrial process by utilizing this “not practical” portion of “waste” energy to produce electricity.

The purpose of this report is to investigate the opportunities for advanced TE devices for large-scale power generation from waste heat energy in industry and to quantify its possible benefits. The report examines the engineering design and details required to install a TEG system in a glass furnace. This level of detail provides valuable insights into the system requirements and highlights the engineering challenges to incorporating a TEG into an industrial waste gas stream. Four additional applications were reviewed in lesser detail. The report also analyzes and prioritizes the practical (technical and economic) barriers that hinder the development and adoption of TEGs in such settings.

Although, currently the application of TE devices is limited to a niche market, numerous companies are involved in manufacturing these devices (Appendix C), attesting to their commercial value. Using TE devices to recover industrial waste heat will require more robust and thermally efficient devices, and significant engineering to configure these devices to provide the heat transfer and power output required in industrial applications.

2. Thermoelectric Concepts

Thermoelectric modules are devices that either convert thermal energy from a temperature gradient into electric energy or vice versa, convert applied electric energy into a temperature gradient. This section provides an understanding of basic concepts and frequently encountered terms used in the latter sections of this report to discuss thermoelectric systems. Many of these discussions typically revolve around the “figure-of-merit” or ZT of the TE materials and its impact on the thermal to electric conversion efficiency in power generation or COP in cooling applications.

2.1 Thermoelectric Basics

i. Thermoelectric Power Generation

The thermoelectric power generation is based on the Seebeck effect – *If heat is applied to a circuit at the junction of two different conductors, a current will be generated.*

Discovering the effect in 1821, Thomas Johann Seebeck observed that the magnitude of the voltage generated was proportional to the temperature difference and depended on the type of conducting material, but was unaffected by the temperature distribution along the conductors. Seebeck tested a wide range of materials, including the naturally found semiconductors ZnSb and PbS. The Seebeck coefficient (frequently measured in microvolts/K) is defined as the open circuit voltage produced between two points on a conductor when a uniform temperature difference of 1 K is applied between those points.²

The simplest TEG consists of a thermocouple consisting of n-type (materials with excess electrons) and p-type (materials with deficit of electrons) elements connected electrically in series and thermally in parallel. Heat is input on one side and rejected from the other side, generating a voltage across the TE couple (Figure 1).³ The magnitude of the voltage produced is proportional to the temperature gradient.

ii. Thermoelectric Heating and Cooling

Thermoelectric heating and cooling devices are based on the Peltier effect – *If a current is passed through a circuit of two dissimilar conductors, there will be a rise or fall in temperature at the junction depending on the direction of the current flow.*

This converse effect to Seebeck was discovered by Jean Peltier in 1834 and was later expanded on by Emil Lenz in 1838. Lenz demonstrated that water could be frozen when placed on a

bismuth-antimony junction by passage of an electric current through the junction. He also observed that if the current was

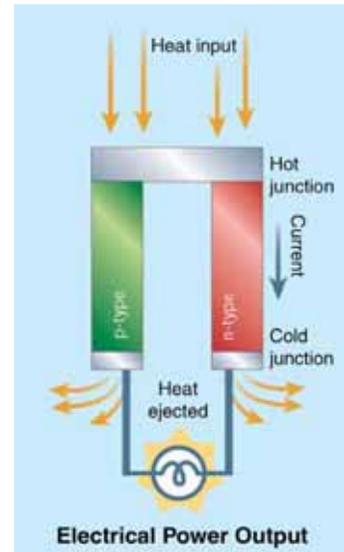


Figure 1: Thermoelectric power generation

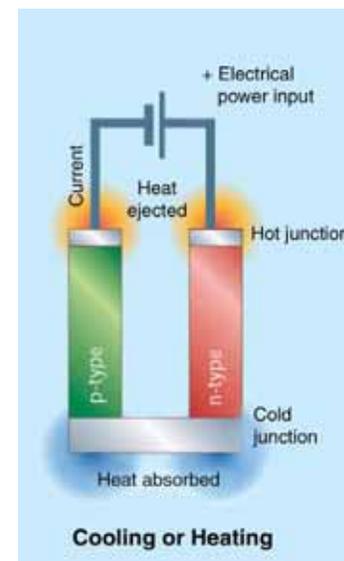


Figure 2: Thermoelectric cooling

reversed, the ice could be melted. Lenz concluded that the direction of the current flow determines whether the heat is absorbed or generated at the junctions.

When electric input is applied to a thermocouple, as shown in Figure 2,³ electrons move from p-type material to n-type material absorbing thermal energy at the cold junction. The electrons dump their extra energy at the hot junction as they flow from n-type back to the p-type material through the electrical connector. Removing heat from the hot side will drop the temperature on the cold side rapidly, the magnitude of the drop depending on the electric current applied.

2.2 Efficiency of Thermoelectric Materials: Figure-of-Merit (ZT)

Good TE materials should have the following characteristics:

- high electrical conductivity to minimize Joule heating (rise in temperature from resistance to electric current flowing through it);
- large Seebeck coefficient for maximum conversion of heat to electrical power or electrical power to cooling performance; and
- low thermal conductivity to prevent thermal conduction through the material.

These three properties are commonly combined into a single metric that measures the overall performance of a thermoelectric device: the “figure-of-merit” or Z . The figure-of-merit of a thermoelectric material is defined as:

$$Z = \alpha^2 \sigma / \lambda \quad [\text{Eq. 1}]$$

where α is the Seebeck coefficient of the material ($\text{volt}\cdot\text{kelvin}^{-1}$),
 σ is the electrical conductivity of the material ($\text{ampere}\cdot\text{volt}^{-1}\cdot\text{meter}^{-1}$), and
 λ is the thermal conductivity of the material ($\text{watt}\cdot\text{meter}^{-1}\cdot\text{kelvin}^{-1}$)

Since Z has a unit of per degree of temperature, a more useful dimensionless figure-of-merit can be defined as $Z\cdot T$, where T is the average operating temperature. This important parameter dictates the magnitude of the maximum power conversion efficiency or the maximum refrigeration coefficient of performance for TE devices (see section 2.3 for further discussion).

Early TE materials research in the 1950s and 1960s yielded bismuth telluride (Bi_2Te_3), lead telluride (PbTe) and silicon-germanium (SiGe) alloys as the materials with the best figure-of-merits in three somewhat distinct temperature ranges. Bi_2Te_3 and its alloys have been used extensively in TE refrigeration applications and some niche low-power generation applications, and have a useful temperature range of 180 K to 450 K. PbTe and SiGe materials have been used extensively in higher temperature power generation applications, particularly spacecraft power generation, and have a useful temperature range of 500 K to 900 K and 800 K to 1300 K, respectively. The discovery of these materials as good candidates for TE devices led to the development of a fledgling TE industry, many of its early participants being still active in the area.

2.3 Maximum ZT

Although there is no known theoretical limit to Z , and therefore ZT , in practice it has been difficult to achieve high ZT values because of the inherent coupling of electrical conductivity and thermal conductivity in most materials. High electrical conductivity is necessary to minimize resistance (Joule) heating of the TE device, while low thermal conductivity is needed to maintain a large temperature gradient between the hot and the cold side. Typically, modifying metals to

change their electrical conductivity results in a proportional change of thermal conductivity and vice versa, as governed by their relationship in the Wiedemann-Franz Law. This relationship is based on the physical fact that both heat and electrical transport involve the free electrons in the metal. This creates challenging limits on increasing ZT of materials, since increasing Z would require no coupling between the two conductivity quantities, or ideally, the relationship should be an inverse proportionality, but this does not occur in real materials. Until about 1990, most researchers focused on semiconductors and metal alloy compounds in efforts to develop better TE materials. This limited TE material performance in many of the compounds investigated to ZT of about ~ 1 .

Research at NASA-JPL, MIT-Lincoln Labs, Michigan State University, and other organizations from about 1995 to the present has led to the discovery, characterization, and laboratory-demonstration of a new generation of TE materials: skutterudites, thin-film superlattice materials, quantum well materials, and PbAgSbTe (LAST) compounds and their derivatives. These materials have either demonstrated ZT of ~ 1.5 -2 or shown great promise for higher ZT approaching 3 or 4. Quantum well materials include 0-dimensional (0-D) dots, 1-dimensional (1-D) wires and 2-D thin-film materials. These materials make it possible to create TE systems that display higher ZT values than those obtained in bulk materials because quantum well effects tend to accomplish two important effects: 1) they tend to significantly increase density of states which increases the Seebeck coefficient in these materials; and 2) they tend to de-couple the electrical and thermal conductivity allowing quantum well materials to exhibit low thermal conductivities without a corresponding decrease in electrical conductivity. The LAST compounds have shown embedded nanostructures within the crystal matrix that may exhibit quantum well effects.

2.4 Efficiency, ZT and Temperature Difference

It is important to recognize that all TE devices are very dependent on temperature, not only the operating temperature gradient, but also the absolute temperature values. TE devices can be used to generate direct current electric power when a temperature difference is available. However, currently available thermoelectric materials have a ZT of less than ~ 1 and the device efficiency of producing electric power rarely exceeds 5%. This performance has limited TE generators to niche applications where requirements for remote operation, reliability, no moving parts, and silent operation have outweighed the more negative aspects of high cost and low conversion efficiency. This has tended to limit TE technology application to small refrigeration systems, spot-cooling, low power, or specialized cooling or power applications. These systems have generally dealt with small amounts of power or thermal energy flow ($< \sim 1000$ W).

The maximum efficiency of a TE device in power generation is given by the following relationship:

$$\eta_{\max} = \left[\frac{T_h - T_c}{T_h} \right] \cdot \left[\frac{(1 + Z^* \bar{T})^{1/2} - 1}{(1 + Z^* \bar{T})^{1/2} + 1} \right] \quad [\text{Eq. 2}]$$

where Z^* is the optimum Z of the p-type/n-type couple in the TE device, T_h and T_c are the temperatures of the hot and the cool sides respectively, and \bar{T} is the average of T_h and T_c .

This relationship is shown in Figure 3 to give an idea of the magnitude of the efficiency in relation to various ZT s and temperature differences. The first part of Eq. 2 shows that maximum TE efficiency is associated with a T_h and T_c difference, similar to a Carnot efficiency. The efficiency of TE devices is often quoted as such, but any technical discussions on the topic must make distinction whether the TE efficiency is quoted as “percent of Carnot” or absolute efficiency.

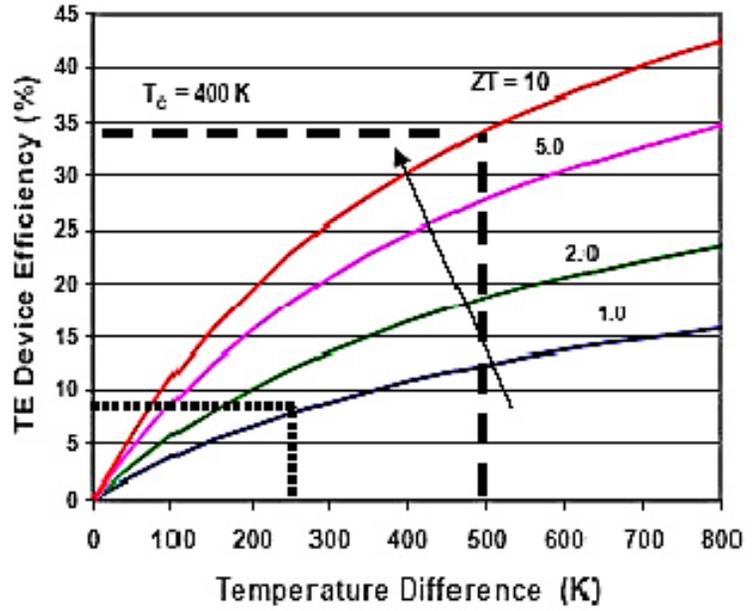


Figure 3: Efficiency as a function of ΔT

In TE cooling applications, the device COP (Coefficient of Performance) is the relevant quantity to measure the efficiency of conversion (similar to other refrigeration technologies). If electrical power, P , is supplied to achieve a certain cooling capacity, Q_c , the maximum COP is given by:

$$COP_{\max} = \left[\frac{Q_c}{P} \right] = \left[\frac{T_c}{T_h - T_c} \right] \cdot \left[\frac{(1 + Z^* \bar{T})^{1/2} - \frac{T_h}{T_c}}{(1 + Z^* \bar{T})^{1/2} + 1} \right] \quad [\text{Eq. 3}]$$

As seen in Figure 3, for a given absolute T , the higher the ZT , the higher the maximum heat-to-electric conversion efficiency in power generation or higher the maximum COP in refrigeration. Increasing ZT is, therefore, the ultimate design goal in most TE applications, although off-nominal or off-design operation is usually unavoidable due to temperature variations in the process application. Predicting off-nominal or off-design performance is much more difficult computationally and in practice when determining actual relevant conditions and assumptions.

2.5 Thermoelectric Generation Module Assemblies

TE generation modules can consist of an array of several to hundreds of p-type/n-type thermocouples joined together electrically in series and thermally in parallel (Figures 4 and 5). They are typically standardized to provide specific amp/volt outputs. The TE elements (or couples) can be embedded in electrically insulating materials to maintain their spacing and the module can be covered in other materials to protect it from its operating environment. The coefficient of thermal expansion of the various internal materials must be considered in the design of a module since internal stresses within the module generated during assembly and thermal cycling during use can lead to failure of the module. Inter-diffusion of materials and sublimation of internal materials and of materials external to the TE device (i.e., connection materials, interface materials) are also important considerations and can lead to module failure. Effective diffusion barriers and coatings are, therefore, required to minimize or eliminate these effects and their impact on failure rates.

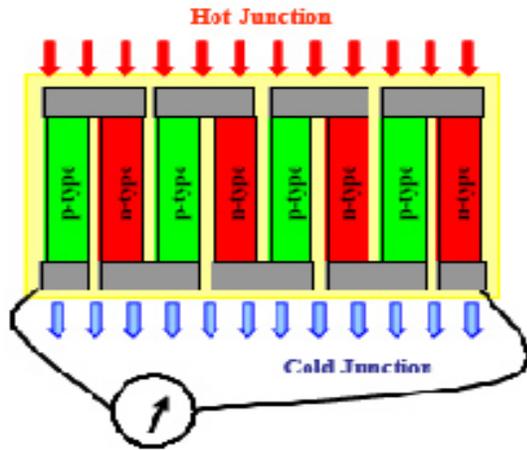


Figure 4: Multi-element thermoelectric device

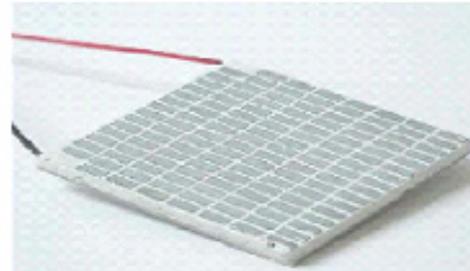


Figure 5: 126-element thermoelectric module

A critical factor for TEG operation is the mean time between failure or the MTBF characteristic. One of the main advantages of TEG and TE cooling systems is their generally high reliability due to no moving parts. In spacecraft TE power system lifetimes of over 10 years have been reported in several deep-space NASA missions. These lifetimes are also the result of extensive system engineering research and development (SER&D) conducted to identify, mitigate and, eliminate failure mechanisms during development in their specific applications. Similar SER&D certainly will be required to achieve comparable lifetimes with the new, advanced TE materials with $ZT \sim 2$ and higher.

Modules can additionally be interconnected, in combinations of parallel and/or series, to create larger assemblies that provide a specific amp/volt output and geometric products. Current and voltage ($I - V$) characteristics shift as hot-side thermal conditions vary and are important system-level drivers in any application. $I - V$ characteristics are driven by the number of couples, TE materials, nature of the parallel-series circuits, and the amount of heat delivered to the TEG module. Figure 6 shows the typical $I - V$ curves for a TEG module assembly as hot-side thermal energy increases.

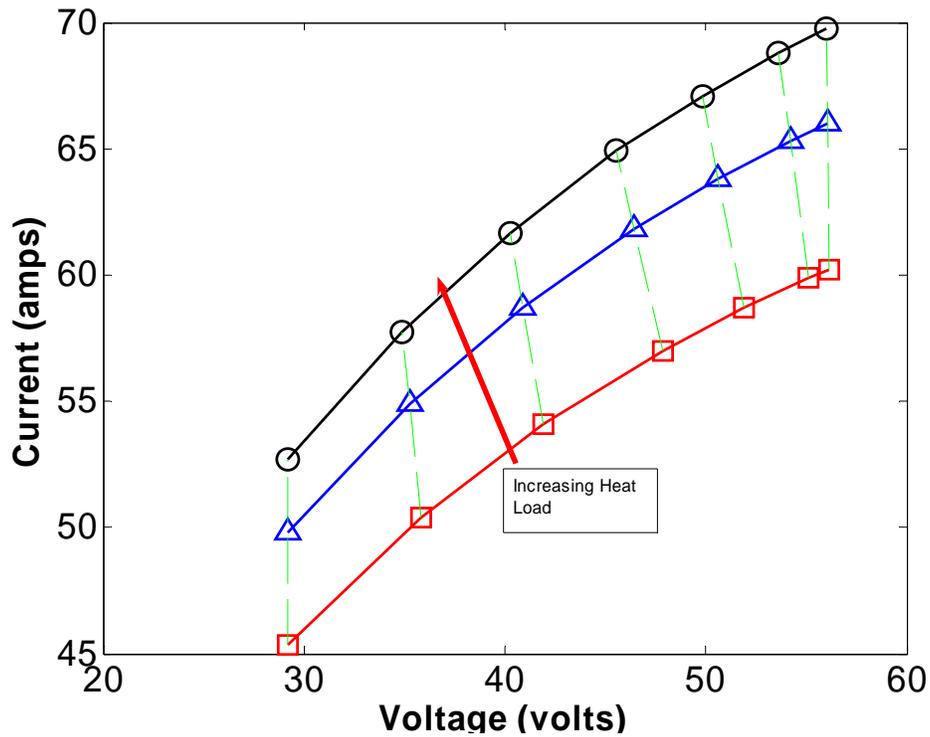


Figure 6: Typical current vs. voltage characteristic for TEG Module

TEG modules are commonly interfaced with hot-side and cold-side heat exchangers in the final TEG system. The nature of the interface is crucial as the interface must efficiently transfer thermal energy into and out of the TEG module. Improper engineering at these critical interfaces can decrease interface heat transfer, severely limiting TEG system performance and creating large discrepancies between the expected and the actual performance.

3. Opportunities for Industrial Sector Waste Heat Recovery

Not all industrial waste heat is of the same quality. It varies from one industrial application to another in terms of its temperature, composition, and accessibility. Waste heat stream composition is very important since it determines heat capacity, thermal conductivity, phase change temperatures, and corrosiveness. In order to identify the best opportunities for waste heat recovery by thermoelectric generation in the industrial sector, this “Scoping Study” examines a few of the major waste heat industrial sources by characterizing these sources in terms of the waste heat quality. A detailed characterization of the potential industrial scenario is necessary since the application temperature limits the utility of thermoelectric (TE) devices; the delta T (hot side vs. cold side) determines the TE device’s efficiency; and the waste heat source composition will determine corrosion, erosion, scaling, fouling and other effects, dictating the demands on the hot-side material composition and the heat transfer surface designs.

3.1 Industrial Process Waste Heat

It is estimated that about 3,143 TBtu of energy is wasted annually by the thousands of processes used in the U.S. manufacturing sector (excluding onsite steam and electric energy generation and distribution losses).⁴ A large portion of this energy is exhausted into the atmosphere as waste heat.

A significant portion of waste heat is contained in gases which are discharged at ~300° F, even though the furnace or process environments that are the sources of the discharges may be operating at substantially higher temperatures. In a large number of industrial processes, large amounts of dilution air are added to reduce the temperature of the co-mingled exhaust in order to reduce capital and operating costs in flue system operations. In many instances the dilution air is added a very short distance from the furnace or process exhaust ports. Thus, high-grade heat is turned into low-grade heat. Effectively, the duct lengths or “residence times” for which the exhaust remains a source of high-quality heat are very short. Temperatures in the range of 300° F represent very low-quality heat and no commercially viable means of recovering this heat is available (Section 3.3 briefly discusses a future technology, piezoelectric generation, which may be applicable at these temperatures).

Many manufacturing industries offer several large opportunities for energy recovery. Aluminum, glass, metal casting and steel, all have process furnaces discharging high-temperature waste heat combustion gases and melt pool gases (such as, aluminum ~775°C and glass ~1,425°C). In some industries, this heat can be used to raise steam, preheat raw materials or combustion air, or be integrated with other processes at the manufacturing site. But in other industries there is limited opportunity to reuse this thermal energy. This makes TEG electricity attractive to these industries. The opportunity to recover waste heat should be large in metals industries also which uses numerous heat treatment furnaces (with relatively clean flue streams of combustion gases only) and in chemical industry, where process heaters are widely used (direct-fired reboilers, reactors, etc.). Additional waste heat opportunities exist in lime kilns, cement kilns, etc.

3.2 Industrial Thermoelectric Generation Waste Heat Opportunities

This “Scoping Study” divides industrial waste heat recovery opportunities into three sets of potential applications to begin to size the overall opportunity for TEG devices in waste heat applications. Each “application set” is defined by a range of operating conditions, and represent different opportunities for TEG applicability, as shown in Table 1.

Table 1: Thermoelectric waste heat opportunities in the U.S. industries

		Temperature C (°F)	Available Waste Heat TBtu/year	TEG Recoverable Waste Heat TBtu/year		
				ZT=1	ZT=2	ZT= 4
Applications Set A: (low hot-side temperature, relatively clean flue gas)						
Commercial	Water/Steam Boilers	150°C (300°F)	560	na	na	na
Industrial	Water/Steam Boilers ⁵	150°C (300°F)	610	na	na	na
	Ethylene Furnace	150°C (300°F)	30	na	na	na
Applications Set B: (medium hot-side temperature, mixed flue gas quality)						
	Aluminum Smelting ⁶	960°C (1750°F)	4.2	0.2	0.6	1.0
	Aluminum Melting ⁷	750°C (1380°F)	28.6	1.4	4.3	7.2
	Metal Casting Iron Cupola	375°C (700°F)				
	Steel Blast Furnace					
	Lime Kiln					
	Cement Kiln (with preheater)	200°C (380°F)	7.0	0.3	1.0	1.7
Applications Set C: (high hot-side temperature, mixed flue gas quality)						
	Cement Kiln (no preheat)	820°C (1500°F)	8.4	0.4	1.3	2.1
	Glass oxy-fuel Furnace	1425°C(2600°F)	4.8	0.2	0.7	1.2
	Glass Regenerative Furnace	480°C (900°F)	11.8	0.6	1.8	3.0
Total			1,265	3.2	9.7	16.2

Based on the significant quantities of waste heat available for recovery, glass, ethylene and aluminum industries, and industrial and commercial boilers were selected for detailed examination of opportunity for application of TEG devices in waste heat recovery (see section 5 for assessments).

