A Thermoelectric Generator Systems Forwaste Heat Recovery- A Review

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Abstract: **The focus of the study is to review the thermoelectric power generators for waste heat recovery. Thermoelectric power generators have emerged as a promising alternative technology due to their distinct advantages. Thermoelectric power generation offer a potential application in the direct conversion of waste-heat energy into electrical power. The thermoelectrics history, theory of thermoelectric concept and the parameter which governs the efficiency were discussed. A review of thermoelectric materials and future were discussed. A application of thermoelectric power generator for waste heat recovery, thermoelectric components and engineering needs and barriers were discussed and reviewed.**

Key words : Thermoelectric power,waste heat recovery, ZT,Efficiency.

1. THERMOELECTRICS HISTORY TIMELINE

Thermoelectrics have a long history of providing simple, reliable power generation solutions. In 1821Seebeck discovers that a circuit made from two dissimilar materials produced a voltage when their junctions were at different temperatures. It is later understood that a voltage will be induced in any material in a temperature gradient, known as the "Seebeck effect," which will be used to create thermoelectric power generators.In 1834Peltier discovers that passing an electric current through two dissimilar materials produces heating or cooling at their junction. This is known as "Peltier effect," and will later be used to make refrigerators. In 1854 William Thomson, also known as Lord Kelvin, finds that the Seebeck and Peltier effects are related, indicating that any thermoelectric material can be used to either generate power in a temperature gradient or pump heat with an applied current. In1909-1911 Altenkirch correctly derives the maximum efficiency of a thermoelectric generator (1909) and performance of a cooler (1911), which later developed into the 'thermoelectric figure of merit' z. In 1928 Ioffe begins to develop the modern theory of semiconductor physics in order to describe thermoelectric energy conversion. This opens up the understanding of how to engineer thermoelectric materials, as well as providing the basis for understanding the physics of transistors and microelectronics. In 1930 the first radio powered by thermoelectrics is publicized. In 1947 Maria Telkes constructs the first thermoelectric power generator with an efficiency of 5%. In 1954H. Julian Goldsmid cools a surface to 0° C using a thermoelectric Peltier cooler based on Bismuth telluride (Bi2Te3). In 1959Westinghouse unveils a fullsizehome refrigerator based on Bismuth Telluride Peltierthermoelectrics. While commercially unsuccessful, later thermoelectric refrigerators would becomeprevalent as wine coolers for homes. In 1959US President Dwight D. Eisenhower unveils the first Radioactive Thermoelectric Generator (RTG)"SNAP III," launched two years later in the first RTG equipped spacecraft, Transit 4A, to orbit earth as an avigational satellite. In 1968SNAP19becomes the first radioisotope thermoelectric generator to be flown on a NASA spacecraft afterthe simplicity and reliability of thermoelectrics prove to be the most viable way to generate powerremotely. Another thermoelectric SNAP generator makes it to the moon the next year. In 1970the first cardiac pacemaker powered by a miniature radioisotope thermoelectric generator, made byMedtronic, is implanted into a human in France.In 1975A group of entrepreneurs acquire Lead Telluride (PbTe) thermoelectric technology from 3M to produceremote terrestrial power generation products, forming Global Thermoelectric. In 1977NASA launches Voyagers 1 and 2 powered by MHWRTG3,a Silicon Germanium (SiGe) thermoelectric generator. In 1993Hicks and Dresselhaus publish a theory paper indicating that nanotechnology may offer significant advances in the efficiency of thermoelectric materials, ushering in the modern era of thermoelectrics. It would be nearly ten years before such improvements were shown experimentally, and twenty before they were incorporated into working systems. In 1995John Fairbanks at the US Department of Energy begins a program to develop thermoelectric generators for automotive engines after Porsche does a prototype study using Iron Silicide thermoelectric materials. In 1998Seiko introduces the Thermic watch, the first watch powered from body heat, which has in it a Bismuth Telluride thermoelectric generator. In 1999Amerigon (now called Gentherm) is founded by Dr. Lon Bell, Advisor to Alphabet Energy, and introducesthe first thermoelectric seat coolers in the Lincoln Navigator and Toyota's Lexus using Bismuth Telluride(Bi Te). In 2001RTI reveals the first significant breakthrough in thermoelectric material efficiency in forty years by using nano scale materials. Starting a new era of rapid advances in thermoelectric materials, nanostructures would be studied in many new thermoelectric materials systems.

Some of the modern materials for powergeneration include the Tellurides, Skutterudites, Half Heuslers, Silicides, and Silicon. In 2004The US Department of Energy (DOE), in conjunction with General Motors, BMW, Caterpillar, and others, fund a program for automotive thermoelectric generators that becomes the driving force for much of there search in the field of thermoelectric generators for the next several years.