3.3 Alternatives to Thermoelectric Generation

There are significant waste heat opportunities at process flow temperatures near 150°C (~302 °F), such as in industrial water/steam boiler applications and ethylene furnaces. In fact, Table 1 shows that the largest waste energy opportunity is in water/steam boilers in the commercial and industrial applications (~1,170 TBtu/yr collectively). Unfortunately, these temperatures are generally too low to efficiently employ thermoelectric power generation. An alternative technology, called piezoelectric power generation (PEPG), is emerging as a low-temperature power generation technology that can directly convert heat into electrical energy. This technology operates on the theory of an oscillatory liquid-to-gas expansion within a closed chamber stressing a piezoelectric thin-film membrane, thereby creating a time-dependent voltage

output.^{8,9} It operates most effectively in the 100°C to 150°C temperature range, so it would be best suited for waste heat recovery in water/steam boilers and ethylene applications (at 150°C). There are other configurations that are intended to capture mechanical energy directly and convert it into an electrical signal.^{10,11,12}

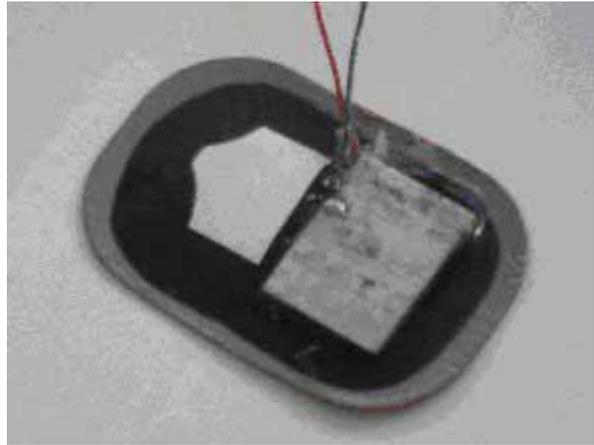
PEPG technology is currently fielded in a thin-film membrane configuration that is only about 1% efficient in converting heat to electrical energy. There are many technical challenges associated with this early-stage power generation technology including:

- Low conversion efficiency
- High internal impedance
- Requirement for oscillatory heat loads
- Oscillatory electrical signals
- Complex oscillatory fluid dynamics within the liquid/vapor chamber
- Difficulties in obtaining high enough oscillatory frequencies
- Long-term reliability and durability
- Very high cost (\$10,000 /W)

The technology usually employs a common piezoelectric oxide material, lead zirconate titanate (PZT), in the active membrane. PZT is used in many microelectromechanical systems (MEMS) applications because of its high piezoelectric and electromechanical coupling coefficients.^{13,14} Different piezoelectric materials and device materials are being investigated to improve performance and manufacturability, and lower the cost of PEPG devices. Current devices can operate at ~100 Hz, but the real need is to operate near 1000 Hz. It is also clear that similar heat transfer interface challenges will exist at the hot- and cold-sides in PEPG systems as in TEG systems. At the lower temperatures applications, there will be less temperature driving potential to transfer the large amounts of heat involved. This will lead to larger heat exchange systems than in the higher temperature heat recovery applications addressed by TEGs if gas flows are used on the PEPG system hot-side. In these applications (150°C), if liquid or two-phase flow streams can be used instead of gas flows, then much better heat transfer conditions on the PEPG hot side can be achieved, which will invariably lead to higher PEPG system performance.

The low energy conversion efficiency of PEPGs can theoretically be overcome by cascading a single device into a multiple number of devices in series thermally and outputting electrically in parallel. However, PEPG cascading has not been demonstrated to date and there are technical challenges associated with this approach, not the least of which is controlling heat losses at each stage. If PEPG cascading can be accomplished and cost-effectively demonstrated, then energy conversion efficiencies of the multi-stage PEPG stack could be 8-10% or even higher. This provides a strong opportunity to recover a significant fraction of the large amount of waste energy available at ~150°C in industrial water/steam boilers and ethylene applications.

Currently, Defense Advanced Research Projects Agency (DARPA) is conducting R&D to advance this technology and is certainly a viable energy conversion technology that DOE could invest in to accelerate its development and demonstration. Industrial interest in this technology should be fostered as much as possible.



PEPG for recovering vibration energy in heavy truck tires (KCF Technologies, State College, PA)

4. Engineering Challenges for Commercial Viability

Three, very different, science and engineering challenges must be overcome to make thermoelectric waste energy recovery practical in the industrial sector:

- **Thermoelectric Materials** – Older bulk thermoelectric materials (i.e., Bi_2Te_3 , PbTe , and SiGe materials) generally have $ZT \sim 1$ and create relatively low-performance, large area, high-cost TE systems with conversion efficiencies of only 3-6%. Their poor performances do not meet industrial waste energy recovery requirements sufficiently to form a solid business case for their development and implementation. New, advanced TE materials must continue to be innovated, developed, and characterized resulting in:
 - greater ZT (~ 2 or higher),
 - better thermal, chemical, and structural stability,
 - well-understood structures and chemical properties,
 - reproducible synthesis/fabrication processes,
 - long term stability (5-10 years) at industrial operating conditions
 - demonstrated materials compatibility with other power system materials and,
 - have low material and fabrication costs.

Advanced TE materials should be developed with a specific target waste heat application in mind.

- **Thermoelectric Device Manufacturing** – New device engineering and fabrication techniques must be developed that enhance efficiency, reliability, and power output or cooling capacity while maintaining low costs. These techniques must be compatible with and amenable to miniaturization as this will be a common theme to fully exploit TE technology in industrial sector applications. The thermoelectric device (thermocouples, heat exchange attachment, wiring, interconnections, etc.) must be engineered in a manner that allows for low-cost large-quantity production. The TE device innovations must be compatible with the high-performance heat exchange/transfer technologies that provide the necessary high interface heat fluxes in miniaturized systems. TE device manufacturing encounters many of the same challenges as fuel cell development and micro-channel heat exchanger and reactor development. These similarities may represent cross-cutting opportunities that could enhance the development of all the technologies.
- **Thermoelectric Generator System Design** – The thermoelectric generator system consists of the thermoelectric device, all heat exchange technology (hot- and cold-side) necessary to maintain the operating conditions appropriate for the device, and an electronic volt/ampere control module. The TEG system must be capable of installation and operation without economically offsetting modifications or new large capital requirements to existing plant equipment and processes.

Ultimately, the specific application conditions and the cost of installing the system will be the factors that determine the viability of thermoelectric generators in the market. Currently, the largest commercially available system is the Global Thermoelectric Model 8550.¹⁵ This system delivers 550 watt (24 Vdc) and costs approximately \$17,500⁹ amounting to roughly \$30/watt capital cost. The Model 8550 uses about 1,695 ft³/day of natural gas, giving it a thermal

efficiency of ~3%. (Note: Approximately 55-60% of the cost of the Model 8550 is from the TE devices.)

The installation of a TEG at an industrial manufacturing site only makes sense if it is reasonably competitive with the local electricity pricing. If the local electric price is assumed to be \$0.08/kWh and a seven-year payback on capital equipment is acceptable, then the capital cost would need to be about \$5/watt assuming the TEG has no operating costs (no-cost waste energy). This requires roughly an 80% decrease in the current TEG system pricing. A combination of more efficient materials (higher ZT), lower device manufacturing costs, and value-engineered systems would be needed to make thermoelectric generation of electricity from waste heat a commercial reality.

4.1 Thermoelectric Materials

There is significant research being performed to develop new, advanced TE materials and techniques for making TE elements. Advanced TE materials range from simple thermocouples, semiconductors, mixed-valence Kondo metals, clathrates, skutterudites, elements consisting of nanostructured wires, quantum dots, quantum wells, thin film super lattices, combinatorial sputtered deposits, and many others.

Key to the commercial development of TE materials is the recognition that these materials not only require higher ZT , but must also be suitable for use under industrial conditions and have a path to cost-effective mass production. They must be thermally, structurally, and chemically stable. They must accommodate vibration and thermal cycling conditions without significant degradation. There must be methods and materials developed to mitigate or eliminate interface material diffusion across the temperature ranges of interest. These materials must be thermal expansion matched with appropriate electrical connection, diffusion barrier, and electrical isolation characteristics. This entire area of advanced TE materials development requires more R&D efforts and funding to develop robust and long-term solutions. For example, there is currently not enough information to determine the extent of quantum and nano-materials/elements susceptibility to degradation from material migration, sublimation, diffusion, thermal cycling, and variable structural effects. Nor are there any methods or materials for mitigating any such effects if they are significant. This area of R&D could benefit from the application of advanced computational techniques.

4.2 Thermoelectric Device Manufacturing

Manufacturing of TE devices, whether it would be a single thermocouple, nanostructured tubes, quantum dots, quantum wells, thin film super lattices, sputtered, or other structures, must have a pathway to cost-effective mass production.

4.2.1 Thermocouple Type Devices

Current thermocouple type device manufacturing is labor intensive, requiring numerous tasks like soldering, wiring, and sophisticated element placement. Mass production of thermocouple type devices in the past often required hundreds of workers making thousands of connections (Figure 7). This manufacturing approach is costly and susceptible to errors and variations that may



Figure 7: TE device manufacturing

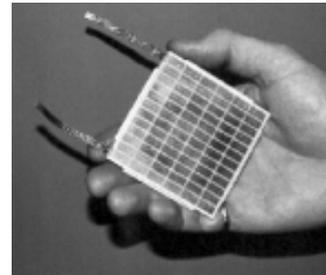
impact short- and long-term device performance and reliability. Several companies have researched and implemented more advanced, automated manufacturing techniques to drive down manufacturing costs and increase device performance and reliability.

4.2.2 Wafer Type Devices

Potential manufacturing with the economies-of-scale similar to the semiconductor chip industry is possible, particularly with some of the newer, advanced TE materials such as thin-film super lattice materials, other quantum well materials, and LAST compounds or their derivatives. In fact, one of the major potential advantages of the new, advanced TE materials is that it appears they can be fabricated, at least at the laboratory scale, by sputtering processes or other fast deposition processes. It is not clear, however, that this can transition to a high-volume manufacturing process for commercial setting and further research and development is necessary to establish mass fabrication techniques for these materials. It is yet to be demonstrated that the new, advanced TE materials are amenable to wafer-type manufacturing.

4.2.3 Earth Element Supplies Needed for TEG Devices

Thermoelectric devices require semiconductor or rare earth elements for their manufacture. It has been suggested that the potential large-scale manufacturing of TEGs for applications like waste heat recovery could create market disruptions and/or price surges by consuming large portions of the world’s semiconductor raw materials. A rough approximation of the projected usage of raw materials incorporated in the production of TEGs and their impact on the world markets is provided below.



The mass of semiconductor materials used in a TEG device can be estimated by examining existing TEGs. For example, Hi-Z Technology, Inc.’s HZ-20 TE module contains bismuth-telluride thermocouples and has dimensions of 2.8" x 2.8" x 0.20" (i.e., a volume of 25.7 cm³) and a mass of about 104 grams. The bismuth and telluride semiconductors used in the module have similar shape and size and are about the same volume. The remainder of the device is filled with a non-conducting epoxy-like material. The density of bismuth is 9.78 g/cm³ and of tellurium is 6.24 g/cm³. If the epoxy-like material has a density of ~1.00 g/cm³, then the following equation can be set up to determine the approximate mass ratios of the materials.

$$9.78 \text{ g/cm}^3 (V \text{ cm}^3) + 6.24 \text{ g/cm}^3 (V \text{ cm}^3) + 1 \text{ g/cm}^3 (25.7 \text{ cm}^3 - 2V \text{ cm}^3) = 104 \text{ g}$$

Solving for V (= 5.6 cm³) allows a calculation of the approximate mass of the materials used in this device.

	Volume, cm³ (%)	Mass, gm (%)
Bismuth.....	5.6 (22%).....	54.6 (53%)
Tellurium.....	5.6 (22%).....	34.8 (33%)
Epoxy	14.5 (56%).....	14.5 (14%)
Total.....	25.7 (100%).....	104.0 (100%)

The TE device in this example produces ~19 watts of power, which provides a calculated value of ~0.35 watt per gram of bismuth and ~.55 watt per gram of tellurium.

The U.S. waste heat discharge accessible to TEGs is ~1,800 trillion Btu/yr. If TEG devices were to capture 10% of this market and had a thermal conversion efficiency of 7%, then nearly 422 MW could be generated. If the TEG technology enters the market at a rate of 5% a year, fully capturing its 10% market share in 20 years, then roughly 21 MW of TEG devices per year would be required. This market capture rate would require 61 tonne/yr of bismuth and 39 tonne/yr of tellurium for manufacturing waste heat TEGs. The world produced about 5,200 metric tonnes of bismuth and only 113 tonnes of tellurium in 2005. This +1.2% additional demand for bismuth would not be disruptive. However, +34.2% increased demand for tellurium would put substantial pressure on the supply and price of this material.

The maximum estimated demand for other semiconductor materials can be approximated by comparing their densities with bismuth's density. The estimated demand for these materials is shown in Table 2. The projected demands show that if TEG device contained germanium and particularly gallium, considerable strain would be placed on the supply and price of these materials.

It should be noted that $ZT \sim 1$ configurations used in the exercise above do not have the cost efficiency to be used in industrial applications. A more realistic impact on future materials supply is made by examining $ZT \sim 2$ configurations. Increasing ZT significantly lowers the area and volume requirements for semiconductor materials (Table 8 on page 37 shows the relative areas of different ZT materials). Since the physical configuration of higher ZT materials is smaller and results in the use of lesser material, the demand for semiconductor materials will be lower. Table 2 shows the impact of a $ZT \sim 2$ material which results in a ~4.9 watt per gram of bismuth use. If advanced TEG devices were built with these newer $ZT \sim 2$ configurations, then the demand for semiconductor materials would be significantly reduced. However, even at these much lower numbers, the demand for tellurium and gallium could result in some pressure in these markets.

Table 2: Projected material demand for TEG device manufacturing in the waste heat market

	Density	2005 World Market	$ZT \approx 1$ TEG @ 0.35 W/gm		$ZT \approx 2$ TEG @ 4.9 W/gm	
	(g/cm ³)	(tonnes)	(tonnes/year)	Market Share	(tonnes/year)	Market Share
Bismuth	9.78	5,200	61	1.2%	4.3	0.1%
Tellurium	6.24	113	39	34.2%	2.8	2.4%
Selenium	4.79	1,350	30	2.2%	2.1	0.2%
Germanium	5.32	90	33	36.6%	2.4	2.6%
Silicon	2.33	5,100,000	14	0.0%	1.0	0.0%
Gallium	5.91	63	37	58.1%	2.6	4.2%
Antimony	6.68	117,000	41	0.0%	3.0	0.0%

4.3 Thermoelectric System Design

This section discusses the TEG system requirements by focusing on the technical challenges and barriers to their use in the application sets developed in Section 3. The discussion is intended to address and/or quantify the following:

- Specific or portions of waste energy application sets that exceed thermoelectric materials/device/system operating limits.
- Achievable power levels and system metrics required
- ZT requirements for each application set
- TEG material and system R&D requirements to eliminate the technical gaps
- Engineering design requirements to maintain thermoelectric materials/device/systems within operating limits, keep operating efficiencies at their maximum and have acceptable costs in terms of energy recovery, operation, and capital

Section 6 provides a conceptual design and performance evaluation of a TEG system in an industrial application.

4.3.1 Increasing Operating Range of Thermoelectric Materials/Systems

Thermoelectric assemblies are made up of multiple components: thermoelectric material, electrical insulators, connectors, heat sinks, interface expansion/compression materials, and interface thermal transfer materials. Each of these items has environmental limits (temperature, pressure, chemical exposure, structural stress, shock and vibration, and cycling) within which they can operate without deterioration. The TEG system combines these components into a system that has its own environmental limits, which in many cases will be more restrictive than any one of the individual component that make up the assembly.

Currently, TEG devices are limited to niche applications where low performance and high cost are not show-stopping barriers. These applications have included remote power and cooling applications in military and spacecraft systems, and medical applications where a premium is placed on high reliability and/or human comfort. As discussed in section 2.2 (page 9), Bi_2Te_3 and its alloys have been used extensively in TE refrigeration applications, such as medical cooling, laser diode cooling, and infrared detector cooling, and some niche low-power generation applications. They generally have a useful temperature range of 180°K to 473°K (93°C to 200°C). PbTe and SiGe materials have been used extensively in higher temperature power generation applications, particularly spacecraft power generation, and have a useful temperature range of 500°K to 900°K (227°C to 627°C) and 800 K to 1300 K (527°C to 1027°C), respectively.

There is just as strong a need for performance improvement in the applications mentioned above as there is for performance improvements to enable new applications in waste energy recovery. Therefore, new devices need to be able to operate in the same environments as current conventional systems, as well as new industrial process and automotive waste energy environments. The new industrial process environments will require advanced TE systems to operate at exhaust temperatures of 1033°K (760°C) or higher, while automotive exhaust environments will require operation at exhaust temperatures of 670°K to 970°K (400°C to 700°C). In addition, TEG devices for new industrial and automotive applications must be able to withstand corrosive and particulate-laden flow environments. Most industrial process

applications will require stationary systems and therefore, certain requirements may be relaxed compared to dynamic environments. For example, automotive exhaust environments will have shock and vibration and severe thermal cycling requirements that are more severe than those anticipated in industrial process applications.

Newer devices will need to accommodate higher heat flux environments and interface with critical high temperature and heat flux materials. As will be discussed in detail in subsequent sections, their heat exchange systems must be tailored and designed to provide the necessary thermal fluxes, possibly as high as $350 - 400 \text{ W/cm}^2$. Section 5 will demonstrate the potential benefits of higher performance TE materials with $ZT \sim 2$ or higher.

4.3.2 Maintaining High ΔT across a Thermoelectric Device

Very high heat flux is required for thermoelectric generators to operate efficiently. The heat/energy flowing through the device is constrained by the hot-side and cold-side heat sink technology. The overall performance (i.e., efficiency-power characteristic) of a thermoelectric generator is a function of the heat sink technology as much as it is of the material's ZT .

Although the heat flow through the system via the heat exchangers is critically important for the efficiency of a thermoelectric device, it is a direct function of the temperature difference between the hot side and the cold side, ΔT , the highest efficiency being obtained with the largest ΔT across the TE device. This requires establishing and maintaining a high heat flux rate across the TE device. Gas streams have thermal conductivities (e.g., Nitrogen = $0.0139 \text{ Btu}/(\text{ft hr } ^\circ\text{F})$) an order of magnitude below that of liquids (e.g., water = $0.320 \text{ Btu}/(\text{ft hr } ^\circ\text{F})$). In addition, waste flue gas flow rates are typically relatively slow, creating a dually difficult challenge to obtain high convective heat transfer coefficients. In any waste flue gas heat application, the cold side will likely be a liquid-cooled heat sink, while the hot side is the waste flue gas (Figure 8). The engineering challenge is transfer of high heat fluxes from the bulk gas stream to the surface of the TE device in a compact, light-weight, and cost-effective manner. R&D is required in this area to fully enable high-performance TEGs and exploit the most recent advanced TE material gains in performance. Section 5 will discuss this at length.

The driving temperature difference (ΔT) across the TE device is dictated by temperature gradients that exist in the hot-side and cold-side heat exchangers that interface with the TE device at temperatures of T_h and T_c respectively. These heat exchanger temperature gradients are created by the thermal boundary layers and thermal conduction mechanisms within the heat exchanger that drive the required heat transfer to/from the TE device. As a result, the TE device hot and cold side temperatures, T_h and T_c , respectively, are always substantially different from the bulk exhaust stream and cooling flow stream temperatures.

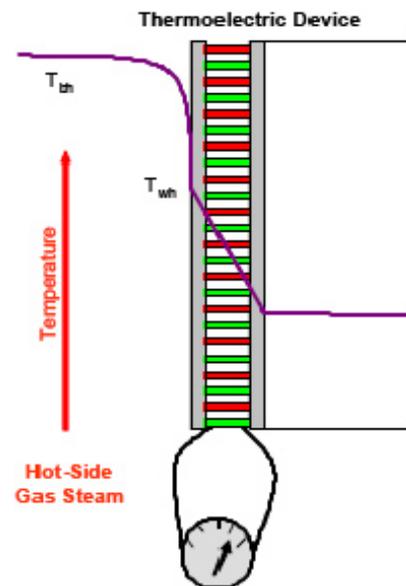


Figure 8: Temperature Profiles from bulk gas to bulk liquid

i. Hot-Side Performance Degrading Phenomena and Control

TE applications in industrial systems commonly face a serious problem of heat exchanger fouling, a performance degrading phenomenon. For example, advanced TE systems in industrial processes will inevitably experience degradation in hot-side (i.e., exhaust flue gas flow) heat exchanger performance due to particulate buildup, scaling, corrosion and other deleterious chemical reactions, and phenomena such as contaminant condensation on the heat transfer surfaces. These fouling processes cause material build up that creates additional heat transfer resistance impeding thermal transfer into the TE device, thereby reducing TE system power output (section 5 will discuss and quantify the importance of hot side heat transfer to TE system performance). The hot side is particularly challenging because there is little inherent control of particulates, dirt, and potentially corrosive gases in the exhaust flue gas. These conditions, however, should not be a major problem on the cold side of the TE system, as that involves filtered and cleaned water-cooled flow.

Heat exchanger fouling is often dealt with in industrial applications through design (over-designing heat transfer surfaces) and regular maintenance (shut-down and cleaning), both of which have economic consequences. Taking no care will ultimately degrade TE performance to an extent that the flow is severely restricted and the unit/device becomes inoperable. Fouling thermal resistance factors have been discussed for many common industrial environments by various researchers (*“Heat Exchangers: Thermal-Hydraulic Fundamentals and Design”*, Kakac et al., 1981).

Application of advanced TE systems, therefore, must incorporate design allowances and consider maintenance impacts. It would be best to design the advanced TE system to allow for system change-out/downtime that does not impact the overall system performance, i.e. replaceable or interchangeable units. There is also an inherent need, and possibly a need for further research, to characterize the potential fouling that can occur in the industrial process environment. It is critical to know whether fouling grows linearly at some time-dependent rate (i.e., falling rate), or asymptotically. It is recommended that R&D address this heat exchanger fouling issue in sufficient detail so that design allowances and maintenance procedures can be adequately quantified and accommodated in future TE systems. Relevant R&D areas to consider include:

- Determining fouling initiating factors
- Establishing fouling growth rates and factors
- Developing & characterizing surface coatings to mitigate fouling
- Developing fouling surface cleaning agents & techniques

Techniques for Hot-Side Heat Transfer

Waste flue gas streams are typically near atmospheric pressure and in large cross-section flues. These conditions do not provide the fluid dynamics required to generate high heat flux transfer. In general, efficient heat transfer technologies and techniques are needed to enable high heat transfer with low temperature differentials between the exhaust gas streams and the TE device hot side. This will allow the TE device hot side to match the temperature of the exhaust gas stream more closely, thereby increasing the system performance (i.e., efficiency and power output). It is anticipated that hot-side pumping power will be required to achieve the necessary flow and heat transfer rates.

This pumping power must be minimized as it represents a parasitic power loss to the system. Technologies and techniques to enhance the heat transfer from the bulk gaseous streams include:

- Microchannel & mini-channel heat-sinks
- Heat pipe systems
- Two-phase flow systems
- Jet impingement or spray heat transfer systems
- Porous media
- Static mixers

Many of these techniques introduce additional capital cost and could introduce additional operating costs (pressure drop) if improper or faulty design techniques are used. The additional capital cost must be weighed against the full waste energy costs that various industrial processes incur, both short-term and long-term, and the impact of those costs on their long-term business plans. A need does exist for significant system design R&D to properly implement the above listed heat transfer technologies to exploit their potential positive impacts on advanced TE system performance. For example, methods for incorporating and integrating heat pipes and microchannel heat exchangers into advanced TE systems are likely possible. This will require innovative approaches to TE module and system design that have not been explored as yet in a systematic engineering manner (i.e., analytically and experimentally).

ii. Cold-Side Performance Phenomena and Control

The cold-side heat exchange with the TE device is also important to the overall advanced TE system performance. Just as on the hot side, there is a strong need for high heat transfer at low temperature differentials between the bulk cooling flow and TE device cold side. The design, engineering, and operation of the cold side of the thermoelectric assembly operating on waste gas is technically easier than the hot side simply because it operates at colder temperatures, for which there is a wider range of material choices, and the cooling media (e.g., water) is usually much more benign and compatible with appropriate heat transfer materials. At the cooler temperatures, all degrading chemical processes have much slower chemical kinetics and therefore, have smaller long-term thermal and structural impacts. Structural properties of most materials are also more robust and stable at lower temperatures.

Techniques for Cold-Side Heat Transfer

Heat transfer technologies that will likely satisfy TEG cold side requirements in industrial process applications include:

- Single-phase liquid systems
- Finned and Pin-Fin extended surface
- Microchannel and mini-channel techniques
- Heat pipe systems

The TEG system cold side in currently envisioned industrial process energy recovery will likely use a liquid phase heat transfer medium, such as water. Liquid media provide thermal conductivities more than 10 times greater than gas and allow high heat transfer to a clean, controllable liquid flow with low mass flow rates and pumping power requirements. Gas-cooling on the TEG system cold side would require larger mass flow rates and enormous pumping powers for the required heat dissipation and therefore, are neither technically nor economically feasible. Closed cooling systems will allow for better control of cold-side surface corrosion and fouling, and require less operational fluid inventory costs.

4.3.3 Maintaining Efficiency Levels in Down-Stream Cascading

The term “cascading” refers to lining up multiple TEG modules in a flow-wise series configuration such that the exhaust stream outlet flow of one serves as the exhaust flow inlet to the next adjacent downstream module. This is an effective method to capture and convert additional amounts of thermal energy from the exhaust flow. In practice, for the glass industry applications analyzed in this report, it is likely that a 3-module cascade will be sufficient to capture and convert a high fraction of the available exhaust stream energy. Additional cascading after 3 TEG modules will likely hit a point of diminishing returns with added cost and complexity; however, this should be investigated on a case-by-case basis.

Each TEG unit in the cascade will operate under slightly different temperature conditions as the exhaust stream cools due to thermal energy (enthalpy) extraction by the hot-side heat exchanger from upstream TEG units. Consequently, when multiple TEG devices are positioned one after the other on a waste-heat flue (in series down the flue), each successive module downstream runs at a successively lower efficiency because the available temperature differential decreases as the exhaust stream cools. It is not likely that the cold-side temperature will change substantially because it is envisioned that parallel, equivalent-temperature cooling flows are possible on each module cold side in industry applications. However, temperature conditions and differentials may change enough that a different set of advanced TE materials may be used in downstream modules compared to upstream modules to maximize the performance at each temperature condition.

The selection of advanced TE materials for each TEG module will depend on the absolute ZT requirement of the system at that point. ZT and fundamental thermoelectric properties tend to be quite temperature sensitive, which may necessitate changes in TE materials as the TE units cascade down the exhaust flow. If advanced TE materials with more constant properties with temperature are developed, there will be less need and motivation to incur the cost and complexity of changing TE materials in adjacent modules of the cascade. One possible R&D goal in future may be to fabricate and implement advanced TE materials with less temperature dependency in the ZT and fundamental properties. This could payoff in significant benefits to the final system design, optimization, and implementation.

4.3.4 Load Matching Requirements

Advanced TEG systems for industrial applications are like any other power system with regard to resistive load matching. In order to maximize power output and efficiency, the resistive load that absorbs the power must be matched to the source resistance, i.e., $R_L = R_S$, where R_L and R_S are the load and source resistances, respectively. In order to maximize system conversion efficiency, $[R_L/R_S]$, it is related to the TE material properties and the ZT of the material and commonly expressed as:

$$\left[\frac{R_L}{R_S} \right] = \sqrt{1 + Z^*T} \quad [\text{Eq. 4}]$$

Equation 4 relationship shows that for $ZT = 1$ to 2 , $[R_L / R_S] \sim 1.4 - 1.7$ to maximize system conversion efficiency, which of course is quite different from the maximum power output

condition of 1. Therefore, operators and system designers will need to make decisions on what conditions are most important to the final industrial energy recovery application. In addition, controlling the load matching may require dynamic control and power management electronics if conditions on the TEG hot side or cold side change too rapidly or the industrial load varies in the industrial process plant. Possibly, the industrial load may need to be integrated with some type of energy storage system if TEG power output is desired during low power demand periods in the industrial environment. In this case, the total network load (industrial load plus the energy storage) must be managed by power management electronics.

The TEG electrical output will generally be direct current (DC) at relatively high voltage, in order to reduce the currents delivered at the high power levels anticipated in most industrial energy recovery applications. The high TEG power output can be used to run various electrical equipment in the industrial process environment, including electrical motors, and compressors. In some cases, it will be necessary to use DC-AC (alternating current) power electronics to convert to AC signals required by some electrical equipment. Fortunately, such power converters have relatively high conversion efficiencies now, and will have even higher conversion efficiencies in the near future (i.e., > 96%) because of considerable on-going R&D in this area by many government agencies. Therefore, energy losses via power conversion are expected to be small in future systems.

5. Assessing Thermoelectric Technology Potential and Requirements in Selected Industries

Obtaining a broad look at industrial waste heat in order to quantify the number of applications and the potential industry-wide energy savings that would result from the widespread adoption of TEG systems would require examining hundreds of industrial processes. This report is limited to the following processes:

- Glass (Section 5.1)
- Primary Aluminum (Section 5.2)
- Molten Metal Furnaces (Section 5.3)
- Ethylene (Section 5.4)
- Industrial/Commercial Boilers (Section 5.5)

These processes were chosen based on industry interest (i.e., glass furnace) and on industrial process knowledge that would indicate that a large TEG opportunity might exist. Although the scope of the industrial assessment is limited, the report looks at a specific application in great detail, providing significant insight into the engineering requirements for building TEG systems and incorporating them into an industrial manufacturing process. The insights gained in one application assessment are broadly applicable and will assist in determining further viable applications for TEGs.

5.1 Glass

5.1.1 Overview of Glass-Making Operation

Glass making is a high-temperature energy-intensive operation, with the U.S. glass industry consuming approximately 278.8 trillion Btu of energy in 2002 to manufacture glass.¹⁶ The glass industry is divided into four product categories:

- Containers (such as bottles, jars and packaging)
- Flat (such as windows, automotive windshields and picture glass)
- Fiber (such as insulation)
- Pressed/Blown (such as table and ovenware, flat panel displays, light bulbs, laboratory glassware, television tubes, textiles and optical fiber)

The quantity of energy used depends heavily on the glass composition, furnace design, furnace/refractory aging, proportion of cullet (scrap glass), scale and methods of operation. In theory, only 2.2 to 2.7 million Btu per ton of glass are required for reactions and melting, depending on the composition of the glass. Actual energy used to produce glass varies widely (Table 3). Thermoelectric generators could be used to a great advantage in the furnace (melting and refining) operations of a glass plant.

Table 3: U.S. glass Industry statistics^a

	Tons/year 1999	Total Energy MBtu/ton	Melting Refining MBtu/ton
Container	9,586,500	5.3 - 11.3	2.8 - 7.8
Flat	5,000,521	8.7 - 15.7	6.5 - 8.8
Fiber	3,040,000	16.4 - 23.3	5.6 - 10.5
Pressed/Blown	2,484,200	12.3 - 21.5	3.6 - 12.0

The most efficient furnaces are those equipped with large regenerators, and cullet and batch preheater systems. These furnaces, with 50% cullet, operate at 3.3 million Btu per ton for container glass and 4.3 to 4.7 million Btu per ton for flat glass.¹⁷

The vast majority of industry-produced glasses are of similar composition. These soda-lime glasses are roughly about 71-75% silicon dioxide (SiO_2 from sand), 12-16% sodium oxide (Na_2O from soda ash or Na_2CO_3) and 10-15% calcium oxide (CaO from limestone or CaCO_3). Low levels of other components are added to impart specific glass properties (e.g., 7-15% boron trioxide to provide higher resistance against chemical corrosion and lower thermal expansion). Glasses are made by melting, refining and homogenizing the raw materials at high temperature. The temperature necessary for melting and refining depends on the composition but ranges from 2372°F to 2822°F (1300°C to 1550°C). The residence time within the furnace is also a function of composition and refining complexity, and varies from 20 to more than 70 hours.

The primary energy source for the U.S. glass industry is natural gas. Approximately 144.1 trillion Btu of natural gas, 12.5 trillion Btu of other fossil fuels (light oil, propane, coal, etc.) and 40.2 trillion Btu of electricity (a total of 131.3 trillion Btu when generation and transmission losses are accounted for) were used for thermal operations in 2001.¹⁰ Natural gas furnaces supply heat mainly by radiation from the refractory structures and from the combustion flames. Electricity for resistive heating is used to “boost” furnace efficiency and to some level, to provide fuel flexibility. Approximately 60 to 80% of thermal operations are associated with the glass melting furnace. Other significant areas of thermal energy use are forehearths, forming, lehr, and other annealing operations. The use of cullet can reduce the energy consumption because the energy required for reactions has already been provided. In general, 10% cullet reduces energy use by 2 to 3%.

The average U.S. furnace capacity is about 800 tons/day, with more than 90% of its glass being melted in natural-gas-fired regenerative furnaces.¹⁸ Regenerative furnaces are world-class design melters for >400 tons/day capacity and are “simplistically” batch operations using two stacks of heat retaining refractory blocks. One stack is heated with the exhaust gas running in one direction while the other stack preheats the incoming air flowing in the other direction. Regenerative furnaces provide higher preheat than recuperative furnaces (greater energy efficiency) which are typically <400 tons/day and use a continuous heat exchanger in which heat from the exhaust gas is conducted through the exchanger to the incoming air.

A modern regenerative container furnace has an overall thermal efficiency of 50-60%. The direction of gas flow changes every 15-20 minutes in a regenerative furnace. The exhaust gas temperature from a new world-class regenerative furnace averages ~900°F. The temperature rises from 750°F to 1050°F over the 15-20 minute cycle, then the exhaust flow reverses and ambient air enters the system. This temperature cycling impacts TEG performance both in terms of the device’s output (thermal efficiency, voltage,...) and mechanical stresses (thermal cycling). Additionally, a regenerative furnace can be viewed as having two separate air/exhaust systems. This can complicate the choice of TEG location.

Many times, glass plants convert from regenerative furnaces to full or partial oxy-fuel systems to increase their furnace capacity without having to build a new furnace. Oxy-fuel firing reduces the furnace energy consumption by eliminating the energy needed to heat the nitrogen that is carried through the furnace in an air-fired system. Oxy-fuel can potentially improve the furnace energy efficiency to 60-80%. Oxy-fuel significantly changes the volume, composition and

exiting temperature of the exhaust gas stream. The exiting temperature increases significantly to ~2660°F for oxy-fuel-fired furnaces since there is no or very little combustion air to preheat (compared to 900°F from regenerative furnaces). The oxy-fuel exhaust can be used to preheat cullet and raw materials.

5.1.2 Glass TEG Energy Conversion Opportunity

A rough estimate of the energy that TEG devices could recover from glass furnaces can be made by generalizing the furnace operations of the glass industry. This study estimates potential energy savings in the operation of a “base-case” modern regenerative container glass furnace. The furnace operates with 30% cullet and an overall energy efficiency of 55%. Full operating parameters assumed for estimating TEG energy conversion opportunity are shown in Table 4. The exiting flue gas at 900°F has a thermal value of 14,000,000 Btu/hr, slightly more than 21% of the total energy input to the “base-case” furnace (Appendix A).

Using the “base-case” as representative of the container glass industry and proportioning the data based on the tonnage and average energy used reported in Table 3, it can be calculated to show that the industry exhausts ~21.3 trillion Btu/yr from melting and refining operations. Knowing the quantity of energy exhausted and an assumed efficiency of a TEG system, the potential energy savings can be calculated (Table 5).

It should be noted that it requires approximately 10,600 Btu of primary fuel to produce 1 kWh or 3,412 Btu of electricity that is on the national grid. When this heat rate is accounted for, thermoelectric devices save approximately three times their output in terms of primary energy.

Table 4: “Base-Case” Container Glass Furnace

Furnace Design: Regenerative	
400 (16.67)	Tons per day (<i>tons/hour</i>)
55%	Thermal Efficiency
2,300,000	Btu/ton Theoretical Requirement
1,898,000	Btu/ton Cullet
3,963,000	Btu/ton in operation
66,050,000	Btu/hr Required
Glass Raw Materials	
5.00 (30%)	tons/hour (%) Cullet
11.67 (70%)	tons/hour (%) Raw Materials
8.52 (73%)	tons/hour SiO ₂ (% of raw materials)
1.63 (14%)	tons/hour Na ₂ O (% of raw materials)
1.52 (13%)	tons/hour CaO (% of raw materials)
Furnace Fuel : Natural Gas	
99%	Combustion Efficiency
1%	Excess Oxygen
none	Oxygen Enrichment

Table 5: Thermoelectric Waste Heat Opportunities in U.S. Glass Industry

Temperature C (F)	Available Waste Heat TBtu/Year	TEG Recoverable Waste Heat TBtu/Year		
		ZT = 1 5%	ZT = 2 15%	ZT = 4 25%
485 (950)	21.3	1.1	3.2	5.3

5.1.3 Glass TEG Operating Conditions and Waste Heat Characterization

The characteristics of the waste heat available for a TEG device operating on a glass furnace flue stream will depend on the furnace design, capacity and the fuel being combusted. These characteristics can be estimated from the “base-case” furnace design parameters assumed for this TEG engineering scoping study (Table 4 on page 29).

Natural gas being the predominant fuel used by the industry, the major components in the emissions from a glass melter are a combination of natural gas combustion products (CO₂ and H₂O), off-gases from the reduction of raw materials (mainly CO₂) and nitrogen (from the combustion air). Further, chemical refining agents (e.g., sodium sulfate, sodium nitrate or potassium nitrate) added to the glass melt to aid

in the removal of bubbles and particulates contribute to additional SO₂ and NO_x in the exhaust gas stream. It should be recognized that the flue gas composition will also contain low levels of other minor gas phase constituents (argon, excess oxygen, unconsumed natural gas components, etc.). It is

also possible to have air-borne particulates that originate from the introduction of powdery raw materials and the breaking of bubbles on the melt surface. Some of these minor components and particulates can be detrimental to the TEG heat exchange surfaces. These assumptions lead to an estimate of flue gas composition for major components and their associated enthalpies to be as shown in Table 6

(Appendix A). Glass furnaces are typically natural draft systems, allowing the flue gas pressures to be typically close to atmospheric pressure.

Table 7 shows the flue gas composition for the “base-case” furnace operating with a oxy-fuel system firing with 1% excess oxygen (Note: typical large scale oxygen plants produce about 93% oxygen the other 7%

Table 6: 400 ton/day glass furnace flue composition

Component	Combustion Products lb/hr	Reaction Products lb/hr	Total Amount cubic feet/hr (900 F)	Enthalpy Btu/hr (900 F)
Nitrogen	40,300		1,523,000	8,490,000
Carbon Dioxide	8,470	4,700	316,000	2,640,000
Water	7,000		387,000	2,770,000
Oxygen	123		4,060	23,700
Argon	683		18,000	69,700
Sulfur Dioxide	6		94	800
TOTAL	56,582	4,700	2,248,154	13,994,200

Table 7: 400 Ton/day oxy-fuel glass furnace flue composition

Component	Combustion Products lb/hr	Reaction Products lb/hr	Total Amount cubic feet/hr (2600°F)	Enthalpy Btu/hr (2600°F)
Nitrogen	500		42,700	349,000
Carbon Dioxide	6,960	4,700	628,500	8,390,000
Water	5,670		692,000	7,820,000
Oxygen	100		7,500	65,000
Argon	9		500	2,700
Sulfur Dioxide	5		174	2,400
TOTAL	13,244	4,700	1,371,374	16,629,100

consist of nitrogen and argon). Oxy-fuel systems are used commonly as retrofits to the existing regenerative furnaces as a means of expanding capacity without building a new furnace. It is very significant to note the dramatic mass flow *decrease* for the flue gas in the oxy-fuel furnace of the same capacity as the regenerative furnace while the heat flow actually increases.

5.1.4 Glass TEG Device and System Performance Requirements

The oxy-fuel fired glass furnace provides a very good opportunity for examining the engineering performance requirements for TEGs. The application is ideal for TEG development. The furnaces, which are typically converted regenerative furnaces, provide constant and high temperature exhaust gas (2,600°F), and long horizon accessible flues. This configuration offers numerous locations where TEG materials and systems could be inserted to optimize to flue conditions with the TEG performance. Generated electricity can be easily used to supplement oxygen plant compressors or resistance boost heaters.

The TEG module will be manufactured to assemble in groupings or banks in order to handle the large volume of exhaust flow and waste heat associated with glass furnace emissions. The TEG system should be designed in a modular fashion for efficiently addressing flow length temperature gradient effects, maintaining adequate TEG temperature isothermality, controlling pressure drops and pumping power, effectively packaging the TEG system within the glass exhaust system dimensions, and providing a logical module trial and growth plan in the industrial physical and business environment. A typical TEG “building-block” module appears to be one designed to intercept approximately 2-3.5% of the total glass process exhaust flow at an exhaust flow temperature of 1400°F (760°C). A preliminary requirements analysis was performed as part of this engineering scoping study to establish potential TEG system power generation benefits, preliminary system configuration, and sizing characteristics (volume, mass, TEG cooling requirements).

The TEG requirements analysis was performed from a complete systems perspective, including the coupled effects of hot side heat exchanger performance, TE device performance and cold side heat exchanger performance. Performing a coupled, integrated systems analysis is the only way to establish the true performance, benefits, and requirements for advanced TE systems tailored for industrial process energy recovery. This requirements analysis incorporates interface thermal contact resistance effects, electrical contact resistance effects, TE property temperature-dependent effects, and heat exchanger performance into an optimum thermoelectric performance analysis across the full spectrum of possible operating temperature conditions.

The analysis is structured around the following key technical terms and their definitions:

\dot{m}_h – Glass Exhaust Mass Flow Rate [kg/sec]

T_{ex} – Glass Exhaust Gas Temperature [K, °C, or °F]

T_{amb} – Ambient Cooling Temperature [K, °C, or °F]

UA_h – Hot Side Heat Exchanger Effective Heat Transfer Coefficient times Heat Transfer Area [W/K]

UA_c – Cold Side Heat Exchanger Effective Heat Transfer Coefficient times Heat Transfer Area [W/K]

ZT – TE Material Figure of Merit, Z, times Average Temperature of TE Material

Understanding these technical terms provides the foundation for appreciating and interpreting the analyses, results and conclusions that follow. (Appendix B provides an in-depth discussion on thermal calculations).

i. TEG System Power Potential

The power output from any advanced TE system depends strongly on the absolute temperatures and temperature differentials maintained across the TEG and the TE materials used in the TEG, as thermal energy is delivered on the hot side and dissipated on the cold side. It is envisioned that advanced heat exchange/transfer mechanisms will be employed on both the hot and cold sides of the system to deliver thermal energy to the TE device and provide the necessary cooling. Figure 9 shows the typical TEG system-level configuration envisioned and studied in this engineering scoping analysis. The hot side heat exchanger absorbs heat from the glass process exhaust stream at T_{ex} , transfers that thermal energy to the TE device hot side at T_h , the TE device converts that thermal energy at a predictable conversion efficiency, and finally, the remaining unconverted thermal energy is transferred from the TE device cold side at T_c to the cold side heat exchanger, and dissipated to the ambient environment at T_{amb} .

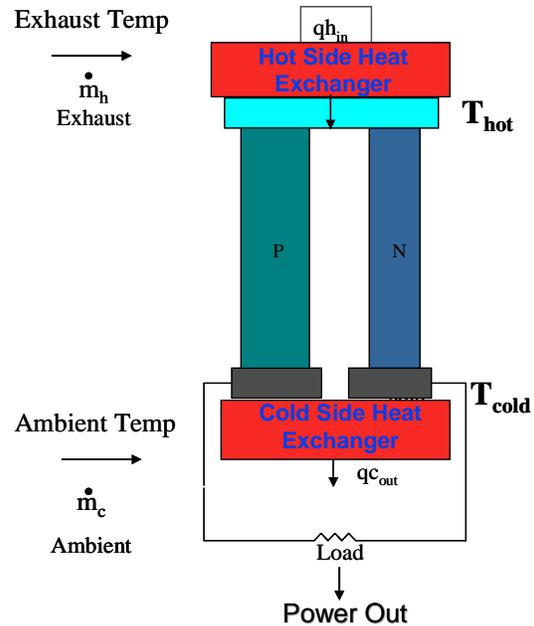


Figure 9: Schematic of typical TEG system envisioned in industrial glass processes

The glass process exhaust temperature and ambient cooling temperature provide the ultimate boundary conditions across which the TEG will operate. However, the TEG efficiency and power output will vary as actual temperatures and temperature differentials across the device, within these ultimate boundary temperatures, change resulting from heat exchanger/TE device thermal interaction. Consequently, an efficiency-power map (shown in Figures 10(a) and 10(b) to 10(d)) is an effective tool to represent the possible optimum performance states as different hot and cold side temperatures prevail. Figures 10(a) demonstrates the potential efficiency-power map from an advanced TEG systems operating at $T_{ex} = 1400^{\circ}\text{F}$ (760°C), using advanced TE materials with $ZT \sim 1$, ~ 2 and $ZT \sim 4$. Advanced TE materials that fall in the $ZT \sim 2$ category would include lead-antimony-silver-telluride (LAST) compounds being developed at Michigan State University, thin-film B_xC and Si/SiGe compounds being developed at Hi-Z Technology, Inc., and other AgPbTe-GeTe compounds being explored and developed at Pacific Northwest National Laboratory. The intent is not to specifically select or focus on any one TE material set, but to show the potential power output possible from this class of advanced TE materials whose integrated ZT performance is near 1, 2 and 4.