At the same time, DOE also funds a program focused on new thermoelectric materials, led by Professor Arun Majumdar at UC Berkeley, which would eventually lead to the formation of Alphabet Energy. In 2008Alphabet Energy is formed in Berkeley, California by Dr. Matthew L. Scullin and Professor Peidong Yang to commercialize new breakthrough nano structured materials after licensing key patents and developing manufacturing schemes for modern nano materials. In 2013Voyager 1 becomes the first manmade object to exit the solar system and enter interstellar space after being continuously powered by a thermoelectric generator for 36 years. In 2014Alphabet Energy introduces the E1, the first ever ther moelectric generator for industrial wasteheatrecovery, and the most powerful thermoelectric generator ever built[1].

2. INTRODUCTION

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. Smaller self-powered systems such as thermoelectric-powered radios were first mentioned in Russia around 1920; a thermoelectric cli-mate-control system in a 1954 Chrysler automobile shows the scope of this technology[2]. Currently, millions of thermoelectric climate-controlled seats that serve as both seat coolers and seat warmers are being installed in luxury cars. In addition, millions of thermoelectric coolers are used to provide cold beverages. Even wristwatches marketed by Seiko and Citizen and biothermoelectric pace-makers are being powered by the very small temperature differences within the body or between a body and its surroundings. 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[2]. 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%[2]. 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.

3. THEORY OF A THERMOELECTRIC POWER GENERATOR

Thermoelectrics is defined as the science and technology associated with thermoelectric electricity generation (Seebeck effect) and refrigeration (Peltier effect). A thermoelectric generator is a solid state heat engine in which electron gas serves as the working fluid and converts a flow of heat to electricity. Thermoelectric generators have several major advantages including being highly reliable, having no moving or complex parts, being environmentally friendly, being maintenance free and silent in operation, having no position-dependence, having long life cycle (more than 100,000 hour steady-state operation), being light and having modular structure as well as adaptability for various sources and types of fuel. Simplest generator is consisting of a single thermocouple with legs or thermo elements made up from n-type and p-type semiconductors. In practice a large number of thermocouples are connected electrically inseries and thermally in parallel by sandwiching them between two high thermal conductivity but low electrical conductivity ceramic plates to form a module so called thermoelectric generator module (TEG) as shown in Figure

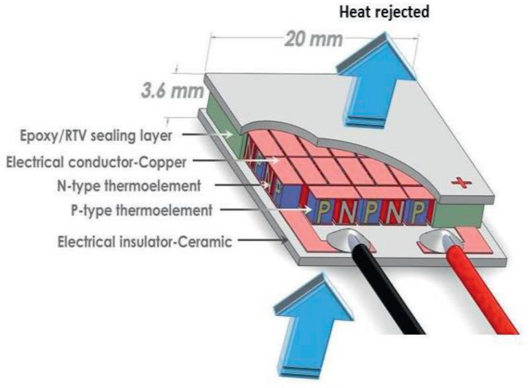

Figure 1: Schematic of a commercial thermoelectric generator module[4]

A module is the building–block of a thermoelectric conversion system and its general construction is very similar for both generation and refrigeration applications. Ideally the geometry of the thermoelements should be wire–like (long and thin) for generation and squat (short and fat) for refrigeration. Bismuth Telluride is the most common material available on the market. It is used for ambient temperature applications and is available at a reasonable price. New materials, such as clathrates, skutterudites, alloys Heusler, phases of Chevrel and oxides, offering great potential are currently being developed[4]. When heat flows through the thermocouples, the N-type semiconductors are loaded negatively (excess of electrons) and P-type components are loaded positively (excess of holes), resulting in the formation of an electric flow. The efficiency of a thermoelectric generator is defined as:

$$\eta = \frac{\text{delivered electrical energy(to the load)}}{\text{absorbed heat energy(from the hot side)}} [4]$$

Conveniently the efficiency can also be expressed as a function of the temperature at which it is operated and a so called ‘goodness factor’ or thermoelectric figure-of-merit of the thermocouple material Z.

$$Z=\frac{\alpha^2\sigma[4]}{\lambda}$$

Where $\alpha^2\sigma$ is referred as the power factor, $\alpha=\frac{\Delta V}{\Delta T}$ is the seebeck coefficient, σ is the electrical conductivity ($\Omega^{-1}m^{-1}$) and λ is the total thermal conductivity ($WK^{-1}m^{-1}$).

The figure-of-merit is often expressed in its dimensionless form, ZT, where T is absolute temperature (K). The highest measured ZT for a thermocouple fabricated from n-type and p- bismuth telluride known to be less than unity. However, in a few new materials it is possible to achieve a value greater than unity. The best measured value in a bulk material (such as skutterudite) Conversion efficiency for a thermoelectric generator, is given by:

$$\eta_{max}=\left[\frac{T_h-T_c}{T_h}\right]\left[\frac{\sqrt{(1+ZT_m)}-1}{\sqrt{1+ZT_m}+\frac{T_c}{T_h}}\right][3]$$

Where, T_h and T_c are the temperatures of the hot and cold side of the thermoelectric generator,
Respectively and Z is average figure-of-merit of thermo-elements and $T_m=\frac{T_h+T_c}{2}$ Interestingly, first fraction in the right hand side of above equation is Carnot efficiency[4]. The Figure 2 give an magnitude of the efficiency in relation to various ZTs and temperature differences

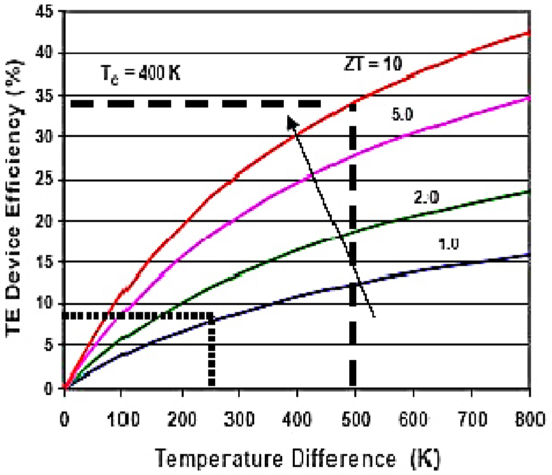

Figure 2: efficiency as a function of ΔT[2]

4. THERMOELECTRIC MATERIAL

As shown in Fig. 3a, the field of thermoelectric advanced rapidly in the 1950s where scientific basis of thermoelectric materials became well established. The first generation of thermoelectric materials,suchasBi_2Te_3, PbTe and SiGe bulk thermoelectric materials, were developed for application sat room temperature, intermediate temperature and hightemperature, respectively.Inthe1960s,theleadingmethodfor improving ZTwastocontroldopingandformsolidsolutions, such asBi_2Te_3–Sb_2Te_3, PbTe–SnTe,and$Si_{1_x}Ge_x$. Although point defectsinsolidsolutionsservetodecreasethelattice thermal conductivitybyincreasingheatcarryingphonons scattering, therewerealsoconcurrentreductionsinthecharge carrier mobility,therefore,theoverallZTenhancementis limited[6]. From1960to1990,thefieldofthermoelectrics received littleattention globally,inwhich$(Bi_{1-x}Sb_x)_2(Se_{1-y}Te_y)_3$ alloyfamily

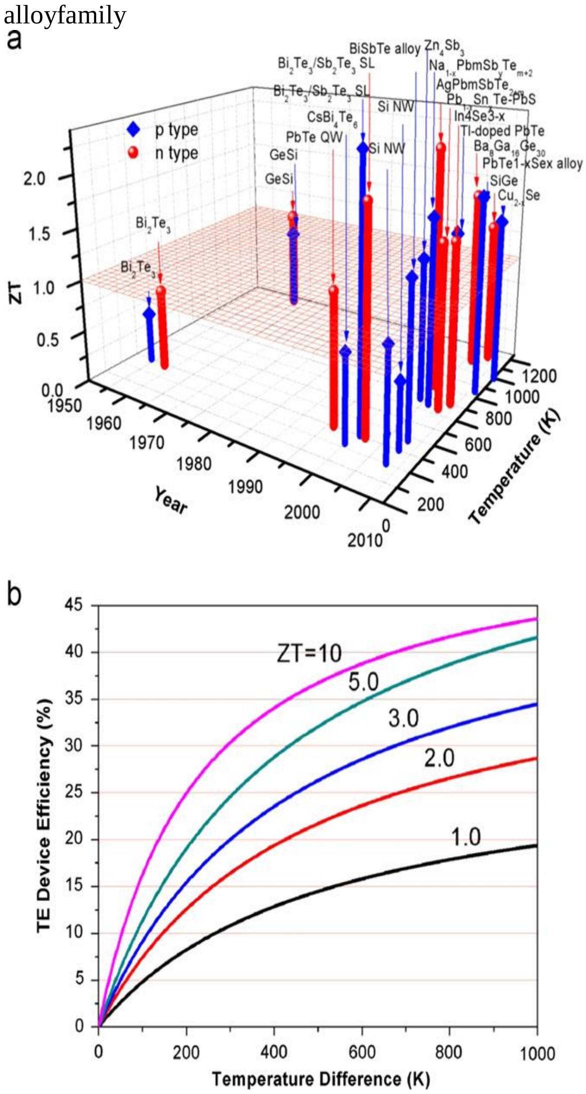

Figure 3(a) ZT as a function of temperature and year revealing the important development of thermoelectric materials. No material has yet achieved the target goal of ZT>3 to date; (b) Thermoelectric energy conversion as a function of ZT at the setting of T_c=300 K[6]