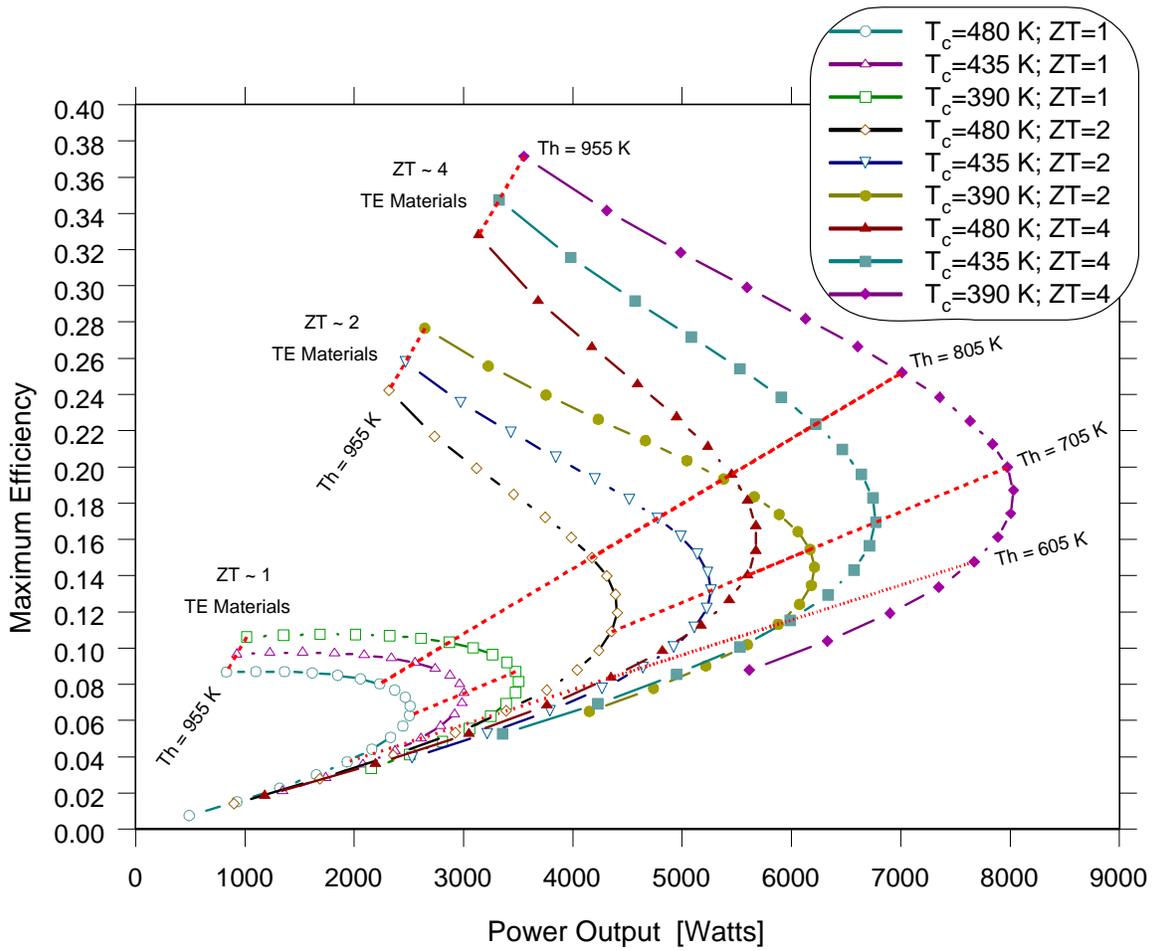


Figure 10(a): Maximum Efficiency vs. Power Potential for ZT ~ 1, ~ 2 and ~ 4 TE Materials
 ($UA_h = 250\text{ W/K}$, $T_{ex} = 1033\text{ K}$, $T_{amb} = 300\text{ K}$, $\dot{m}_h = 0.3\text{ kg/sec}$)

a) $ZT \sim 1$ TE Materials

Figure 10(b) shows the anticipated maximum efficiency-power map from $ZT \sim 1$ TE materials and hot-side heat exchanger performance characterized by $UA_h = 250$ W/K. TE materials with $ZT \sim 1$ properties at these temperatures would include bulk TAGS and PbTe materials developed several years ago and used extensively in spacecraft power systems.

The major point to note is the dramatic reduction in maximum efficiency-power for a TEG using $ZT \sim 1$ TE materials compared to systems with TE materials of $ZT \sim 2$ and $ZT \sim 4$ shown in Figure 10(a). Maximum power output falls to 2300-3500 watts and maximum efficiency reduces to near 8-10% for the same hot side heat exchanger conditions and cold side temperature conditions. The efficiency using $ZT \sim 1$ TE materials is at this level only because of the relatively high glass process exhaust stream temperatures, and therefore, the relatively high available temperature differentials.

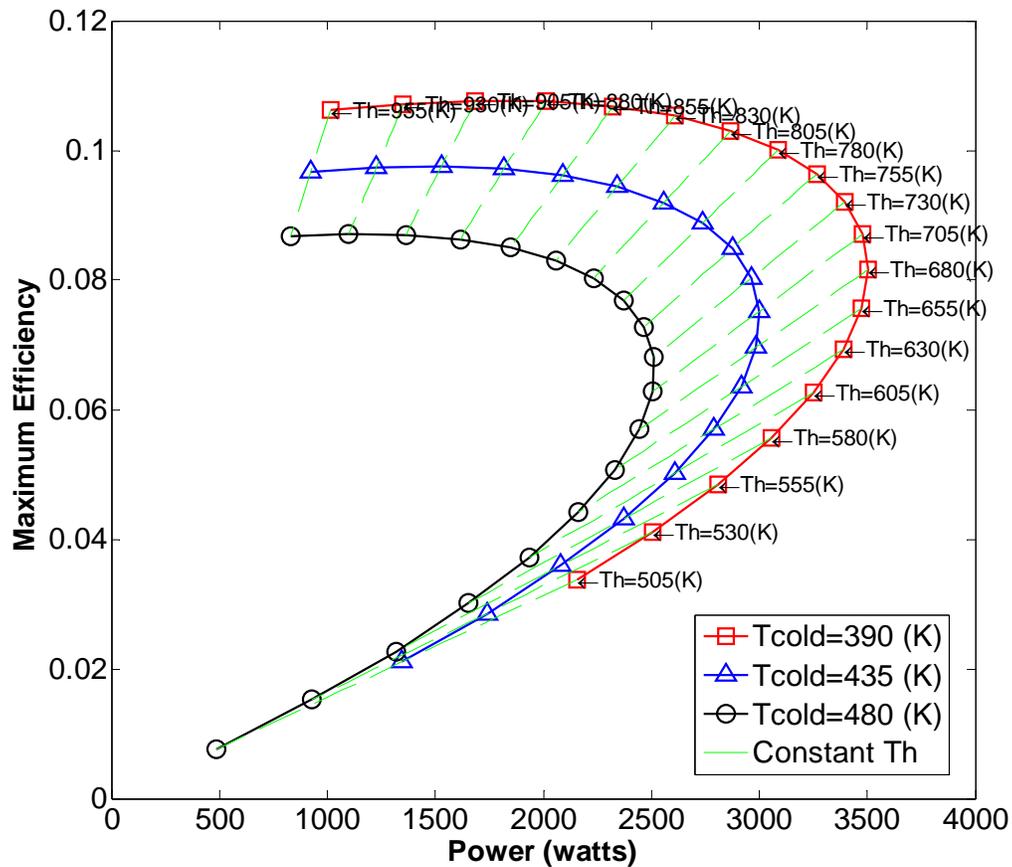


Figure 10(b): Maximum Efficiency vs. Power Potential for $ZT \sim 1$ TE Materials ($UA_h = 250$ W/K, $T_{ex} = 1033$ K, $T_{amb} = 300$ K, $\dot{m}_h = 0.3$ kg/sec)

b) $ZT \sim 2$ TE Materials

Figure 10(c) demonstrates the anticipated maximum efficiency-power tradeoff expected from $ZT \sim 2$ class of TE materials for a hot-side heat exchanger performance characterized by $UA_h = 250$ W/K. This chart essentially shows the loci of maximum TE conversion efficiency vs. power output achievable under the stated conditions. The efficiency and power vary such that operating conditions with maximum TEG conversion efficiency are quite different from operating conditions showing maximum power output, this being the result of the heat exchanger / TE device performance interaction. The points of maximum power output are seen to be about 4000-6000 watts with maximum TE conversion efficiencies of 15% for this scenario. The range of power sited depends on TE device cold-side temperature as shown in Figure 10(c). The bulk flue gas temperature is set at 760°C ($T_{ex} = 1033$ K). The temperatures shown on the curve in Figure 10(c) are the TE device hot-side temperatures when the cold side is maintained at 117°C ($T_{cold} = 390$ K). It is interesting and quite significant to note in Figure 10(c) that there are points of maximum efficiency as high as 18-20% which also produce appreciable power output near 3500-5500 watts. These results quantify the strong opportunity that exists for energy recovery in glass process applications using advanced TEG systems with TE materials of $ZT \sim 2$ property performance.

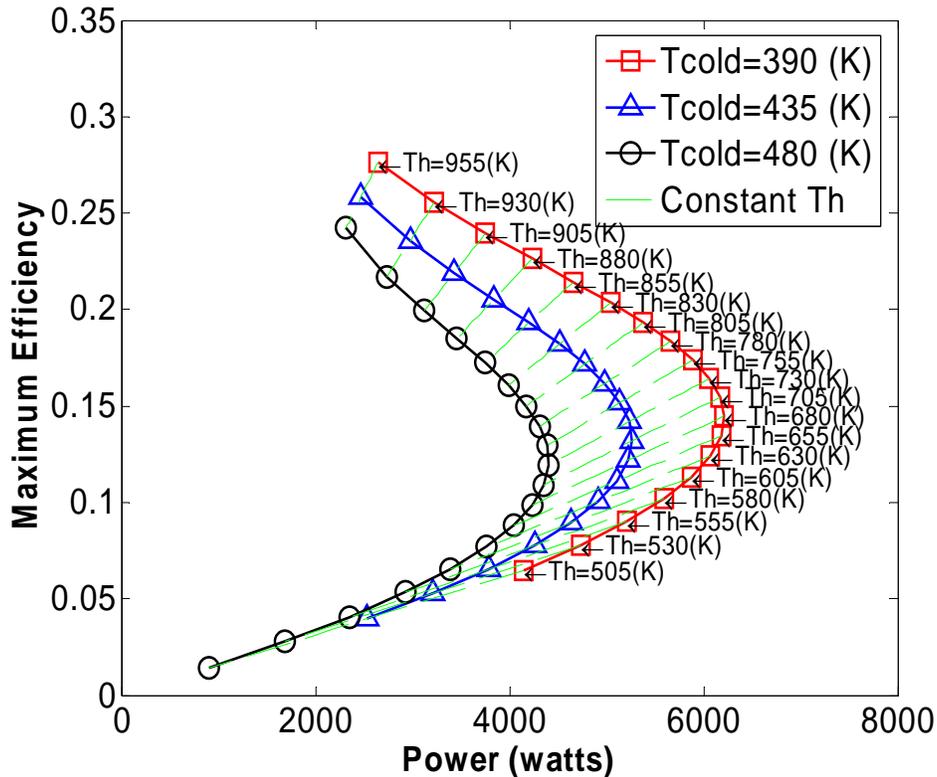


Figure 10(c): Maximum Efficiency vs. Power Potential for $ZT \sim 2$ TE materials ($UA_h = 250$ W/K, $T_{ex} = 1033$ K, $T_{amb} = 300$ K, $\dot{m}_h = 0.3$ kg/sec)

c) $ZT \sim 4$ TE Materials

Figure 10(d) demonstrates the anticipated maximum efficiency-power tradeoff expected from $ZT \sim 4$ class of TE materials for the same hot side heat exchanger performance characterized by $UA_h = 250$ W/K. Similar to Figure 10(a-c), this chart essentially shows the loci of maximum TE conversion efficiency vs. power output achievable under the stated conditions. The points of maximum power output for this TE material class ($ZT \sim 4$) are seen to be about 5800-8000 watts with maximum TE conversion efficiencies of 20%. This represents a significant performance increase attributable to the increase in TE material performance from $ZT \sim 2$ to $ZT \sim 4$. It is again interesting and significant to note in Figure 10(d) that there are points of maximum efficiency as high as 25-30% which also produce appreciable power output near 4000-6500 watts. These potential performance enhancements for a $ZT \sim 4$ TE material provides strong motivate to pursue these types of high-performance TE materials in a long-term coordinated R&D plan.

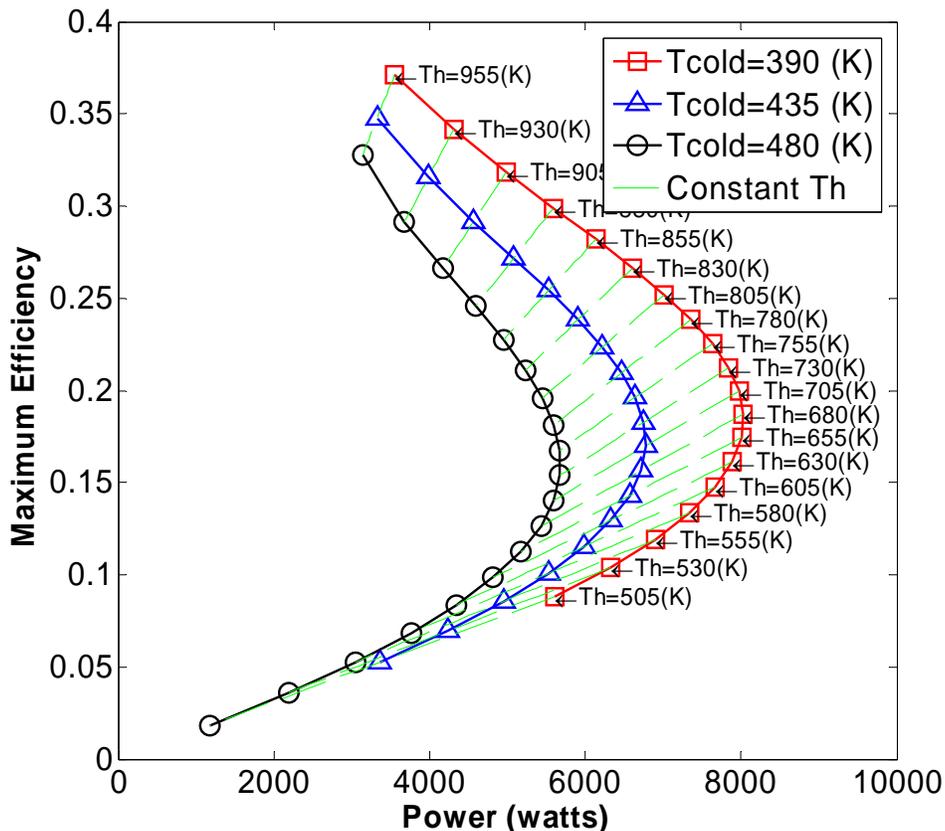


Figure 10(d): Maximum Efficiency vs. Power Potential for $ZT \sim 4$ TE Materials ($UA_h = 250$ W/K, $T_{ex} = 1033$ K, $T_{amb} = 300$ K, $\dot{m}_h = 0.3$ kg/sec)

The results in Figures 10(a)-(d) demonstrate the potential performance benefits associated with new, advanced TE materials having $ZT \sim 2$ properties that have recently been developed and characterized in the laboratory and advanced TE materials with $ZT \sim 4$ envisioned in the long-term future. The anticipated TEG performance with these TE materials would offer much more attractive energy recovery and conversion performance levels for glass industry applications and provide a basis for a stronger glass-industry business case to implement thermoelectric technology in energy recovery plans.

ii. TEG Area Requirements

The TEG system requirements analysis also determined the critical TE area requirements for an industrial glass process energy recovery system. This is key information as it defines the basic size (area and volume) of the TEG waste energy recovery system and defines the number of TEG modules required and how they might be packaged in the glass process furnace/exhaust system. The required TE area will also be a strong function of the absolute temperatures and temperature differentials across the TE conversion device, and therefore, will be tied to hot side and cold side heat exchanger performance. In fact, each efficiency-power point in Figures 10(a)-(d) has an optimum TE area associated with it. Table 8 shows the TEG area requirements at the maximum power points in Figures 10(a)-(d), which are the most likely and desirable design points for the industrial glass process applications. Table 8 also displays the expected power density of the TE devices at maximum power conditions for ZT of 4, 2, and 1 cases in the industrial glass process application. It is clear that $ZT \sim 2$ and $ZT \sim 4$ TE materials create more than a factor of 25 increase in power density compared to the $ZT \sim 1$ materials. Therefore, much more power output is expected from smaller TE devices using the $ZT \sim 2$ and $ZT \sim 4$ TE materials, thus creating a strong opportunity for power system miniaturization in these applications. This is indeed one of

Table 8: TEG area requirements at maximum power conditions

	UA_h (W/K)	
	100	250
TEG Area [cm^2]		
$ZT \sim 1$	934 - 985	1717 - 1913
$ZT \sim 2$	54 - 56	98 - 110
$ZT \sim 4$	67 - 71	123 - 138
Power Density [W/cm^2]		
$ZT \sim 1$	2.0	2.0
$ZT \sim 2$	63.1 - 65.1	63.1 - 65.1
$ZT \sim 4$	63.1 - 65.1	63.1 - 65.1
Hot-Side Heat Flux [W/cm^2]		
$ZT \sim 1$	25	25
$ZT \sim 2$	350 - 430	350 - 430
$ZT \sim 4$	350 - 430	350 - 430

the major features and advantages of the higher performance, advanced TE materials with $ZT \sim 2$ properties. At this point, the TE materials with $ZT \sim 4$ properties are less well characterized and more speculative as to their specific properties. If they were ever developed, verified, and implemented, what is known at this point is that they would create a similar increase in TE device power density as $ZT \sim 2$ TE materials. It is also possible that $ZT \sim 4$ TE materials may have ultimate TE properties that further increase TE device power density and increasingly drive this technology toward miniaturization.

Table 8 also shows the hot-side heat flux required for the TE device to achieve the higher power densities shown for $ZT \sim 2$ and 4 TE materials. The shown heat fluxes of 350-430 W/cm^2 required at the hot side for $ZT \sim 2$ and 4 property cases would be considered high by most thermal heat transfer experts. These high values certainly pose a major engineering challenge that must be addressed with parallel, enabling R&D to allow this advanced TE technology to achieve its full performance potential at the device level. There are advanced thermal transfer technologies, such as jet impingement or spray cooling, two-phase flow systems, some heat pipe systems, and porous media heat transfer, capable of achieving these thermal flux levels under certain conditions, but they have not been integrated into or specifically designed for systems compatible with advanced TE devices envisioned using $ZT \sim 2$ and 4 TE materials. These thermal technologies also have not been integrated into glass process systems or tailored for their specific system requirements.

If TE materials with $ZT \sim 4$ properties were developed, verified, and implemented, it is possible, depending on the exact TE material formulations and resulting TE properties, that this engineering challenge associated with providing the necessary hot-side thermal flux would be

compounded. It is for this reason that it is strongly recommended that any future TE material R&D efforts to increase fundamental TE material performance be strongly coupled (i.e., lock-stepped) with fundamental engineering and system R&D to develop the critical hot-side thermal exchanger and transfer technologies in configurations amenable to industrial glass processes and requirements.

iii. Hot-Side Heat Exchanger Performance Effects

Figures 10(a)-(d) and Table 8 give only the partial story since they only address power output and TE device area requirements for hot-side heat exchanger performance characterized by $UA_h = 100$ W/K and 250 W/K and $ZT \sim 2$ and 4 properties. Figure 11 demonstrates the maximum power output potential for the modularized TEGs envisioned here using $ZT \sim 2$ and ~ 4 TE materials across a wider range of hot-side heat exchanger performance from $UA_h = 50$ W/K to 500 W/K and exhaust mass flow rates, \dot{m}_h , of 0.3 to 0.5 kg/sec. It shows that the maximum power output of each modular TEG using $ZT \sim 4$ TE materials could actually increase to 11,000-13,000 W per power module if UA_h increased to 500 W/K at the given \dot{m}_h of 0.3 to 0.5 kg/sec. The maximum power output of a modular TEG using $ZT \sim 2$ TE materials would increase to 8,000-10,000 watts for the same UA_h and \dot{m}_h conditions. The module power penalty incurred is also clear if UA_h decreased to 50 W/K at the given \dot{m}_h of 0.3 to 0.5 kg/sec – the power is seen dropping to ~ 2000 W.

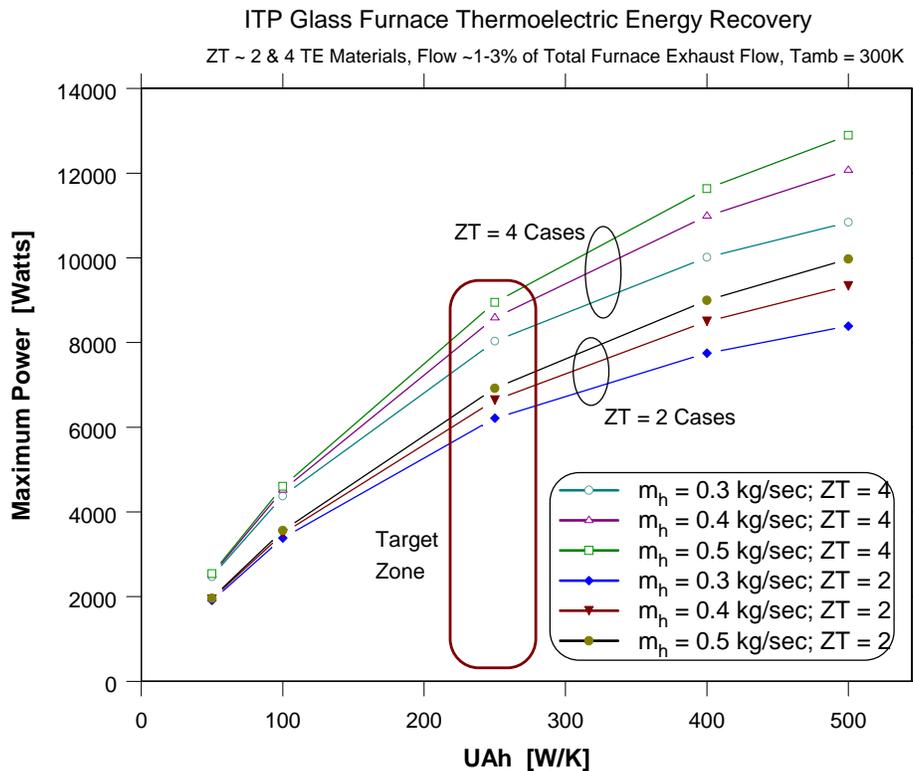


Figure 11: Potential Maximum Power Output vs. Hot-Side Heat Exchanger Performance

Module power, therefore, strongly depends on hot-side heat exchanger performance, as UA_h actually dictates how much thermal energy is transferred into the TE device for conversion. Figure 11 demonstrates the maximum power output relationship with UA_h in a manner that

quantifies the impacts on power output as hot-side heat exchanger performance increases. The Figure 11 data shows relatively large increases in power output as UA_h increases from 50 W/K up to about 250 W/K. After that point there appears to be a point of diminishing returns in power output possible as the UA_h increases up to 400 W/K and 500 W/K. Therefore, the additional expense and effort associated with achieving these higher UA_h in advanced heat exchanger performance will produce smaller benefits in power output. It appears from this work that the benefit-to-cost ratio of achieving higher $UA_h > 250$ W/K in advanced heat exchanger designs does not warrant the R&D and engineering effort and resources. A $UA_h \sim 250$ W/K appears to be a sufficient hot-side heat exchanger performance “target zone” that can extract a major portion of potential power output available under these exhaust and ambient temperature conditions. This work supports a $UA_h \sim 250$ W/K as an achievable performance level, which can show strong power output benefits, with reasonable R&D expenditures in hot side heat exchange.