remainedthebestcommercialmaterialwithZT=1.In 1990s, thermoelectric community is encouraged to re-investigate advanced thermoelectric materials with high performance for thermoelectric power generation and cooling applications. For this reason, there is a revival of interest in the development of high-performance thermoelectric materials and the relevant thermoelectric theory. Over the past two decades, two different approaches have been developed to search for the next generation of thermoelectric materials: one is finding and using new families of bulk thermoelectric materials with complex crystal structures, and the other is synthesizing and using low-dimensional thermoelectric materials systems. Significant ZT improvement has been reported in the PGEC materials, and nanostructured materials, such as superlattices, quantum dots, nanowires, and nanocomposite. The key breakthroughs are highlighted in Fig. 1a.

Thermoelectric material which greatly affects the efficiency is of huge importance for thermoelectric power generation. Apart from the large Seebeck coefficient, good electrical conductivity, and small thermal conductivity, the thermoelectric materials must present excellent thermal and chemical stability at high temperature. The three factors α, σ and k are interrelated and make it quite challenging to optimize *ZT*. The high Seebeck coefficients are important for a good thermoelectric material. Nevertheless, an increase in α is almost always accompanied with a decrease in σ. Typically semiconductors and semimetals have higher α but lower σ than metals because of their rather lower carrier concentrations At room temperature, T = 300 K, desired values for the thermoelectric parameters are α = 225 μV/K, σ = 105 $\Omega^{-1}\cdot m^{-1}$, and k = 1.5 W/mK, which results in a $ZT \approx 1$[5]. These values are typical for the best *TE* materials such as Bi_2Te_3 and Sb_2Te_3 alloys, which are presently used by industry in devices that operate near room temperature and are well investigated. Current *TE* devices operate at an efficiency of about 5% - 6%. By increasing *ZT* by a factor of 4 predicted efficiencies can increase to 30% [5].

Current thermoelectric materials, as shown in Figure 4, have *ZT* = 1, and new materials with *ZT* values of 2 - 3 are sought to provide the desired conversion efficiencies. The current materials exhibit conversion efficiencies of 7% - 8% depending on the specific materials and the temperature differences involved.

Tirtt *et al*. proved that a value of *ZT* > 4 does not significantly increase the conversion efficiency over that of a material with *ZT* = 2 - 3.5 Therefore, they believed that the "Holy Grail" of thermoelectric materials research is to find bulk materials (both *n*-type and *p*-type) with a *ZT* value on the order of 2 - 3 (efficiency = 15% - 20%) with low parasitic losses (e.g., contact resistance, radiation effects, and inter diffusion of the metals) and low manufacturing costs[5]

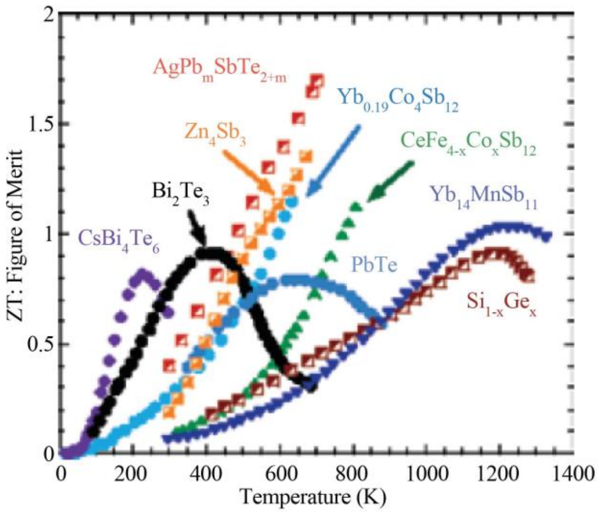

Figure 4.Figure of merit (*ZT*) as a function of temperature forseveral high-efficiency bulk thermoelectric materials[7]