What is also important in Figure 11 is the increasing power differential between $ZT \sim 2$ and $ZT \sim 4$ TE materials at the higher UA_h levels, showing that increases in TE material performance are only important if increases in hot-side heat transfer performance are simultaneously achievable. This is again an indication of how critical hot-side heat exchange mechanisms are in the overall system design and performance.

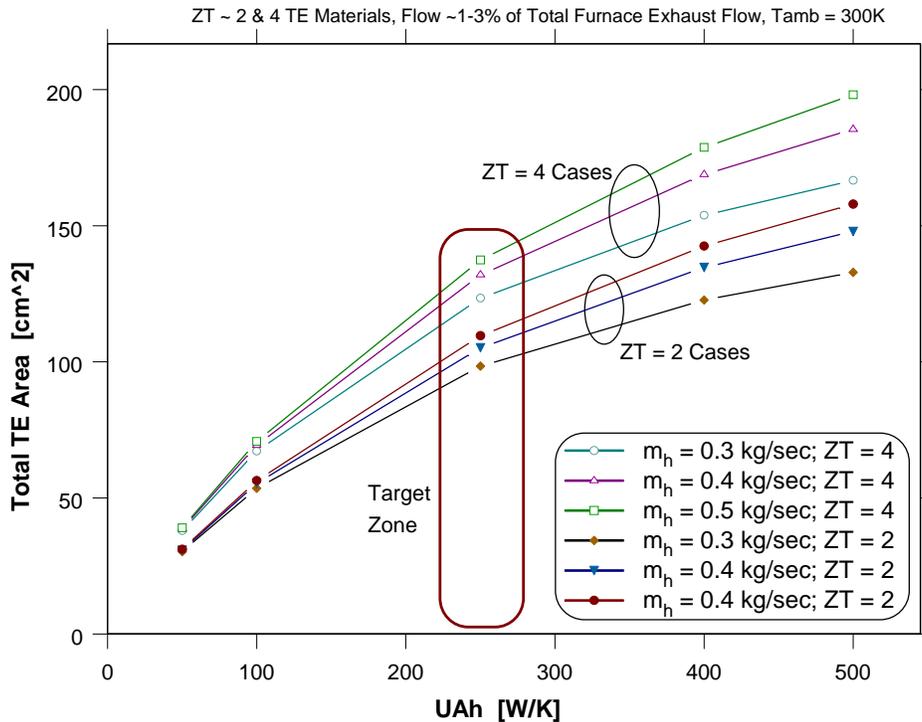


Figure 12: Total Required TE Device Area vs. Hot Side Heat Exchanger Performance

Figure 12 demonstrates the required TE device area at maximum power design points using $ZT \sim 2$ and $ZT \sim 4$ TE materials for the same set of UA_h and \dot{m}_h conditions. The TE device area is seen to increase significantly as hot-side heat exchanger performance increases, but it is important to realize that in using $ZT \sim 2$ and $ZT \sim 4$ TE materials, TE devices with relatively small areas of 100 cm² to 200 cm² could potentially be sufficient to produce 6-12 kW power. This increase in TE device area requirements with hot-side heat exchanger performance could also lead to increased device costs unless cost-reducing R&D is implemented. It is suggested that

cost-effective device manufacturing and fabrication be an important criteria in future waste energy R&D projects, so that the corresponding enhanced TE system performance shown in Figure 11 is achievable without severe cost penalties that would jeopardize acceptance and business opportunities

With TE device areas of 100-200 cm², it is likely that the hot-side heat exchanger technologies to transfer the necessary thermal energy will likely be larger in size and footprint than the TE conversion device in $ZT \sim 2$ and $ZT \sim 4$ designs. This will lead to a “thermal funneling” effect in transferring the required thermal energy from the hot-side heat exchanger systems to the TE device, and then a corresponding “thermal expanding” effect on the cold-side heat exchangers to dissipate the remaining thermal energy. This could be controlled somewhat with specific TE device design (i.e., element sizing) using $ZT \sim 2$ and $ZT \sim 4$ TE materials, but probably not entirely eliminated.

Figures 11 and 12 also display the “target region” for heat exchanger performance that is potentially achievable and desirable for the industrial glass process applications. Within this target region, although the potential power output is still reasonably high, the power output and total required TE device area are less sensitive to the glass process exhaust mass flow rate, \dot{m}_h . This could have important system design ramifications in the final applications. As a starting point, R&D research should seek thermal transfer technologies that can provide at least this level of thermal performance in cost-effective ways. Heat transfer technologies that could be implemented to satisfy the necessary hot-side thermal transfer requirements would include:

- Heat Pipe technologies
- Micro channel heat transfer technologies
- Porous media heat transfer technologies
- Nanofluid heat transfer fluids
- Spray cooling technologies

Current technologies indicate that gas-flow mini-channel heat exchangers can be used to achieve some of the lower values of UA (~100 W/K) without excessive pumping power requirements, with convective heat transfer coefficients of approximately 120 W/m²-K possible in low-temperature turbulent flows (e.g., 350 K) and 200 W/m²-K possible in high temperature turbulent gas flows (e.g. 900 K). Gas thermal conductivity increases significantly as temperature increases, therefore many energy recovery applications with high temperature gas flows (i.e., 800-1000 K) have the potential for the enhanced heat transfer coefficients. He, Xe and H₂ flows create higher UAs because of their higher thermal conductivity compared to air and are being considered in some applications. Finned heat pipe systems can achieve the higher UA values (>200 W/K) for gas flow systems as higher effective heat transfer areas can be achieved. Water and liquid flow micro channel heat exchangers with generally laminar flow can easily achieve UA ~ 500-1500 W/K because of relatively large heat transfer coefficients possible (~10-30 kW/m²-K). University of Maryland (College Park) researchers also have demonstrated heat transfer coefficients of 5-10 kW/m²-K in carbon dioxide microchannel designs.

iv. Cold-Side Heat Exchanger Impacts

A major derived requirement that will come about for the advanced TEG systems will be to provide adequate cold side cooling to dissipate remaining un-converted waste energy. The cold-side heat dissipation will require high heat transfer to a clean, controllable liquid flow with low flow pressure drops and pumping power. Liquid flows will be required because gas cooling on

the TEG system cold-side would require larger mass flow rates and enormous pumping powers for the required heat dissipation. In general, the cold side mass flow rate will depend on the TEG system power and hot-side thermal energy supplied. This TEG systems requirements analysis simultaneously determined the required cold side mass flow rate at each maximum power point shown in Figure 11, assuming clean, 300 K (81°F) water cooling. Figure 13 displays the required cold-side water flow for each maximum power point as UA_h increases and more thermal energy is supplied at the system hot side. Associated with each required cold side mass flow rate in Figure 13 is also the approximate cold side UA_c that would satisfy cold side thermal transfer requirements at each maximum power point, assuming convective heat transfer mechanisms dominate the cold-side process.

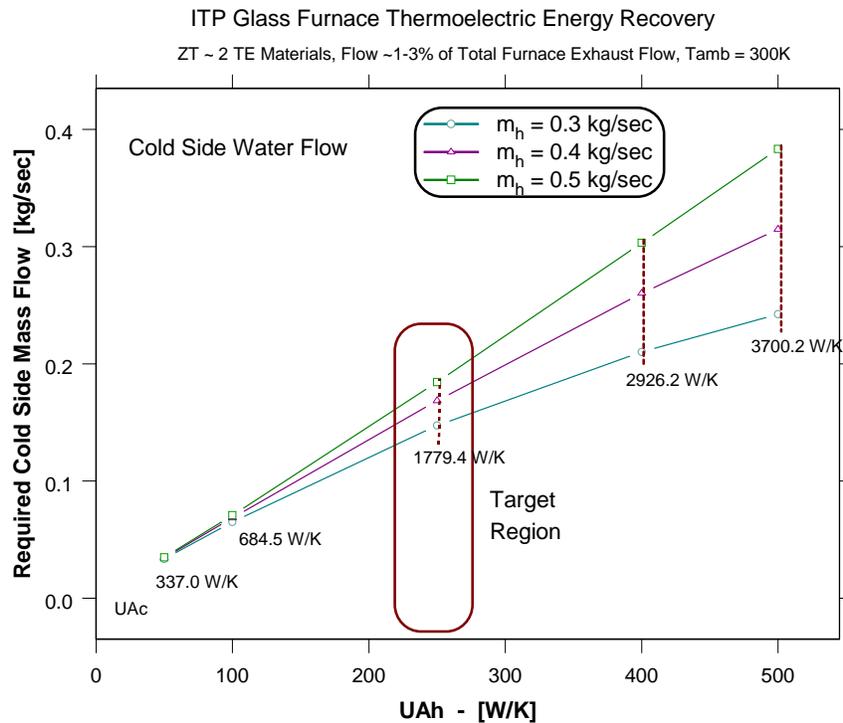


Figure 13: Required cold-side water flow at maximum power points for $ZT \sim 4$ TE materials
($ZT \sim 2$ TE materials create levels 6-14 % higher than shown)

Critically important system aspects of this required cold-side mass flow are the required system pressure drops, system pumping powers, and the heat transfer/pumping power ratios associated with this to achieve the necessary cold-side heat transfer and UA_c levels. These parameters are generally going to be configuration-specific and depend on the heat transfer technologies employed. In advanced TEG systems, the total system pumping power, both cold side and hot side, must be minimized relative to the system power output. Heat transfer technologies that could be implemented to satisfy the necessary cold-side thermal transfer requirements are similar to the hot-side thermal technologies and would include:

- Micro channel heat transfer technologies
- Porous media heat transfer technologies
- Nanofluid heat transfer fluids
- Spray cooling technologies

v. TEG Pumping Power Requirements for Hot-Side and Cold-Side Heat Transfer

Micro channel heat transfer technologies, relying entirely on convective heat transfer mechanisms to dissipate TEG cold-side thermal energy, could provide the necessary cold-side heat transfer at the “target region” flow rates with relatively low pumping power requirements. The pumping power for typical micro channel heat exchanger configurations is dependent on fluid properties, mass flow rate, and micro channel dimensions. Analyzing various cold-side copper-water micro channel configurations for advanced TEG systems ($ZT \sim 2$) in glass processing applications led to results in Figure 14 demonstrating the typical heat transfer performance vs. pumping power relationship for varying micro channel widths and two H_2O flow rates, 0.15 kg/sec and 0.18 kg/sec. At relatively large micro channel widths ($\sim 285 \mu\text{m}$), the heat transfer performance as characterized by UA_c is quite sensitive to channel width, while pumping power increases only incrementally. As micro channel width is decreased ($\sim 80\text{-}100 \mu\text{m}$), the pumping power increases dramatically for smaller increases in heat transfer performance (UA_c). Figure 14 results also show that the impact of 20% increase in H_2O flow rates to 0.18 kg/sec is to increase pressure drop without necessarily increasing heat transfer performance, a behavior that is typical for laminar flow systems.

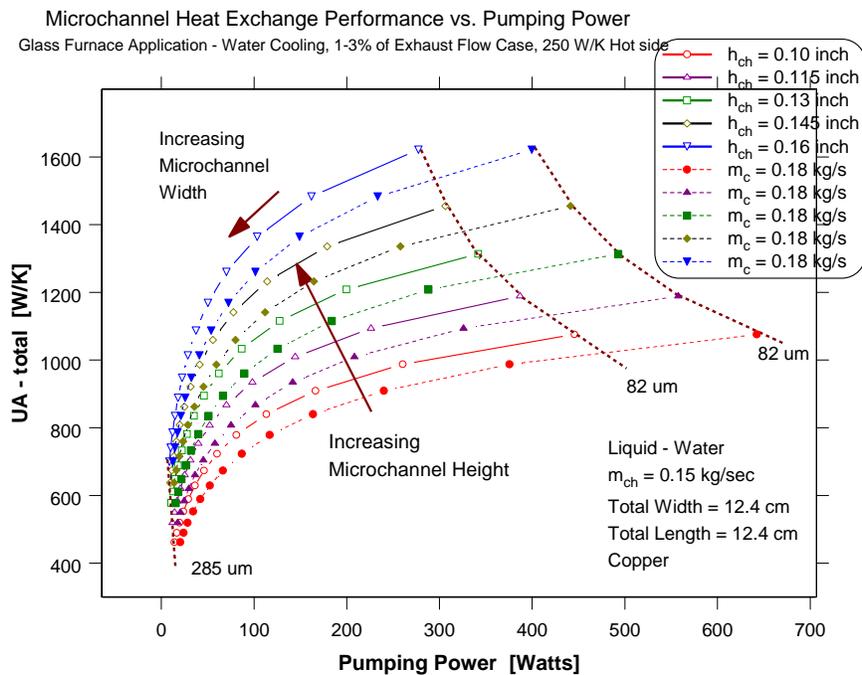


Figure 14: Cold-Side Heat Transfer Performance vs. Pumping Power for Cu/ H_2O Micro Channel Systems

Figure 14 shows very high heat transfer performance (i.e., $UA_c \sim 1500 \text{ W/K}$) that meets cold side heat transfer requirements in the target region (see Figure 13) is certainly possible with relatively small pumping power (~ 200 watts). Figure 15 further demonstrates this showing the very high heat transfer / pumping power factors at various micro channel dimensions cross-plotted against cold-side heat transfer with the required cold-side heat transfer level highlighted. Several Cu/ H_2O micro channel configurations satisfy the cold-side heat transfer requirements of 35 kW in an 8 kW advanced TEG system module envisioned for industrial glass process applications. The heat transfer / pumping power factors are 1000-4000 for the micro channel configurations satisfying the cold-side heat transfer requirement of 35 kW, so Cu/ H_2O micro channel heat exchangers can be highly effective and efficient for glass process TEG systems. This indicates that Cu/ H_2O micro channel heat exchangers on the TEG cold side generally will

not require large pumping power in satisfying heat transfer performance requirements for the industrial glass application.

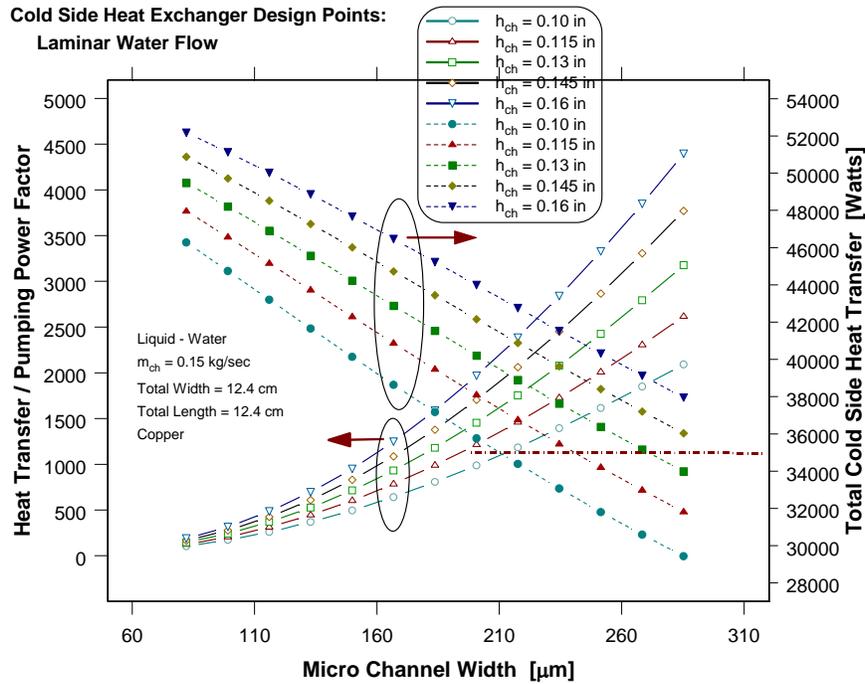


Figure 15: Heat Transfer / Pumping Power Factor & Total Cold-Side Heat Transfer for Cu/H₂O Micro Channel Systems

The hot-side heat exchanger poses a more severe pumping power challenge to provide the necessary hot-side heat transfer to satisfy the TEG hot-side heat flux levels shown in Table 8. The glass process exhaust flows at exhaust gas temperatures of 1033.2 K are typically low-velocity gas flows that provide low heat transfer performance, even in micro channel configurations that provide the best convective heat transfer. Figure 16 demonstrates the typical heat transfer performance vs. pumping power characteristics for various conventional mini-channel heat exchanger configurations at exhaust mass flow rates of $\dot{m}_h = 0.3$ kg/sec, which tend to be turbulent gas flows at dimensions shown in Figure 16. The results show that relatively low heat transfer performance ($UA_h \sim 75\text{-}88$ W/K) comes at the expense of large pumping power requirements (1100-1600 watts) for exhaust flow rates that are about 2% of the total glass process exhaust flow envisioned in a full-up glass process plant. Figure 17 shows the heat transfer / pumping power factors for such hot-side mini-channel heat exchange configurations are 15-20, at least two orders of magnitude lower than those on the cold-side micro-channel configurations in Figure 15. The total hot-side heat transfer requirements can be satisfied, but at the expense of exorbitantly high pumping powers and, just as critical, at the expense of relatively large, bulky, and heavy heat exchange configurations. Consequently, achieving the required hot-side heat transfer at low pumping power with compact, light-weight systems using convective gas heat transfer alone will be a major technical challenge in the TEG systems envisioned in industrial glass application.

Hot Side Heat Exchanger Design Points: Turbulent Exhaust Air Flow

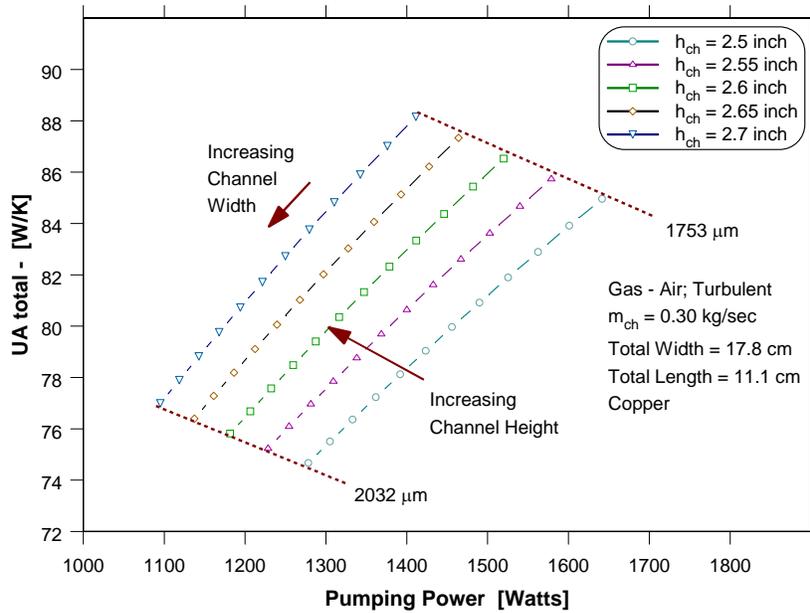


Figure 16: Hot-Side Heat Transfer Performance vs. Pumping Power for Cu/Gas Mini-Channel Heat Exchange Systems

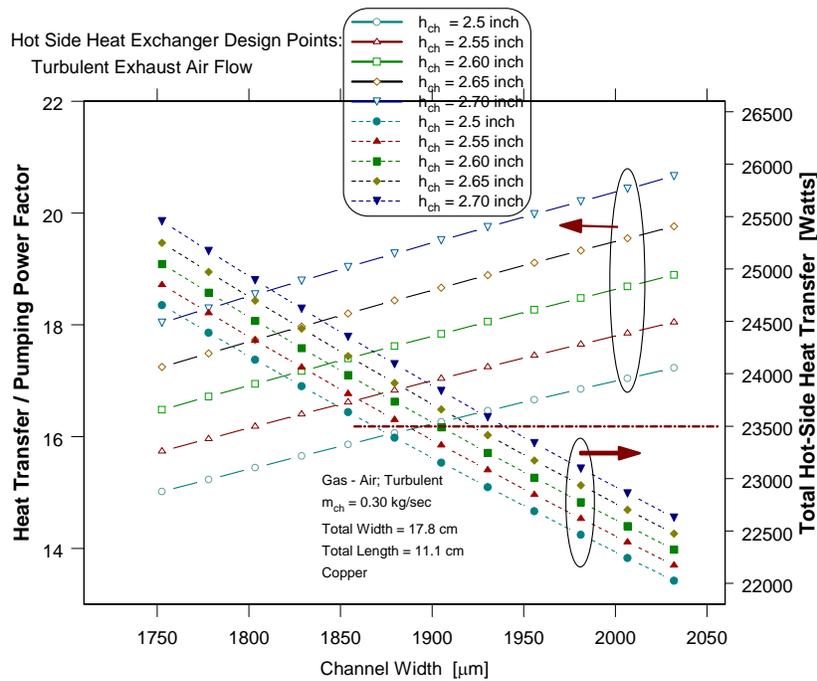


Figure 17: Heat Transfer / Pumping Power Factor & Total Hot-Side Heat Transfer for Cu/Gas Mini-Channel Heat Exchange Systems

It should be realized heat transfer systems studied here rely entirely on convective heat transfer mechanisms to deliver the thermal energy to the TEG system hot side. As mentioned above, convective gas heat transfer mechanisms may not be sufficient to satisfy heat transfer and pumping power requirements on the hot side of the TEG system. Gas radiation is another heat

transfer mechanism that must be considered and possibly exploited at the exhaust gas temperatures in the industrial glass process. Gas radiation from the glass exhaust constituents (mainly CO₂ and H₂O) have been neglected in this analysis and would augment the anticipated heat exchanger performance levels discussed earlier. Preliminary gas radiation analysis shows that radiative heat fluxes of ~1.5 W/cm² could exist on TEG hot-side heat exchange surfaces at exhaust gas temperatures of 1400°F (760°C) farther downstream in the exhaust flow. In upstream exhaust gas regions at temperatures of 2580°F (1416°C), radiative heat fluxes on TEG hot-side heat exchange surfaces could be much higher, possibly 12-13 W/cm². It is recommended that system design and radiation absorption techniques and approaches be researched and developed to exploit these gas radiation heat fluxes and integrate such techniques into the advanced TEG system configurations envisioned for industrial glass process applications.