5. DOMESTIC WASTE HEAT APPLICATIONS

Rowe reported that a waste heat-based thermoelectric power generator is used in a domestic central heating system with the modules located between the heat source and the water jacket. In this application, the heat output provided by the gas/oil burner passes through the generator before reaching the central heating hot-water exchanger. The generator converts about 5% of the input heat to electrical power, the remainder of 95% transfers to the hot water heat exchanger for its intended use in heating the radiator system. It was concluded that two modules based on PbTe technology when operated at hot and cold side temperatures of 550℃ and 50℃, respectively, would generate the 50W required to power the circulating pump. Waste heat energy can also be utilized proportionally from 20-50kW wood- or diesel-heated stoves, especially, during the winter months in rural regions where electric power supply is unreliable or intermittent, to power thermoelectric generators. For example in a thermoelectric power generator to produce electricity from stovetop surface temperatures of 100-300℃ was designed and evaluated. In this application, two commercially available thermoelectric modules were considered and 100W of electrical power output was targeted for a minimum domestic use. In this invention, the following general criteria for selecting thermoelectric modules for domestic waste heat application were considered: a high Z value; stability, and resistance to oxidation, sublimation, and evaporation; effective contact properties; non-toxicity; low component cost; and simplicity of design. When considering a wasteheat 'Parasitic' application, the primary criterion is a high power factor. Optimization requires a high power factor even at the expense of somewhat reducing Z. In this case, and given that the maximum temperature available on the stove surface is approximately 550 K, the modules options reported by for their design of the waste heat powered thermoelectric generator, include:

• $FeSi_2$. This has excellent stability at high temperatures and may be used in open flames. The power output is, however, too low to make this an interesting preposition.

• PbTe. But this offers no advantage in this temperature limited regime. In fact, in this range Bi_2Te_3 has an advantage in both power factor and Z as well.

• Use densely packed large area modules based on Bi_2Te_3. These may suffer somewhat from contact inadequacy leading to some power loss and could use some redesign for more power. They are limited to a maximum temperature of approximately 500-530K leading to a loss of some available heat. They appear costly per module at first.

• Use so-called high-temperature Bi_2Te_3 Peltier modulesin power generation mode. These suffer from optimization inappropriate for power generation. Additionally, being limited to a maximum hot temperature of approximately 450K requires significant attenuation and heat availability loss. While here the advantage in power factor over PbTe material is reduced (due to attenuation), it still exists.

In their invention, a simplified model of the generator was modeled using a 2-dimensional heat transfer program. Figure (5) shows a half-section of the generator model. The program assigns appropriate thermal conductivities to each material section as well as a convective heattransfer boundary condition to the top side. In their generator that can be used to convert waste heat into electrical power to drive an electronic chip. Model, typical thermal conductivity values were used for the materials such as aluminum, insulator, steel screws, Bi_2Te_3, and Al_2O_3. Furthermore, the conductive coefficient used was typical of forced air convection. Figure(6) shows the temperature profile through a section of the generator from the hot plate to the fin base. As shown in Fig. (5), the fixing screws present a significant heat leak path thus causing cold side temperatures to be high (and a resultant low T). It was concluded in that in practice, the situation is not as bad as presented in Fig. (6), since the model is only two-dimensional and it does not show the situation deeper within the generator. A similar application is reported in. In this application, thermoelectric power generators were used to generate small amounts of electrical power to remote regions for example Northern Sweden, as an alternative to costly gasoline powered engine generators. The generator uses heat from a wood burning stove with the cold side cooled with a 12 volt, 2.2W fan. The generator produces around 10 watts.

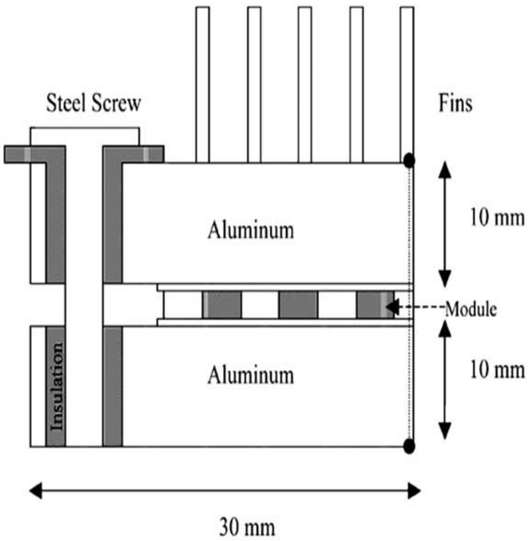

Figure 5. Model of single module generator test rig. Half the generator is seen and the view is at slice through the edge of the rig through the fixing screws. Dark parts represent insulation