Potential TEG system Performance for More Advanced, Innovative Micro Channel Systems

More advanced and innovative micro channel configurations and systems are possible and certainly needed, as are possible gas radiation absorption systems, to satisfy interface and system requirements, particularly on the TEG hot side. It is recommended that research and development activities investigate and demonstrate high-performance heat transfer technologies to enable advanced TEG systems using $ZT \sim 2$ and $ZT \sim 4$ TE materials to achieve their full performance potential.

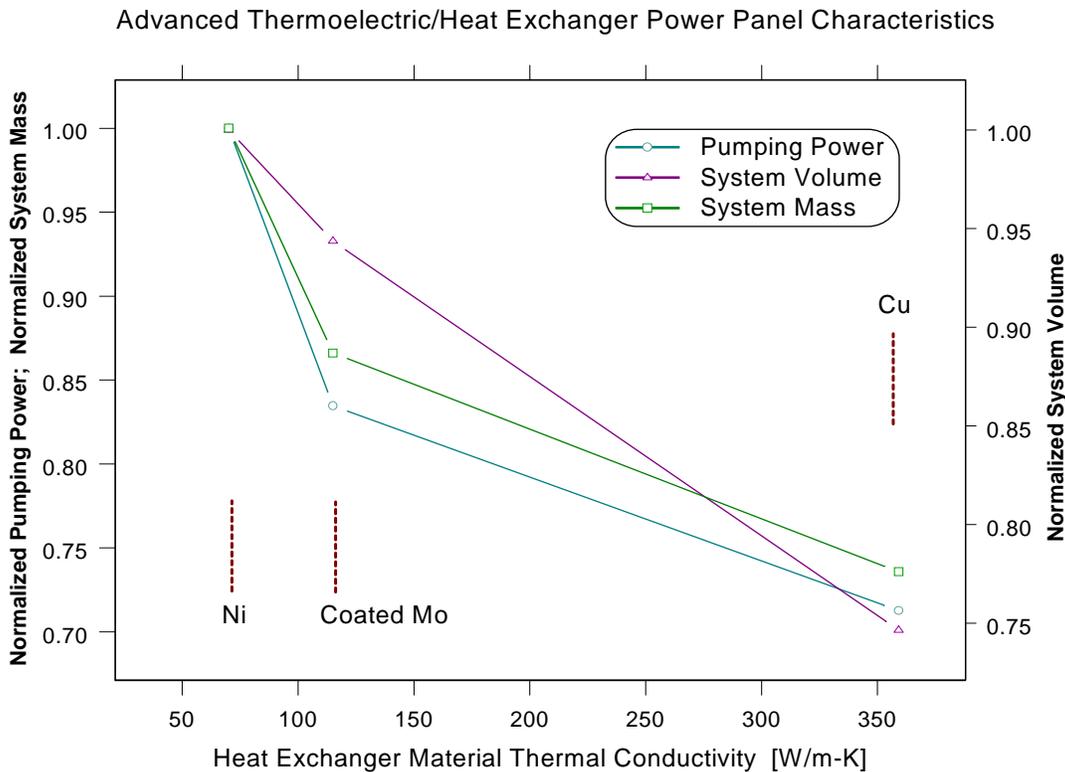


Figure 18: Hot-side heat exchanger material impacts on TEG system pumping power, mass & volume in advanced micro channel heat exchange configurations

Figure 18 exhibits an example of how heat exchanger characteristics (i.e., pumping power, volume and mass) are dependent on the thermal conductivity of the base heat exchanger material.

This shows what would be possible in the way of mass and volume reductions with more innovative configurations and better heat transfer materials to fully enable and exploit advanced TEG system performance. The performance of these innovative configurations and systems is intimately tied to basic system material selections and their properties, as shown in Figure 18. Ultimate performance could benefit from fundamental materials research as well to develop more high temperature, high thermal conductivity options for advanced heat transfer configurations and technologies such as micro channels.

Advanced TEG systems using $ZT \sim 2$ TE materials are already pushing the limits of current thermal transfer technologies, as shown by this engineering scoping work, to supply the required TEG interface heat fluxes and hot-side heat transfer. It is possible that advanced TEG systems using $ZT \sim 4$ TE materials, depending on their exact formulation and TE properties, could overwhelm current thermal transfer technologies and may require exotic/ultra-advanced heat exchanger technologies that are not well defined or characterized at this point. It is, therefore, recommended that closely coordinated, parallel R&D projects be executed in lock-step fashion to research, develop, validate, and demonstrate advanced TE materials, heat transfer materials, & heat exchanger technologies required to enable advanced TEG systems to satisfy industrial glass process energy recovery requirements.

5.2 Primary Aluminum

Approximately 2,758,000 metric tons (2003) of primary aluminum are produced annually in the United States by the reduction of alumina in Hall-Héroult electrolytic cells. The reduction reaction ($2\text{Al}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Al} + 3\text{CO}_2$) consumes a carbon anode and releases CO_2 at an idealized rate of 1.22 kg CO_2 /kg Al. In addition, a portion of the carbon anode material “burns” (non-ideal) to release additional CO_2 at a rate of 0.30 kg CO_2 /kg Al. Annually, approximately 4,200,000 tonnes of CO_2 are released at roughly 960°C directly above the anodes in enclosed cells. In addition to CO_2 , very small amounts (ppm) of carbon monoxide (CO), sulfur dioxide (SO_2), hydrogen fluoride (HF) from the bath, perfluorocarbons (predominantly CF_4 and C_2F_6) from periodic “anode effects”, and organic tars and oils from the anodes are released as gases; these gases carry small particulates of alumina (Al_2O_3), sodium fluoride, aluminum fluoride, and carbon fragments.

Primary plants operating in the United States use their alumina feedstock as an adsorbent material in dry flue gas scrubbers to remove fluorinated off-gases, tars and oils. Cell exhaust gases are mixed with large quantities of air near the cell to lower the temperature to about 150°C so that the exhaust manifolds can be constructed from mild carbon steel. The exhaust gas temperature is kept above the water and HF dew point. The gas components can form a hard gray scale on heat exchange surfaces. The quantity of alumina added in scrubbing is sufficient to lower the flue gas temperature to 90°C-160°C range. This low-temperature range is necessary to ensure the condensation and adsorption of the oils and tars and to protect the downstream bag house. A TEG operating near the cell could be envisioned to lower the flue gas temperature to about 500°C prior to air dilution and transport to the scrubber. This lowered temperature is above the HF dew point and would not impact the performance of the scrubber as it removes fluorinated compounds, tars, oils or particulates. The 500°C TEG exit temperature is sufficiently high to avoid condensation of the organic compounds on heat exchange surfaces. Fluorinated gas adsorption on alumina is reported to be nearly complete at room temperatures.

Primary aluminum plants have little practical opportunity to use their cell discharge gas for heat exchange. They consume nearly 14 kWh of direct current voltage for each kilogram of aluminum produced. It may be possible to integrate the TEG system in such a manner as to provide a small portion of their electrical needs.

[Note: Reduction cells that utilize Soderberg anodes (baked-in-place) vs. modern prebaked anode cells have to contend with a heavier load of hydrocarbons from the cell off-gas. These hydrocarbons are associated with the anode raw materials. Soderberg plants in the United States have been idled because of their inherently higher energy consumption and operating costs. Many Soderberg plants were designed with a combination of dry and wet scrubbers in order to remove the volatile organic compounds (VOC).]

5.2.1 Primary Aluminum Energy Conversion Opportunity

The 4,200,000 tonnes of CO₂ released at roughly 960°C from the cells represent over 4.2 trillion Btu/yr of lost energy. An estimate of the energy that could be recovered from primary aluminum cells can be made by estimating the TEG system efficiency.

Table 9: Thermoelectric waste heat opportunities in U.S. primary aluminum industry

Temperature C (F)	Available Waste Heat TBtu/Year	TEG Recoverable Waste Heat TBtu/Year		
		ZT = 1 5%	ZT = 2 15%	ZT = 4 25%
960 (1750)	4.2	0.2	0.6	1.0

5.2.2 Primary Aluminum TEG system and Performance

The gas composition and typical flow rates for a primary aluminum facility are listed in Table 10.

Table 10: Flue characteristics for a typical 200,000 ton/yr U.S. primary aluminum plant

Component	Combustion lb/hr	Reaction lb/hr	Total cubic feet/hr 960 C	Enthalpy Btu/hr 960 C
Nitrogen	~0.0	~0.0	~0.0	~0.0
Carbon Dioxide	~0.0	76,500	3,000,000	34,700,000
Water	~0.0	~0.0	~0.0	~0.0
Oxygen	~0.0	~0.0	~0.0	~0.0
Argon	~0.0	~0.0	~0.0	~0.0
Fluorides	~0.0	ppm	~0.0	~0.0
TOTAL	0	76,500	0	34,700,000

The CO₂ streams flowing at 900-960°C are high-temperature energy sources that can create large temperature differentials across a TEG system, thus providing the opportunity for high power outputs in TEG systems in the primary aluminum plant.

The major difference with the other waste energy recovery opportunities is that the thermophysical properties of CO₂ gas flow are slightly different from those of the exhaust flow in industrial oxy-fuel glass processes and other combustion-based gas streams. When compared with glass process exhaust stream, for example, since at high temperatures, the thermal conductivity of CO₂ is approximately the same as that of air (or any of its components), CO₂ has about the same thermal transfer capability as the gases that typically make up the glass process exhaust stream at 1,400°F (1,033 K). The viscosity of CO₂ is about 10% less than air, but the density is 50% higher. This leads to lesser pressure, requiring somewhat higher pumping power for the same mass flow rates as in a glass process exhaust stream. Therefore, one would expect the hot-side heat exchangers in the aluminum flow applications to be approximately the same size to slightly larger as compared to in glass process. This will be an important factor for consideration when integrating TEG systems into the aluminum process CO₂ streams.

Another factor to consider is that although CO₂ flow stream are at high temperatures, it may be difficult to fully utilize these high temperatures because of temperature and structural limitations in known advanced and current state-of-the-art TE materials and heat exchanger materials. Fortunately, the hot side heat exchanger isolates the TE materials from the bulk stream and these materials are not exposed to the bulk stream temperature. It is unlikely that TE material survival temperatures above ~527°C (800 K) would be possible, even in advanced TE materials envisioned based on today's materials R&D.

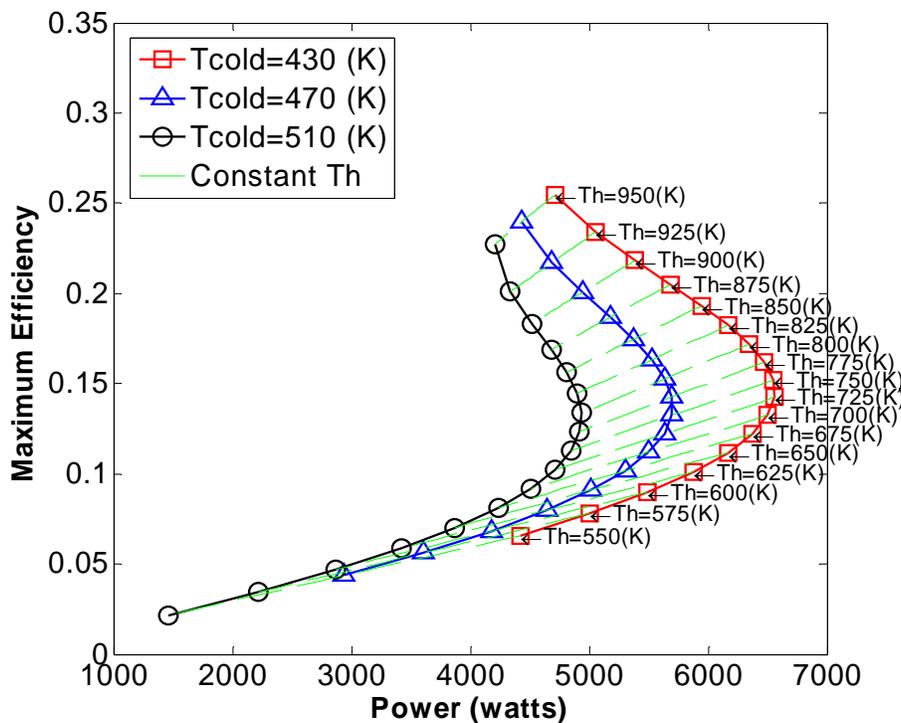


Figure 19: Maximum Efficiency vs. Power Potential for ZT ~ 2 TE Materials
 $(UA_h = 250 \text{ W/K}, T_{ex} = 1100 \text{ K}, T_{amb} = 300 \text{ K}, \dot{m}_h = 0.29 \text{ kg CO}_2/\text{sec})$

Figure 19 shows power output and TEG efficiency that would be possible if one could access CO₂ exhaust flows at 1100 K (1520°F) with an advanced TEG using ZT ~ 2 TE materials with $UA_h = 250 \text{ W/K}$. TEG efficiencies are somewhat higher (~15%) than in glass process exhaust flows (~13%) for the same cold-side temperature conditions of T_c near 430°K. This is because of

the higher TEG hot-side temperatures near 750°K (versus ~700°K in glass process waste energy recovery applications). The CO₂ flow rate of 0.29 kg/sec in Figure 19 represents about 3% of total CO₂ flow rate available in typical aluminum primary plant. The maximum potential power output shown for UA_h = 250 W/K is about 6,600 W (at 15% efficiency) for this 1/10-scale TEG modular system. It could then be replicated as desired to increase total TEG output to the aluminum processing plant.

With the higher CO₂ temperatures, there would be high hot-side heat transfer and heat fluxes to contend with in a ZT~2 TEG system just as in a glass process waste energy recovery application, with hot-side heat fluxes being potentially as high as 430 W/cm² and the optimum TEG area around 110 cm². As in glass process WER applications, this will create serious engineering challenges at the hot-side interface of the TEG system and requirements for high-temperature, high-heat-flux materials, components, and system techniques to enable high-performance advanced TEG systems. The higher hot-side heat transfer would also create higher cold-side heat transfer, which requires the TEG cold side to run at somewhat higher temperatures than in glass process WER to dissipate the cold-side thermal energy. This compromises TEG system performance a small amount. The cold-side cooling water flow required in such a system would be ~0.11 kg/sec for T_c (TEG cold-side temperature) ~ 430°K and T_{amb} = 300°K. This system cold-side flow is similar to that discussed for glass process waste energy recovery applications in section 5.1.4.

5.3 Molten Metal Furnaces

Waste heat recovery from gases in metals and non-metallic minerals processing (excluding calcining) is estimated to be ~235 TBtu/yr.¹⁹ Industries that produce molten metal can provide a sizeable opportunity for TEG recovery of waste heat. Many molten metal operations use the energy from the combustion of fuels to melt and hold vast pools of molten metal. The combustion gases in these operations are frequently discharged from the furnace at high temperatures to the atmosphere, in a manner very similar to the glass furnaces (section 5.1). Like the glass furnaces, in many instances, thermal energy can be recovered using recuperators or regenerators (heat exchangers) to preheat combustion air. Also, like in the glass industry, furnace operators desiring to improve energy efficiency and/or productivity may consider oxy-fuel systems in which there is no or very little air requiring preheating. Additionally many molten metal operations lack options where thermal energy could be exchanged with other fluids or solids.

TEG use in molten metal furnace operations is most likely when the installed TEG cost is competitive with bulky recuperator/regenerator systems or when oxy-fuel systems are employed. The small size of TEG systems (ZT ~2), their potential modularity, and simplicity of installation may contribute to their utility vis-à-vis a recuperator/regenerator in air-fired systems. Their convenient size and modularity should allow them to be placed in duct work prior to dilution cooling air without significant capital expenditure in new duct work. However, a concern is that in many applications (e.g., aluminum), the TEG hot-side heat exchanger will have to contend with flue stream compositions that have traditionally made thermal recovery systems short lived and/or high maintenance to the point where they have to be removed. These applications will, therefore, require significant development of TEG heat exchange materials and surfaces.

U.S. aluminum manufacturing industry melts over 16 billion pounds of aluminum annually and consumes over 55 TBtu/yr for melting and holding molten aluminum. Most aluminum melting is

accomplished in large reverberatory furnaces, where approximately 22% (~12 TBtu/yr) of the energy used is lost as ~750°C flue gas discharge. This temperature is high enough to allow a TEG ($ZT \sim 2$) to operate in its optimal power delivery range. However, aluminum furnace flue gas can contain non-combustion-related components that are corrosive and fouling; also the gas volume is variable as the combustion systems operate in on/off cycles depending on thermal demand.

Aluminum furnace operations vary widely in practice. Chlorine and inert gas (e.g., argon) are frequently bubbled or “snigfed” (spinning nozzle inert gas fluxing) into molten aluminum to remove highly soluble hydrogen (which forms porosity in cast components) and other impurities. Other fluxing and alloying materials are added to the furnaces that produce airborne chloride particles (NaCl and KCl) and oxides (MgO and Al₂O₃). Most furnace systems cool flue gases with the introduction of ambient air and use a bag-house to capture particulates and treat combustion gas products. The hot exhaust side of aluminum furnaces has been particularly hostile to shell and tube thermal recuperators and ceramic thermal regenerators. Corrosion, thermal shock, high maintenance, and low reliability have contributed to removing these systems from many plants. Efficient TEG use in aluminum furnace operations may require duct systems capable of diverting the fluxing and alloying gasses away from the operating TEG hot-side heat exchange surfaces.

Iron/steel furnaces would appear to represent another large potential opportunity for TEG recovery of waste energy. The theoretical melting temperature of iron is 1,200°F and steel 1,225°F. The molten metal temperatures of these furnaces are many times over 2,000°F. The operating exhaust temperature and composition vary significantly in different setups (Table 11). The majority of iron is melted in cupola furnaces, which are typically batch loaded near the top; the combustion and reduction gases in cupolas are used to provide a significant portion of solids and combustion air preheating. This practice provides cupolas with thermal efficiencies higher than in reverberatory furnaces. However, this also lowers the exhaust temperature to about 250°C-500°C, a temperature range that is lower than the TEG ($ZT \sim 2$) optimal range. Further, the batch loading aspect creates cycling in the exhaust temperature. These factors combined will impact the economic value provided by TEG in waste heat recovery in cupolas.

Induction and arc furnaces do provide higher-temperature exhaust for TEG but lower exhaust volumes since these are limited to the reduction gases.

Table 11: TEG opportunity in iron/steel furnaces

Furnace Type	Tons Shipped ^a	Btu/ton ^b	Thermal Efficiency ^c	Exhaust Temperature	Exhaust Btu/yr
Iron Cupola	6,374,400	8,000,000	40-50%	250-500°C	
Iron Induction	4,249,600	4,560,000	50-70%		
Steel Arc	1,586,000	5,070,000	35-45%		

a – 2002 AFS Metalcasting Forecast and Trends

b – J.F. Shifo, “Theoretical/Best Practice Energy Use in Metalcasting Operations” KERAMIDA Environmental, Inc. Indianapolis, IN, May 2004

c – Advanced Melting Technologies: Energy Saving Concepts and Opportunities

for the Metal Casting Industry, ITP Metal Casting, U.S. Department of Energy, November 2005, pg. i

Although TEG opportunities in molten metal flue gases do exist and could provide significant energy recovery, the application of TEG will require more robust TE devices to handle thermal

cycling and specialized hot-side heat exchange surfaces to handle the corrosive and sometimes particle-laden exhaust gases.

5.4 Ethylene

Ethylene is the largest volume petrochemical produced in the United States and worldwide. Having no direct end use, it is a basic building block for the production of numerous chemical products. The United States has 43 operating plants that produced 28.3 million tons of ethylene and consumed approximately 645 trillion Btu in 2004. The ethylene furnace reactions occur at ~850°C. The large-scale production and high temperatures warranted the examination of ethylene furnaces as a potential TEG opportunity.

Ethylene production is energy intensive, requiring about 16.7 million Btu per ton when produced from ethane and over 27.4 million Btu per ton when produced from naphtha/gas oil feedstocks. Using estimates of the U.S. feedstock mix, an average of 22.8 million Btu per ton is spent on ethylene production in the United States.

Roughly 58% of the total energy input to an ethylene facility is associated with the furnace operation, 15% with compression and 27% with separations. Roughly 40% of the furnace energy is associated with the chemical reactions necessary to produce ethylene.²⁰ The ethylene reaction takes place in gas-fired furnace at ~850°C, the large volume and high-temperature exhaust combustion gases offering an opportunity for energy recovery.

Current ethylene furnaces can be described as having two sections – a radiant section containing reactor tubes in which the pyrolysis/steam cracking reactions occur and a convection section which is optimized to provide specific plant operating preferences (combinations of feedstock preheating and steam generation). The roughly 60% of the energy supplied to the furnace that is not used in reactions is discharged from the radiant section of the furnace at over 850°C into the convection section. Ethylene facilities are highly heat integrated and this valuable energy discharge is used in the convection section to preheat feedstock (up to as high as 550°C to 650°C) and to make high-pressure steam. Facilities use steam for heat and to turn the large mechanical compressors (~15% of the total energy) used to move the gas feedstocks and products, and to operate the separation columns. Most facilities have higher demand

for steam/mechanical energy than what is generated from the furnace convection section. The ethylene furnace exhaust design temperature is 300°F (same as in case of conventional water/steam boiler, chosen to avoid condensation). The use of thermal heat integration and the low exiting temperature leaves little opportunity for TEG use.

5.4.1 Ethylene Energy Conversion Opportunity

A rough estimate of the energy that could be recovered from ethylene furnaces assuming a device capable of capturing low-temperature thermal energy can be made by generalizing the furnace operations (Table 12).

Table 12: TEG base case ethylene furnace assumptions

Ethylene Furnace Design	
200,000	tons per day
22,800,000	Btu/ton Requirement
58%	% of Energy Related to Furnace
13,224,000	Furnace Btu/ton
3,963,000	Btu/ton in Operation
Furnace Fuel : Natural Gas	
99%	Combustion Efficiency
1%	Excess Oxygen
none	Oxygen Enrichment

Approximately 374 trillion Btu per year are associated with ethylene furnace operations (~58% of 645 trillion Btu), equivalent to 22.8 million Btu/ton of ethylene. These furnaces are designed to have an exiting flue temperature of 300°F. This assumption leads to a value of about 28 to 35 trillion Btu annually lost to emissions from ethylene furnaces. If a waste heat recovery electric generator device with a high thermal recovery efficiency (e.g., 20%) were utilized throughout the industry, there would be a potential to recover ~6.5 trillion Btu of electric energy annually. This is equivalent to a primary fuel savings of ~20 trillion Btu (if generation and transmission losses for electric energy are factored in).

Although TEG offers little advantage in recovering low-temperature waste heat, a future technology, piezoelectric generation, may have application at ~300°F temperature. This technology is discussed in Section 3.3.

5.4.2 Ethylene Waste Heat Operating Conditions and Characterization

The characteristics of the waste heat available for a recovery device operating on an ethylene furnace flue stream will depend on the furnace design, capacity and the fuel being combusted. These characteristics can be estimated by assuming a “typical” furnace design, capacity and fuel. The “typical” base case ethylene furnace is shown in Table 12. Natural gas is the predominant fuel used by the industry, however, many other refinery-based fuels are also used. The major components in the emissions are fuel combustion products (CO₂ and H₂O) and nitrogen (from the combustion air). It should be recognized that the flue gas stream will also contain low levels of SO₂, NO_x and other minor gas phase constituents (argon, excess oxygen, unconsumed natural gas components, etc.). Some of these minor components can be detrimental to heat exchange surfaces necessary for recovering thermal energy.

Based on these assumptions, the flue gas composition for major components and associated enthalpies are estimated as shown in Table 13. Ethylene furnaces are designed typically as natural draft systems and the flue gas pressure is typically close to atmospheric pressure (i.e., less than 20 inches of water).

Table 13: 200,000 ton/yr Ethylene furnace flue composition

Component	Combustion lb/hr	Reaction lb/hr	Total Amount cubic feet/hr 300°F	Enthalpy Btu/hr 300°F
Nitrogen	184,000		3,888,000	10,180,000
Carbon Dioxide	38,700		316,600	1,860,000
Water	31,500			3,159,000
Oxygen	560		6,280	27,800
Argon	3,120		46,300	86,374
TOTAL	257,880	0	4,257,180	15,313,174

5.5 Industrial and Commercial Water/Steam Boilers

Boilers for producing steam and hot water are used in nearly every good size industrial plant and commercial facilities (e.g., hospitals, large office buildings, and schools). A recent report, “Characterization of the U.S. Industrial/Commercial Boiler Population,”²¹ lists nearly 120,000 commercial boilers utilizing 3,300 TBtu/yr and 43,000 industrial boilers utilizing 4,800 TBtu/yr. Steam boilers typically operate at 80 to 85% thermal efficiency, the largest thermal losses being (in decreasing order): flue gases, steam/water leaks, and infrastructure conduction.. This implies that there is over 1,200 to 1,600 TBtu/year of energy loss from boilers. In other words, probably over a quad of energy ($>10^{15}$ Btu) is available for recovery if appropriate technology is available to recover the waste heat from water/steam boilers.

The majority of commercial boilers consume natural gas (2,700 TBtu/yr)²² or fuel oil (600 TBtu/yr). These combustion streams would be relatively free of fouling and corrosive materials compared to other industrial processes. The boiler industry recognizes the large opportunity to recover energy in its exhaust gases. Today most boilers contain “economizers” or heat exchangers that recover excess heat.

Natural gas provides about 56% of the energy used by industrial boilers. Most of the remaining energy supply comes from industrial byproducts. Byproduct boilers include pulp and paper Tomlinson boilers which utilize black liquor as fuel and refinery boilers firing residual oils. Byproduct-fueled boilers have waste heat flue gas compositions that create significantly more severe operating environment than a natural-gas-fired boiler. Industrial boilers also make use of economizers / heat exchangers to recover excess heat.

The $>10^{15}$ Btu of energy that is discharged to the atmosphere by industrial and commercial water/steam boilers is low-temperature waste heat (300°F). The discharge temperature is chosen to avoid corrosive condensation forming on the economizer/heat exchanger surfaces. Similar to the case of ethylene furnaces, this temperature is too low for TEG use, but could be an opportunity for waste heat recovery using piezoelectric generation technology (Section 3.3).

6. Conceptual Thermoelectric System Installation

A simple thermoelectric generator consists of a hot side heat exchange, a TE device, a cold side heat exchanger and an electrical control device. Numerous design options and configurations can be imagined. Hot and cold side heat exchanger designs might be based on microchannel, heat pipe, porous media or other advanced concepts. The TE device itself could have various geometries and power outputs. Many combinations are possible of how these components may be assembled into an industrial grade TEG apparatus. Future experience with building and operating prototype TEG systems for waste heat recovery, even if those systems use currently available $ZT \sim 1$ materials, will begin to narrow these numerous options into practical industrial use designs.

Conceptually, as a starting point, consider a TEG system applied to the industrial application described in section 5.2 (primary aluminum). A simple design concept can be developed using the performance information for the $ZT \sim 2$ TE device described in Figure 19 and assuming the hot side thermal exchange to be provided by a heat pipe and the cold side thermal exchange by a microchannel device. Table 8 indicates that this device would have an area of approximately 100 cm^2 . A cylindrical or closed "C" TE device would be 10 cm tall with a 10 cm circumference (100 cm^2). This circumference is roughly equivalent to 1.25 inches and would approximate the outside diameter of a 1-inch pipe. A well-designed heat pipe protruding 18 inches into the ductwork could provide 500 cm^2 of heat exchange area and the addition of fins to the evaporator section could enlarge the effective area. This heat pipe may provide the 250 W/K UA_h required for performance in Figure 19. The cold side heat exchange could also have a closed "C" configuration. The combined heat pipe, TE device and cold side heat exchanger could be clamped together to form a solid high heat conductive TEG assembly (Figure 20). This assembly could be easily mounted to ductwork through a 4-inch opening. The mounting could be simple allowing easy removal for periodic cleaning of the heat pipe surfaces. The TE device, in this design and most others, is isolated from the waste heat stream by the hot side heat exchanger. This isolation effectively shields the TE device from the bulk stream composition and temperature by the hot side heat exchanger.

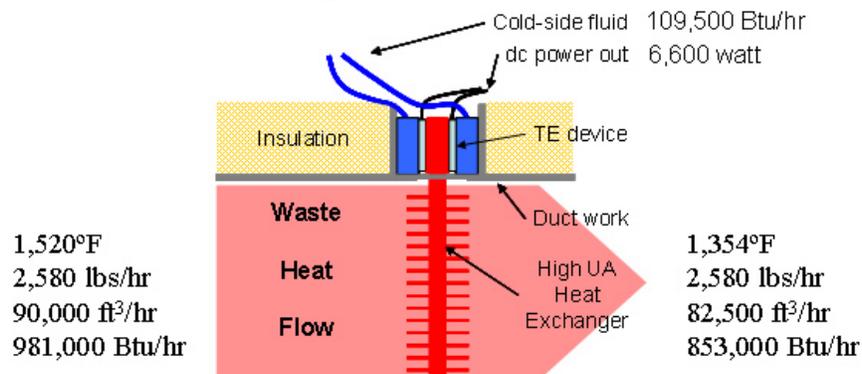


Figure 20: Conceptual TEG design for application in primary aluminum, using $ZT \sim 2$ material and providing 250 W/K UA_h

Figure 20 shows the flow rates and performance of the assembly. These values represent the combined flow of the off gases from seven Hall-Hèroult cells, about 3% of a typical (200,000 tonne per year) production line. The velocity upstream of the TEG systems is about 12.5 ft/sec (0.32 kg/sec) and represents a stream originally at 1,760°F (960°C) and 1,041,000 Btu/hr that has

been diluted with about 10% air to bring the off gas temperature down to about 1,521°F (827°C) and 981,000 Btu/hr. This decrease in temperature is required to meet an assumed maximum operating temperature for advanced TE materials (800°K). This single TEG assembly would remove about 12% of the energy from the 1,041,000 Btu/hr stream that originated from the seven Hall-Hèroult cells. The assembly would convert about 2% of the off gas energy into electricity and about 10% would be lost to the cold side heat exchange fluid. The flowing gas downstream of the single TEG device would have an energy value of 853,000 Btu/hr.

Additional TEG assemblies can be added to the off gas ductwork (Figure 21). The small size of the assembly (4 inch diameter) would allow close spacing and not require significant or extended ductwork. These assemblies could be arranged to ensure good bulk gas stream mixing. Experience could determine if simple baffles or static mixers are needed to reestablish a uniform temperature profile in the gas stream.

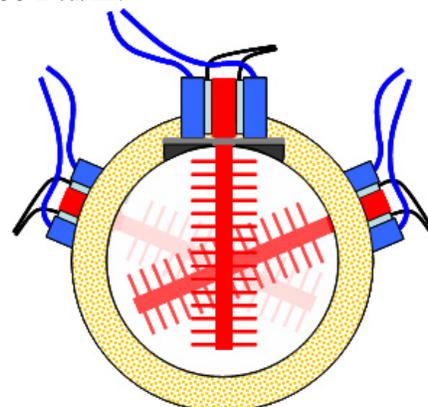


Figure 21: TEG assemblies mounted to ductwork

Each subsequent downstream assembly will experience a lower temperature, lower velocity and lower Btu content stream than the one before it. Table 14 explores the performance of one possible configuration containing a series of downstream assemblies. As the off gas temperature decreases, the efficiency and output of the subsequent TE devices change. There is a diminishing return as TEG assemblies are added. This can be seen in Figure 19, the efficiency decreasing as the TE device hot side temperature (T_h) becomes lower.

Table 14: Conceptual cascading TEG assembly performance

Position	Upstream Bulk Values			Module Hot Side Temperature			TE Device Performance				Energy Removed		
	Btu/hr	Temperature			Temperature			Output			% Energy Recovery	Btu/hr	%
		°C	°K	°F	°C	°K	°F	efficiency	watt	Btu/hr			
pre air dilution	1,041,000	960	1,233	1,760									
TEG 1	981,000	827	1,100	1,521	527	800	981	17.0%	6,400	21,800	2%	128,500	12%
TEG 2	853,000	734	1,007	1,354	434	707	814	13.5%	6,500	22,200	4%	130,500	25%
TEG 3	722,000	638	911	1,181	338	611	641	10.0%	6,000	20,500	6%	120,400	36%
TEG 4	602,000	546	819	1,015	246	519	475	6.0%	3,500	11,900	7%	70,200	43%
TEG 5	532,000	493	766	920	193	466	380	3.0%	2,500	8,500	8%	50,200	48%
down stream	481,000	453	726	848									

The first TEG assembly in the primary aluminum off gas conceptual configuration operates at about 17% conversion efficiency. The fifth device downstream would operate at about 3% conversion efficiency. Overall a five TEG assembly group could convert about 8% of the off gas stream energy directly into electrical power.

The above example illustrates one conceptual TEG configuration. Numerous configurations are possible and these could be further optimized by tailoring the specific hot-side heat exchanger design, the specific TE materials, specific TE device design, and the cold-side heat exchanger design to the expected temperature, flow conditions, and duct geometry at each position shown in Figure 21. Other conceptual TEG configurations could be considered to optimize certain system characteristics and exhaust ducting geometry, as well as exploit the most advantageous positions (i.e., temperatures, flow dynamics) along the industrial exhaust flow stream or ducting length.

7. Conclusion: TEG System Engineering Needs & Barriers

This engineering scoping analysis identified large-scale waste heat recovery opportunities that are suitable for advanced TEG systems. The study made engineering design assumptions and calculated the anticipated performance of advanced TE materials in these applications. The study has identified significant technical challenges that must be addressed in order for TEGs to be widely accepted as an option for practical and economic recovery of the energy embedded in industrial waste heat emissions. These challenges result from a need to integrate high-performance heat exchangers with advanced TE materials into a TEG system or assembly. Successfully addressing these challenges is a prerequisite to achieving advanced TEG systems that satisfy performance, reliability, lifetime and cost requirements in industrial process waste energy recovery.

Major conclusions and technical issues identified in this scoping analysis are as follows:

- $ZT \sim 1$ materials will not provide the thermal efficiency and system costs to be the long term solution to industrial scale waste heat recovery. However, they can serve as prototype system components to demonstrate TEG waste heat recovery concepts and provide lessons learned for industrial applications where heat exchange degradation, thermal cycling, vibration and other deleterious operating conditions are commonly encountered.
- Satisfying hot-side heat flux requirements in the advanced TEG systems will be a serious technical challenge, although not necessarily an insurmountable engineering and scientific test. Advanced high-heat-flux heat transfer materials and heat exchange systems will be key enabling technologies for advanced TEG systems in industrial process applications. This will include advanced convective and radiative systems.
- Satisfying cold-side thermal performance requirements appears feasible with current heat transfer technologies at low pumping powers. The scoping study results indicate that liquid (e.g., water, Dow ThermTM, ...) microchannel heat exchangers are one technology that can satisfy cold-side cooling requirements. Leakage of any cooling liquid would need to be compatible with the surrounding materials.
- Satisfying component and system cost requirements are critical to successful commercialization. This work indicates that packaged systems costs of <\$5/watt (including TE devices, heat exchangers and process modifications) will be required to foster technology adoption and commercialization.
- Coupling TEG systems to existing process equipment will require engineering design work to ensure equipment accessibility and location in optimal performance regions
- Integrating the TEG power output with the existing process electrical network (load matching) needs further study
- Advanced TE materials having $ZT \sim 2$ properties that have recently been developed and characterized and new advanced TE materials with $ZT \sim 4$ envisioned in the long-term future will strongly enhance TEG commercialization by providing the thermal conversion efficiencies needed to make TEG economically attractive. This study shows that 20% energy conversion efficiency appears possible in advanced TEG systems operating at hot-side temperatures of $\sim 1000^\circ\text{K}$.
- Manufacturing techniques for low-cost high-volume production of TE devices that incorporate the new, advanced TE materials ($ZT \sim 2$) must be developed. Currently, these

advanced TE materials which show great promise have been characterized, but no standardized method has been developed to build TE devices with these materials.

- Waste heat applications with large mass flow rates, high temperatures and no on-site opportunities for thermal exchange with other fluids/solids have been identified (e.g., glass furnaces, primary aluminum cells, and aluminum furnaces). Integrating TEG systems into the exhaust manifolds of these processes is practical. The development of these applications can provide the foundation for a new industry dedicated to recovering the energy losses associated with industrial manufacturing.
- The quantity of most rare semiconductor materials (e.g., gallium) needed to manufacture advanced TE devices with $ZT \sim 2$ or greater for widespread use in industrial waste heat recovery is probably less than 4% of the available material supply. This low percentage would not significantly impact world supply and price. Other semiconductor materials are more abundant.
- Enhanced TEG performance ($ZT \sim 2$ and $>15\%$ thermal efficiency) will provide for a more attractive business case, both for the TEG developer and the end-user. Higher efficiency levels will produce more power output at higher power density, thereby creating a stronger value proposition for the industry (i.e., more power output will be possible from smaller devices and systems).
- Advanced TE materials with $ZT \sim 2-4$ will drive this technology toward miniaturization because the higher performance devices will require much smaller optimum device areas. This will also create the requirement for high-heat-flux heat exchange systems and thermal interface materials.

The technical issues identified in this scoping analysis point to a list of needs for future engineering and scientific work. These include work in the following areas:

- Advanced TE materials development and manufacturing techniques to achieve $ZT \sim 2$ or higher in operating TE devices
- High-performance, high-temperature heat exchanger configurations including convective systems and radiative systems to absorb and transfer convective and radiative heat fluxes to the TE devices
- High-temperature, high-thermal-conductivity heat transfer materials and surfaces to improve heat exchanger performance
- High-heat-flux interface materials to enable efficient heat transfer between heat exchangers and the TE device
- High-temperature, corrosion-resistant, and chemically stable coating materials to withstand the potentially corrosive and fouling environments encountered in industrial process exhaust streams
- Economical TEG manufacturing and fabrication techniques to enable cost-effective TEG waste heat recovery technology that satisfies industry business constraints and support commercialization of this technology
- Identifying the process and cost impacts of modifying existing process equipment to accommodate TEG systems.

Finally, this study has identified a strong need for closely coordinated and parallel research, development, validation, and demonstration of advanced TE materials, heat transfer materials, and heat exchanger technologies. Since the performance gain from advancement in one TEG component is limited by advances in other TEG components, all TEG system components must be developed in tandem to maximize the technology's thermal-to-electric conversion efficiency and enable their commercial viability in industrial waste energy recovery. Isolated development

such as making advanced TE materials (i.e., $ZT > 2$) available for gaseous waste heat applications risks not having other TEG system components available that are required to make the system work efficiently.

Although this study has identified pertinent technical requirements in various areas (e.g., potential power outputs, interface heat fluxes, heat transfer to pumping power factors, and area requirements), periodic review of engineering issues is required and further work is warranted to incorporate future technical advances as waste energy recovery projects mature.

Appendix A: Glass Furnace TEG Application

The following tables provide the data and calculations that were used in developing the hot flue gas composition and thermodynamic properties for glass manufacturing used in Section 5.1 of Section 5 Assessing Thermoelectric Technology Potential and Requirements in Selected Industries. These data are based on a typical size furnace and operation. Tables A - C are for an air fired regenerative furnace and Table D - F are for an oxy-fuel fired furnace.

Table A - Glass Container Regenerative Furnace TEG "Base Case" data and information

400 tons per day Regenerative Furnace	
55% Thermal efficiency of a modern Regenerative Furnace	
2,300,000 Btu/ton	Theoretical Minimum Energy Requirement (Sandia) ^a for raw materials
1,898,000 Btu/ton	Energy requirement for melting cullet
30% Cullet	
3,963,000 Btu/ton of raw materials and cullet consumed in operation	
66,050,000 Btu/hr Required	
Natural gas firing	
99% Combustion Efficiency	
1% Excess Oxygen	
900 °F average exhaust gas temperature	482 °C
14,000,000 Flue gas energy content Btu/hr (from Table B)	
840,000 Flue gas energy content Btu/ton of glass	
21.2% Flue gas energy as a percent of total Btu input	

a- <http://www.ca.sandia.gov/crf/research/combustionProcesses/indProc/glassMelt.php>

Table B- Container Glass Furnace Flue Gas Composition Based on Table A Operations

Components	Combustion	Reaction	Gas			Mol. Wt.	900°F Enthalpy Btu/hr
	Products	Products	Density	ft ³ /hr	STD ft ³ /hr		
	lb/hr	lb/hr	STD lb/ft ³				
N ₂	40,252		0.08	1,522,465	514,729	28	8,490,000
O ₂	123		0.09	4,062	1,373	32	23,700
CO ₂	8,474	4,702	0.12	315,556	106,686	44	2,640,000
Ar	683		0.11	18,126	6,128	40	69,700
H ₂ O	7,132		0.05	386,938	130,820	18	2,770,000
SO ₂	5.80		0.18	94	32	66	800
CH ₄	30.55		0.04	2,017	682	16	
C ₂ H ₆	0.31		0.08	11	4	30	
C ₂ H ₄	-		0.08	-	-	28	
C ₃ H ₈	0.16		-	-	-	44	
C ₃ H ₆	-		-	-	-	42	
C ₄ H ₁₀	0.03		0.16	1	0	58	
H ₂	-		-	-	-	2	
CO	-		0.08	-	-	28	
H ₂ S	0.03		-	-	-	36	
S	-		-	-	-	34	
TOTAL	56,700			2,249,270	760,454		13,994,200

Table C: Fuel Air Combustion work sheet for Regenerative Container Glass Furnace

INPUT DATA		66,050,000	Enter the Heating Requirement in Btu per hour
		1	Enter Fuel Choice Number 1 - For Natural Gas
		99.0%	Combustion Efficiency 2 - Refinery Gas
Percent Excess O ₂		1.0%	3 - Fuel Oil
Humidity Level %		30.0%	
Percent O ₂ Enrichment		0.0%	23.1% wt O ₂ feed

Percent O₂ Enrichment is a measure of where the O₂ is coming from with 0% enrichment being 23.2 wt% oxygen (100% air), 50% enrichment is 37.7 wt% oxygen (air supplies 50% of the combustion oxygen) and 100% enrichment is 100% oxygen (no air)

Fuel Component	Moles of O ₂ required per mole of fuel	moles/hr	Mol. Wt.	Total weight (lb/hr)	Net heating value, Btu/lb	Actual Heating obtained, Btu/hr	Total moles of O ₂ /hr reacted	Combustion Products			FLUE GAS Composition		
								CO ₂ lb/hr	H ₂ O lb/hr	SO ₂ lb/hr	Non-Combusted fuels		
								CO ₂ lb/hr	H ₂ O lb/hr	SO ₂ lb/hr	lb/hr	weight percent	
Methane (CH ₄)	2	190.42	16	3,055.0	21,502	65,031,504	377.04	8,296.78	6,792.52	-	CH ₄	30.55	0.05%
Ethane (C ₂ H ₆)	3.5	1.04	30	31.2	20,416	630,071	3.59	90.34	55.47	-	C ₂ H ₆	0.31	0.00%
Ethylene (C ₂ H ₄)	3	0.00	28	-	20,276	-	-	-	-	-	C ₂ H ₄	-	0.00%
Propane (C ₃ H ₈)	5	0.35	44	15.6	19,929	307,521	1.75	46.20	25.22	-	C ₃ H ₈	0.16	0.00%
Propylene (C ₃ H ₆)	4.5	0.00	42	-	19,683	-	-	-	-	-	C ₃ H ₆	-	0.00%
Butane (C ₄ H ₁₀)	6.5	0.05	58	3.1	19,665	60,689	0.35	9.35	4.78	-	C ₄ H ₁₀	0.03	0.00%
Butylene (C ₄ H ₈)	6	0.00	56	-	19,420	-	-	-	-	-	C ₄ H ₈	-	0.00%
Pentane (C ₅ H ₁₂)	8	0.00	72	-	19,499	-	-	-	-	-	C ₅ H ₁₂	-	0.00%
Hexane (C ₆ H ₁₄)	9.5	0.00	86	-	19,391	-	-	-	-	-	C ₆ H ₁₄	-	0.00%
Hydrogen (H ₂)	0.5	0.00	2	-	51,571	-	-	-	-	-	H ₂	-	0.00%
Carbon Monoxide (CO)	0.5	0.00	28	-	4,344	-	-	-	-	-	CO	-	0.00%
Hydrogen sulfide (H ₂ S)	1.5	0.09	34	3.1	6,550	20,214	0.14	-	1.63	5.80	H ₂ S	0.03	0.00%
Sulfur (S)	1	0.00	32	-	-	-	-	-	-	-	S	-	0.00%
AIR/Oxygen - required for 100% combustion					ft ³ /hr						SO ₂	6	0.01%
Nitrogen (N ₂)		1,437	28	40,252							N ₂	40,252	70.99%
Combustion Oxygen (O ₂)		383	32	12,251							O ₂	123	0.22%
Excess or Non-Combusted Oxygen (O ₂)		4	32	122.51							CO ₂	8,474	14.95%
Argon (Ar)		17	40	683							Ar	683	1.20%
Carbon dioxide (CO ₂)		1	44	31							H ₂ O	7,132	12.58%
Water (H ₂ O) humidity		14	18	253									
Enriched Oxygen													
Combustion Oxygen (O ₂)		-	32	-	0								
Excess or Non-Combusted Oxygen (O ₂)		-	32	-									
Argon (Ar)		-	40	-									
Nitrogen (N ₂)		-	28	0									

Total Fuel				3,108		66,050,000	382.86						
Total Air/Oxygen				53,593									56,700.49
Total Input				56,700		56,700	Total Exhaust						
				-		-	Material Balance						

Enriched Oxygen System	Feed	Product
	- lbs/hr of air feed	- lb/hr Oxygen (O ₂)
	- tons/day	- tons/day
	- ft ³ /min	- scfm
		- scfh
		0 Nitrogen (N ₂) lb/hr
		0 Argon (Ar) lb/hr
95% wt Percent O ₂		
0.02 ratio Ar/N ₂		

TABLE D: TEG Glass Container furnace with 100% O₂ Enrichment application "Base Case" data.