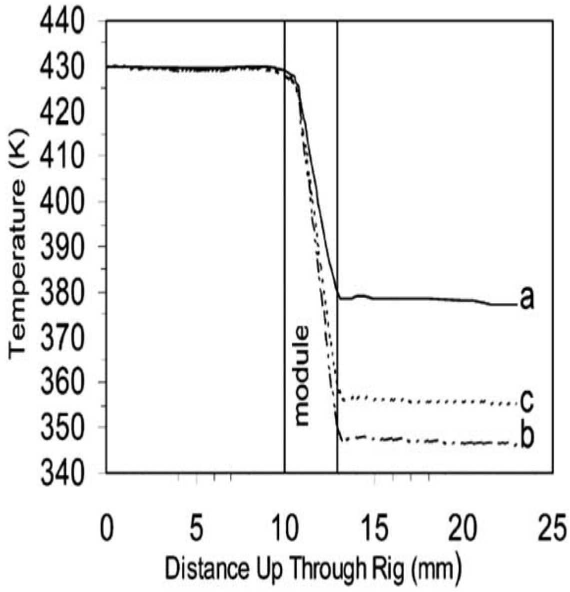

Figure 6.Temperature profile through center of single module generator from hot side via module to fin base. Convective coefficient *h* =100 W/m2K. (a) Aluminum screws and nuts with no insulating gasket above it. (b) Steel screws and nuts with an insulating gasket above it. (c) As in (b), but convective coefficient is 75 W/m2K [8].

6. 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.

		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**

Table 1: Thermoelectric waste heat opportunities in the U.S. industries[2]

7. WASTE HEAT FROM EXHAUST GASES OF I.C ENGINE

Benefits of ‘waste heat recovery’ can be broadly classified in two categories:

1. Direct Benefits: Recovery of waste heat has a direct effect on the combustion process efficiency. This is reflected by reduction in the utility consumption and process cost.

2. Indirect Benefits:

a) Reduction in pollution: A number of toxic combustible wastes such as carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) etc, releasing to atmosphere. Recovering of heat reduces the environmental pollution levels.

b) Reduction in equipment sizes: Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes.

c) Reduction in auxiliary energy consumption: Reduction in equipment sizes gives additional benefits in the form of reduction in auxiliary energy consumption [10].

Availability of Waste heat from I.C engines[9]:

Waste heat produced by fuel combustion or chemical reaction, and then “dumped” into the environment even though it may still be reused for some useful and economic purpose. Output energy from I.C engine is about 30 to 40% of the total heat and residual parts of the heat waste in the form of cooling, friction in bearing & exhaust gas of the engine. Waste heat losses from equipment in the form of efficiencies reduction and from thermodynamics limitations on equipment and process. It means about 60 to 70% energy losses as a waste heat through the engine, 30 to 40% in the form of exhaust gas, 30 to 40% waste energy in the form of cooling system. Temperature of exhaust gases immediately leaving the engine may have temperature in the range of 450-600℃. This temperature is low through recovery of exhaust gas and change into useful work and low temperature of exhaust gas in the environment. The literature is available on the Adsorption cooling with the exhaust gas heat of the engine. Consequently, these exhaust gases have high heat content, carrying away as exhaust emission. Efforts can be made to design more energy efficient through engine with better heat transfer and lower exhaust temperatures. However, the laws of thermodynamics place a lower limit on the temperature of exhaust gases

Waste Heat From Exhaust Gases Generated From Automobiles Applications[8]:

The utilization of waste heat energy from exhaust gases in reciprocating internal combustion engines (e.g. automobiles) is another application of electricity generation using thermoelectric power generators. Although a reciprocating piston engine converts the chemical energy available in fossil fuels efficiently into mechanical work a substantial amount of thermal energy is dissipated to the environment through exhaust gas, radiation, cooling water and lubricating oils. For example, in a gasoline powered engine, approximately 30% of the primary gasoline fuel energy is dissipated as waste heat energy in the exhaust gases; waste heat energy discharged in the exhaust gases from a typical passenger car travelling at a regular speed is 20-30 kW. A comprehensive theoretical study concluded that a thermoelectric generator powered by exhaust heat could meet the electrical requirements of a medium sized automobile. It was reported in that among the established thermoelectric materials, those modules based on PbTe technology were the most suitable for converting waste heat energy from automobiles into electrical power. Wide scale applications of thermoelectrics in the automobile industry would lead to some reductions in fuel consumption, and thus environmental global warming, but this technology is not yet proven. Since 1914 the possibility of using thermoelectric power generation to recover some of waste heat energy from reciprocating engines has been explored and patented. A schematic diagram showing this patent of converting waste heat into electrical power applied to an internal combustion engine using a thermoelectric power generator is shown in Fig. (9). In this invention, the exhaust gases in the pipe provide the heat source to the thermoelectric power generator, whereas the heat sink (cold side) is suggested to be provided by circulation of cooling water. More recently, Taguchi invented an exhaust gas based thermoelectric power generator for an automobile application. A schematic diagram showing this recent patent applied to an automobile for converting waste heat available in exhaust gases directly into electrical power using a thermoelectric power generator is shown in Fig. (10). In this patent, a pump supplies cooling water through each of cooling water circulation paths. The cooling water circulation path includes a cooling water pipe arranged along the exhaust pipe to pass the cooling water. At stacks a plurality of thermoelectric generation elements are attached to the exhaust pipe and the cooling water pipe successively in a direction from the upstream toward downstream of the exhaust gas. The cooling water pipe and the exhaust pipe pass the cooling water and the exhaust gas, respectively, in opposite directions so that the downstream stack has an increased difference in temperature between the exhaust pipe and the cooling water pipe, and the stacks provide power outputs having a reduced difference, and hence an increased total power output. This invention is proposed to provide increased thermoelectric conversion efficiency without complicated piping

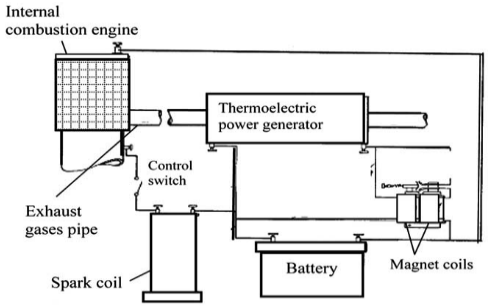

Figure 9. Schematic diagram showing early invention of converting waste heat into electrical power applied to an internal combustion engine using a thermoelectric power generator [8].

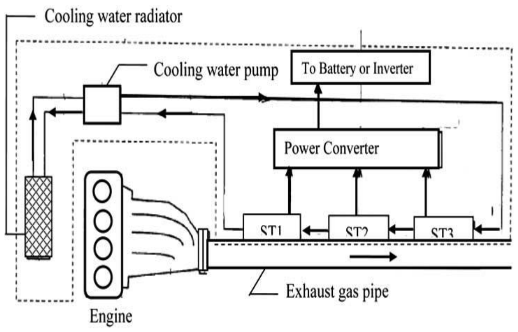

Figure 10. Schematic diagram showing a recent patent applied to an automobile for converting waste heat directly into electrical power using a thermoelectric power generator [8].

Ajay *et al*[11]in 2013 carried out the experiment for waste heat recovery from exhaust gases through I C Engine, 4 thermoelectric modules in series are used having operatingtemperature range of 60℃ to 180℃ and experiment is performed on these. When experiment is performed on engine exhaust pipe, this Thermoelectric Generator givesmaximum power of 0.9062 watt, this is low because hot side temperature was low and it was 83℃. So to get hot side temperaturehigher, a separate setup is fabricated and connection of modules was in same arrangement that is series arrangement.

In second setup max power produced was 1.72 watts with hot side temperature 178.2℃. So it is clear that power can be produced from waste heat of exhaust gases

from I C Engine.We know that Carnot efficiency is the maximum efficiency which can be achieved by any power producing engine andit is 12%, maximum for first setup and 20.2%, maximum, because Carnot efficiency is low then, generating efficiency

will be lower and this is 1.26%, maximum for first setup and 2.78%, maximum, for second setup. So to get higher power

and higher efficiency, high range thermoelectric module should be used.

8. THERMOELECTRIC CELLS COGENERATION FROM BIOMASS POWER PLANT:

Augusto Bianchini *et al* [12] carried out, the test facility has been configured to reproduce, in scale, the working conditions of a typicalbiomass power plant. Commercial thermoelectric cells (also named Seebeck cells) are characterized by direct low efficiency (upto 5%) conversion from thermal to electric energy.