400 tons per day Regenerative Furnace	
67% Thermal efficiency	
2,300,000 Btu/ton	Theoretical Minimum Energy Requirement (Sandia) ^a for raw materials
1,898,000 Btu/ton	Energy requirement for melting cullet
30% Cullet	
3,267,000 Btu/ton in operation	
54,450,000 Btu/hr Required	
Natural gas firing	
99% Combustion Efficiency	
1% Excess Oxygen	
2600 °F average exhaust gas temperature	1427 °C
16,627,000 Flue gas energy content Btu/hr	
997,620 Flue gas energy content Btu/ton of glass	
30.5% Flue gas energy as a percent of total Btu input	

a- <http://www.ca.sandia.gov/crf/research/combustionProcesses/indProc/glassMelt.php>

Table E: 100% Oxygen Flue gas case

Flue Gas Components	Combustion Products	Reaction Products	Gas Density			Mol. Wt.	2600°F Enthalpy
	lb/hr	lb/hr	STD lb/ft3	ft3/hr	STD ft3/hr		Btu/hr
N ₂	501		0.08	42,674	6,411	28	349,000
O ₂	101		0.09	7,536	1,132	32	65,000
CO ₂	6,960	4,702	0.12	628,482	94,425	44	8,390,000
Ar	9		0.11	517	78	40	2,700
H ₂ O	5,671		0.05	692,353	104,022	18	7,820,000
SO ₂	4.78		0.18	174	26	64	2,400
CH ₄	25.18		0.04	3,742	562	16	-
C ₂ H ₆	0.26		0.08	20	3	30	-
C ₂ H ₄	-		0.08	-	-	28	-
C ₃ H ₈	0.13		-	-	-	44	-
C ₃ H ₆	-		-	-	-	42	-
C ₄ H ₁₀	0.03		0.16	1	0	58	-
H ₂	-		-	-	-	86	-
CO	-		0.08	-	-	2	-
H ₂ S	0.03		-	-	-	120	-
S	-		-	-	-	34	-
TOTAL	13,273			1,375,500	206,660		16,629,100

Table F: Fuel Air Combustion work sheet

INPUT DATA		
	54,450,000	Enter the Heating Requirement in Btu per hour
	1	Enter Fuel Choice Number 1 - For Natural Gas 2 - Refinery Gas 3 - Fuel Oil
	99.0%	Combustion Efficiency
Percent Excess O2	1.0%	
Humidity Level %	0.0%	
Percent O2 Enrichment	100.0%	95.2% wt O ₂ feed

Percent O₂ Enrichment is a measure of where the O₂ is coming from with 0% enrichment being 23.2 wt% oxygen (100% air), 50% enrichment is 37.7 wt% oxygen (air supplies 50% of the combustion oxygen) and 100% enrichment is 100% oxygen (no air)

Fuel Component	Moles of O ₂ required per mole of fuel	moles/hr	Mol. Wt.	Total weight (lb/hr)	Net heating value, Btu/lb	Actual Heating obtained, Btu/hr	Total moles of O ₂ /hr reacted	Combustion Products			FLUE GAS Composition		
								CO2 lb/hr	H2O lb/hr	SO2 lb/hr	Non-Combusted fuels lb/hr	weight percent	
Methane (CH4)	2	156.98	16	2,518.5	21,502	53,610,377	310.82	6,839.66	5,599.59	-	CH4	25.18	0.19%
Ethane (C2H6)	3.5	0.85	30	25.7	20,416	519,415	2.96	74.47	45.73	-	C2H6	0.26	0.00%
Ethylene (C2H4)	3	0.00	28	-	20,276	-	-	-	-	-	C2H4	-	0.00%
Propane (C3H8)	5	0.29	44	12.8	19,929	253,513	1.44	38.09	20.79	-	C3H8	0.13	0.00%
Propylene (C3H6)	4.5	0.00	42	-	19,683	-	-	-	-	-	C3H6	-	0.00%
Butane (C4H10)	6.5	0.04	58	2.6	19,665	50,031	0.28	7.71	3.94	-	C4H10	0.03	0.00%
Butylene (C4H8)	6	0.00	56	-	19,420	-	-	-	-	-	C4H8	-	0.00%
Pentane (C5H12)	8	0.00	72	-	19,499	-	-	-	-	-	C5H12	-	0.00%
Hexane (C6H14)	9.5	0.00	86	-	19,391	-	-	-	-	-	C6H14	-	0.00%
Hydrogen (H2)	0.5	0.00	2	-	51,571	-	-	-	-	-	H2	-	0.00%
Carbon Monoxide (CO)	0.5	0.00	28	-	4,344	-	-	-	-	-	CO	-	0.00%
Hydrogen sulfide (H2S)	1.5	0.08	34	2.6	6,550	16,664	0.11	-	1.34	4.78	H2S	0.03	0.00%
Sulfur (S)	1	0.00	32	-	-	-	-	-	-	-	S	-	0.00%
AIR/Oxygen - required for 100% combustion					ft ³ /hr						SO2	5	0.04%
Nitrogen (N2)		-	28	-							N2	501	3.78%
Combustion Oxygen (O2)		-	32	-							O2	101	0.76%
Excess or Non-Combusted Oxygen (O2)		-	32	-							CO2	6,960	52.44%
Argon (Ar)		-	40	-							Ar	9	0.07%
Carbon dioxide (CO2)		-	44	-							H2O	5,671	42.73%
Water (H2O) humidity		-	18	-									
Enriched Oxygen													
Combustion Oxygen (O2)		316	32	10,100	113,224								
Excess or Non-Combusted Oxygen (O2)		3	32	101.00									
Argon (Ar)		0	40	9									
Nitrogen (N2)		18	28	501									
Total Fuel				2,562.15		54,450,000	315.62						13,272.74
Total Air/Oxygen				10,710.60									
			Total Input	13,272.74	13,272.74	Total Exhaust							
				-									

Enriched Oxygen System	Feed	Product
	43,968 lbs/hr of air feed	10,201 lb/hr Oxygen (O ₂)
95% wt Percent O ₂	21.98 tons/day	122 tons/day
0.02 ratio Ar/N ₂	3,289 ft ³ /min	1,906 scfm
		114,356 scfh
		501 Nitrogen (N ₂) lb/hr
		9 Argon (Ar) lb/hr

Appendix B: TEG Systems-Level Design Approach

The TEG analysis described in this report is based on an integrated system-level design approach that couples heat exchanger and TE device behavior in predicting system performance. Hendricks and Lustbader^{23,24,25} discuss this TE system-level analysis approach, where the heat exchanger performance, parasitic heat loss effects, temperature-dependent TE material effects, and thermal and electrical interface resistance effects are directly and simultaneously coupled with the thermoelectric device performance, to simultaneously analyze and characterize the expected heat transfer requirements and power available in various industrial applications. The technical approach is based on the conservation of energy at key component interfaces. The heat transfer through the hot-side heat exchanger and supplied to the TEG is generally given by:

$$Q_{h,ex} = \frac{(T_{exh} - T_h) \cdot (1 - \sigma_{TE,h})}{\left(\frac{1}{\dot{m}_h \cdot C_{p,h} \cdot \varepsilon_h \cdot (1 - \sigma_{ex,h})} + R_{th,h} \right)} \quad [1]$$

The analysis generally requires hot-side conservation of energy and equates Eq. 1 to the TEG hot-side thermal energy given by:

$$Q_{h,TE} = N \cdot \left[\alpha \cdot I \cdot T_h + (\kappa_n \cdot A_n / L + \kappa_p \cdot A_p / L) \cdot (T_h - T_c) - 0.5 \cdot I^2 \cdot (\rho_n \cdot L / A_n + \rho_p \cdot L / A_p) \right] \quad [2]$$

in determining valid performance conditions and optimum heat exchanger and TE device designs. An additional important aspect of the analysis is the determination of cold-side performance conditions by requiring the cold side conservation of energy

$$Q_{c,ex} = \frac{(T_c - T_{amb})}{\left(\frac{(1 - \sigma_{ex,c})}{\dot{m}_c \cdot C_{p,c} \cdot \varepsilon_c} + R_{th,c} \right) \cdot (1 - \sigma_{TE,c})} = Q_{h,TE} - P_{TE} \quad [3]$$

TE device conversion efficiency, η , is given in section 2.4 of the main report.

The TE system analysis defines optimum TE designs that maximize TE device conversion efficiency, η , while simultaneously coupling TE device performance to heat exchanger performance, for a variety of T_h and T_c combinations and a given T_{exh} . This system analysis technique provides a system-level extension of TE device optimization techniques presented by Angrist²⁶ and Rowe.²⁷ The analysis simultaneously determines optimum TE area requirements, optimum operating temperatures, power output, interface heat flux requirements, and cold-side mass flow rate requirements for any waste energy recovery application of interest. The analysis can be performed for any given TE materials of interest, assuming that temperature-dependent properties (Seebeck coefficient, electrical resistivity, and thermal conductivity) are known or can be approximated.

Nomenclature

- A_p - p-type element area [m²]
- A_n - n-type element area [m²]
- C_p - Specific heat of gas/liquid stream [J/kg-K]
- I - Device current [A]

L - TE element length [m]
 \dot{m}_c - Cold-side (ambient) mass flow rate [kg/sec]
 \dot{m}_h - Hot-side (exhaust) mass flow rate [kg/sec]
N - Number of TE couples
P - Device power [W]
 Q_h - Hot-side thermal energy transfer [W]
 Q_c - Cold-side thermal energy transfer [W]
 $R_{th,c}$ - Cold-side TE/HX interface thermal resistance [K/W]
 $R_{th,h}$ - Hot-side TE/HX interface thermal resistance [K/W]
 T_{amb} - Ambient temperature [K]
 T_{exh} - Exhaust gas temperature [K]
 T_h - TE hot-side temperature [K]
 T_c - TE cold-side temperature [K]
U - Total effective heat exchanger conductance [$W/m^2 \cdot K$]
UA - Effective heat exchanger conductance *area [W/K]
V - Device voltage [V]

Greek Symbols:

α - TE couple Seebeck Coefficient [V/K]
 ϵ_c - Cold-side heat exchanger effectiveness
 ϵ_h - Hot-side heat exchanger effectiveness
 η - Thermoelectric conversion efficiency
 κ - TE material thermal conductivity [W/m-K]
 σ - Parasitic heat loss fraction – fraction of input heat lost
 ρ - TE material electrical resistivity [$\Omega \cdot m$]

Subscripts

c - Cold-side of TE device
ex - Associated with heat exchanger itself
h - Hot-side of TE device
n - n material
p - p material
TE - Associated with thermoelectric device itself

Appendix C: Thermoelectric Generation Companies

Thermoelectric Generator Manufacturers

D.T.S.

Halle, Germany

+49 (0) 345 52 44 292 (3/04)

Manufactures low power (10-40uW) thin film thermoelectric power generators.

<http://www.dts-generator.com>

Global Thermoelectric

Calgary, Alberta, Canada

403-236-5556, FAX 403-236-5575 (3/04)

Manufactures Lead Tin-Telluride thermoelectric power generators.

<http://www.globalte.com>

Hi-Z Technology

San Diego, CA

858-695-6660, FAX 858-695-8870 (3/04)

Manufactures thermoelectric power generator modules.

<http://www.hi-z.com>

Hui Mau Cooling Equipment

Beijing, P.R.China

0086 13501215859, FAX 0086-10-68189379,60275767 (3/04)

Manufactures power generating and cooling modules.

<http://www.huimao.com>

Legelab

Laerbro, Sweden

+46 498 243723, FAX +46 498 243723 (8/04)

Thermoelectric power generators.

<http://www.legelab.com>

Taihuaxing Trading/Thermonamic Electronics

Xiamen, P.R. of China

+86-592-5714012, FAX +86-592-5714010 (3/04)

Manufacturer of thermoelectric cooling and power generating modules.

<http://www.sitechina.com/thermoelectric/home.html>

Teledyne Brown Engineering

Hunt Valley, MD

410-771-8600, FAX 410-771-8618 (3/04)

BiTe based generator manufacturer.

<http://www.teledyneenergysystems.com>

Thermoelectric Device Manufacturers & Distributors

ADV-Engineering

Moscow, Russia
7-095-239 9153, FAX 7-095-239 9153 (4/05)
Manufactures bismuth telluride ingots, wafers, pellets,
Peltier modules & thermoelectric cooling & generator devices.
<http://www.adv-engineering.com>

Beijing Huimau Cooling Equipment

Beijing, China
0086 13501215859, FAX 0086-10-60279837,60275767 (4/05)
Manufactures Peltier modules.
<http://www.huimao.com>

Cidete Ingenieros SL

Barcelona, Spain
34 938157003, FAX 34 938157003 (4/05)
Peltier module manufacturer.
<http://www.arrakis.es/~cidete>

Ferrotec (USA)

Nashua, NH
603-883-9800, FAX 603-883-2308 (4/05)
Manufactures thermoelectric modules.
Single & multi stage units, silicone edge seal available.
Operating temperatures as high as 200C.
<http://www.ferrotec.com>

Fujitaka, Nagaokakyo-shi

Kyoto, Japan
+81 75 955 9900, FAX +81 75 954 6122 (7/05)
Peltier module & assemblies manufacturer.
<http://www.fujitaka.com/pub/peltier/english/index.html>

Global Thermoelectric

Calgary, Alberta, Canada
403-236-5556, FAX 403-236-5575 (4/05)
Manufactures Lead Tin-Telluride thermoelectric power generators.
<http://www.globalte.com>

Hebei IT Shanghai

Shanghai, China
+86-21-58526062, FAX +86-21-58523251 (3/05)
Peltier module manufacturer.
<http://www.hebeild.com.cn/?p=peltier.module>

HiTech Technologies

Yardley, PA
800-755-4507, 215-321-6012, FAX 215-321-6067 (4/05)
Manufactures Bismuth Telluride thermoelectric modules.
Temperature ranges from -150°C to +200°C
<http://www.hitechtec.com>

Hi-Z Technology

San Diego, CA
858-695-6660, FAX 858-695-8870 (4/05)
Manufactures thermoelectric power generator modules.

<http://www.hi-z.com>

Infineon Technologies AG

Munich, Germany

+49 89 234 85481 (7/05)

Thin film peltier module manufacturer.

<http://www.micropelt.com>

Komatsu Electronics

Japan

81-463-22-8724, FAX 81-463-22-3692 (4/05)

Manufactures Bismuth Telluride thermoelectric modules, controllers, cold & hot plates, isothermal baths, gas dehumidifiers.

<http://www.komatsu-electronics.co.jp/english>

Kryotherm

Saint Petersburg, Russia

+7 812 394 1310, FAX +7 812 394 1267 (7/05)

Manufactures single & multistage Peltier modules, TE generators. Temperature range: -150°C - +200°C.

<http://www.kryotherm.ru>

Marlow Industries

Dallas, TX

214-340-4900, FAX 214-341-5212 (7/05)

Manufactures single & multi stage thermoelectric modules.

<http://www.marlow.com>

Osterm

Saint Petersburg, Russia

7-812-312-5732, FAX 7-812-571-5239 (7/05)

Manufactures thermoelectric modules.

<http://www.osterm.ru>

QUICK-OHM Kuepper

Wuppertal, Germany

+49-(0)202-4043-22, FAX +49-(0)202-4043-50 (7/05)

Peltier module distributor & system integrator, Supplier of heat transfer peripherals to Peltier modules.

<http://www.quick-cool-heattransfer.com>

RIF Corporation

Voronezh, Russia

+7-0732-316451, FAX +7-0732-704734 (7/05)

Peltier/Seebeck product manufacturer (modules and solutions).

http://www.rif.vrn.ru/product/thermo/index_.html

S&PF "Modul"

Kiev, Ukraine

+380 44 419 9030, FAX +380 44 464 7051 (7/05)

Manufacturer of thermoelectric modules and thermoelectric semiconductor materials.

<http://www.ukrainetrade.com/modul>

Seiko Instruments

Torrance, CA

310-517-8113, FAX 310-517-7792 (7/05)

Manufacturer of ultra-small Peltier element devices in either Sn-Sb or Sn-Cu material.

<http://www.siifiber.com>

Supercool AB

Goteborg, Sweden

+46 31-42 05 30, FAX +46 31-24 79 09 (3/04)

Markets TE modules. Manufactures thermoelectric assemblies, systems & temperature controllers
<http://www.supercool.se>

Taicang TE Cooler

Taicang City, Jiangsu, P.R.China
86-512-53426033, FAX 86-512-53429412 (7/05)
Peltier module manufacturer.
<http://www.taileng.com>

Taihuaxing Trading/Thermonamic Electronics

Xiamen P.R. of China
+86-592-5714012, FAX +86-592-5714010 (7/05)
Manufacturer of thermoelectric cooling & power generating modules.
<http://www.sitechina.com/thermoelectric/home.html>

Tellurex

Traverse City, MI
231-947-0110, FAX 231-947-5821 (7/05)
Manufactures thermoelectric heating/cooling modules
<http://www.tellurex.com>

TE Technology

Traverse City, MI
231-929-3966, FAX 231-929-4163 (7/05)
Manufactures thermoelectric cooler modules, assemblies, temperature controllers, TE module test systems.
<http://www.tetech.com>

Thermolyte

Salisbury, MD
800-843-5983, 410-546-8547, FAX 410-546-1291
Thermoelectric module manufacturer. Single & multistage, customs, low & high quantities. All available to 200°C.
<http://www.thermolytecorp.com>

Endnotes

- ¹ *Energy Use, Loss and Opportunity Analysis: U. S. Manufacturing and Mining*, December 2004, Energetics, Inc., E3M, Incorporated, Table 11-3, page 73
- ² <http://www.thermoelectrics.com/introduction.htm>
- ³ *Semiconductors are cool*, Cronin B. Vining, Nature 413, 577-578 (11 Oct 2001) News and Views
- ⁴ *Energy Use, Loss and Opportunity Analysis: U. S. Manufacturing and Mining*, December 2004, Energetics, Inc., E3M, Incorporated, page 10
- ⁵ Boiler flue gas temperatures are typically about 300°F. Most high-pressure boilers, which produce hotter steam, utilize economizers which result in similar exhaust temperatures.
- ⁶ Aluminum smelters typically operate at 960°C and an overall 40% thermal efficiency. Approximately 35% of the waste heat is lost to sidewalls. The remaining 65% is exhausted as waste gas. It requires approximately 2320 Btu/lb of aluminum produced. Annual U.S. production is about 8.5 (10⁹) lbs. This calculates to about 7.7 (10¹²) Btu/yr contained in the gases coming off the smelter.
- ⁷ Aluminum melting furnaces typically run at 750°C and their exhaust gases are also in this temperature range. The corrosive nature of the exhaust gases has hindered the use of recuperators for air or ingot preheating.
- ⁸ Cho, J., Anderson, M., Richards, R., Bahr, D., Richards, C. “Optimization of Electromechanical Coupling for a Thin-Film PZT Membrane: I. Modeling”, *Journal of Micromechanics and Microengineering*, **15** (2005), 1797-1803, Institute of Physics Publishing, United Kingdom.
- ⁹ Cho, J., Anderson, M., Richards, R., Bahr, D., Richards, C., “Optimization of Electromechanical Coupling for a Thin-Film PZT Membrane: II. Experiment”, *Journal of Micromechanics and Microengineering*, **15** (2005), 1804-1809, Institute of Physics Publishing, United Kingdom.
- ¹⁰ Schmidt, V.H., “Piezoelectric Energy Conversion in Windmills”, *Proceedings of IEEE Ultrasonics Symposium*, pp, 897-904, 1992.
- ¹¹ Kymiss, J., Kendall, C., Paradiso, J., and Gershenfeld, N., “Parasitic Power Harvesting in Shoes”, *2nd IEEE International Conference on Wearable Computing*, pp. 132-137, October 1998.
- ¹² Kasyap, A., Lim, J., Johnson, D., Horowitz, S., Nishida, T., Ngo, K., Sheplak, M., and Cattafesta, L., “Energy Reclamation From a Vibrating Piezoelectric Composite Beam”, *9th Annual Conference on Sound and Vibration*, Orlando, FL, pp. 36-43, 2002.
- ¹³ Xu, R., Trolier-McKinstry, S., Ren, W., Xu, B., Xie, Z.-L. and Hemker, K.J., “Domain Wall Motion and Its Contribution to the Dielectric and Piezoelectric Properties of Lead Zirconate Titanate Films”, *Journal of Applied Physics*, **89**, 1336-48, 2001.
- ¹⁴ Polla, D.L. and Francis, L.F., “Processing and Characterization of Piezoelectric Materials and Integration into Microelectromechanical Systems”, *Annual Review of Material Science*, **28**, 563-97, 1998.
- ¹⁵ <http://www.globalte.com/media/8550spec.pdf>
- ¹⁶ Annual Energy Outlook 2004 Supplemental Tables: Table 28, page 30.
- ¹⁷ *Glass Melting Technology: A Technical and Economic Assessment*, Glass Manufacturing Industrial Council, Oct 2004, page 15.
- ¹⁸ *Glass Melting Technology: A Technical and Economic Assessment*, Glass Manufacturing Industrial Council, Oct 2004, page 132.
- ¹⁹ *Energy Use, Loss and Opportunity Analysis: U. S. Manufacturing and Mining*, December 2004, Energetics, Inc., E3M, Incorporated
- ²⁰ *Energy Use and Energy Intensity of the U.S. Chemical Industry*, Worrell, Phylipsen, Einstein and Martin, LBNL, April 2000, page 24.

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- ²¹ *Characterization of the U.S. Industrial/Commercial Boiler Population*, Oak Ridge National Laboratory, May 2005, prepared by Energy and Environmental Analysis, Inc.
- ²² Proportioned from 3,300 TBtu based on AEO 20003 Commercial Sector Energy Consumption, page 40.
- ²³ Hendricks, T.J. and Lustbader, J.A., “Advanced Thermoelectric Power System Investigations for Light-Duty and Heavy-Duty Vehicle Applications: Part I,” *Proceedings of the 21st International Conference on Thermoelectrics*, Long Beach, CA, IEEE Catalogue #02TH8657, p. 381-386, 2002.
- ²⁴ Hendricks, T.J. and Lustbader, J.A., “Advanced Thermoelectric Power System Investigations for Light-Duty and Heavy-Duty Vehicle Applications: Part II,” *Proceedings of the 21st International Conference on Thermoelectrics*, Long Beach, CA, IEEE Catalogue #02TH8657, p. 387-394, 2002.
- ²⁵ Hendricks, T.J. and Lustbader, J.A., “Thermoelectric Energy Recovery Systems in Future Advanced Vehicles,” *Proceedings of the 6th ASME-JSME Thermal Engineering Joint Conference*, Japan Society of Mechanical Engineers, Paper #A4-334, 2003.
- ²⁶ Angrist, S.W., “Direct Energy Conversion”, 4th Ed., Allyn and Bacon, Boston, MA, 1982.
- ²⁷ Rowe D.M.,Ed., “CRC Handbook of Thermoelectrics” *CRC Press* Boca Raton, FL, 1995.