Thermoelectrical material-Bismuth Telluride (n/p),Weight (g)-115,Module dimensions (mm)-75x75x5.08, Number of couples-N71Maximum hot operating temperature TH (°C)-250,Thermal conductivity λ (W/mK)-2.4,Internal electric resistance R (Ω) 0.3

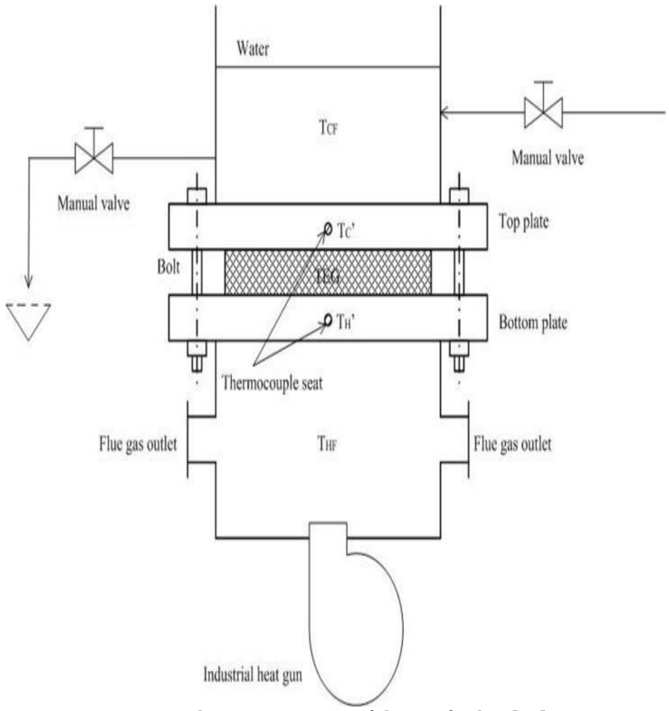

Figure 11 Schematic overview of the test facility [12].

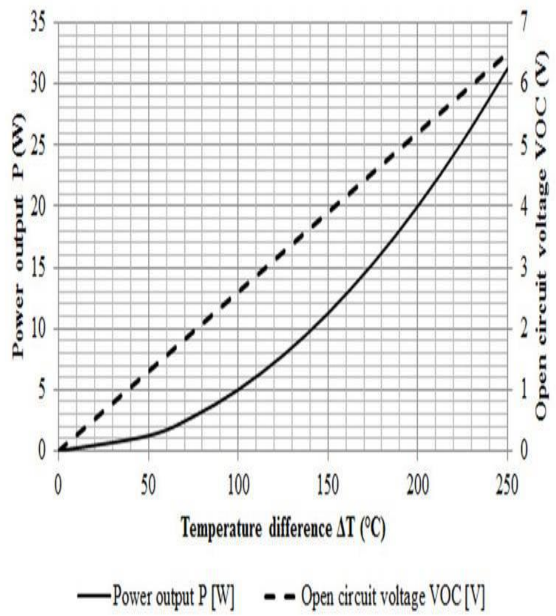

Figure 12. HZ-20 module power output P and open circuit voltage VOC as a function of temperature difference ΔT under matched load conditions[12].

9. WASTE HEAT RECOVERY FROM A MARINE WASTE INCINERATOR USING A THERMOELECTRIC GENERATOR(13)

A marine waste incinerator has been evaluated for waste heat harvesting using thermoelectric generators (TEG). The application has been evaluated using mathematical modeling to optimize the heat exchanger and some vital design parameters of the TEG. The calculation shows that it is possible to extract 58 kW_{el} at a price of 6.6 US$/W from an 850-$kW_{th}$ incinerator when optimizing for maximum power. However, minimizing the cost, it is possible to get 25 kW_{el} at a price of 2.5 US$/W. A trade-off between the two targets leads to a combination that gives 38 kW_{el} at a price of 2.7 US$/W.
A marine incinerator is primarily used to burn sludge. Sludge is a waste oil/water fraction from preparing heavy fuel oil before it is used in diesel engines on board ships. The incinerator is also used to destroy any solid waste generated on board, typically
from packaging and normal household waste. The heat from combustion is not used for electricity generation because of an intermittent running pattern and relatively small energy quantities. It is not used for heat because the heat demand on board is
well covered by an exhaust boiler on the main engine. Incinerators range in size from 2 m^3 to 16 m^3 and210 kW_{th} to 1500 kW_{th}. Approximately 2000 shipsare built every year with incinerators. In total,42,000 commercial ships larger than 300 dead weighttonnes and with propulsion power larger than 1 MW,not counting passenger and special operation ships,were in service in 2011 according to the Comprehensive
Ships, Companies & Ship Builders Database
from IHS Fairplay. It can beestimated, based on the total consumption of bunker
fuel,2 that 4.5 9 107 GJ of energy from sludge oil is incinerated every year on ships.
Typical operation costs of an incinerator amount to man-hours and electricity consumption, which is mainly due to the flue gas fan and varies with the size of incinerator. The smallest ones use less than
8 kW and the largest ones up to 40 kW. In addition there is some diesel consumption during the start-up phase of the incinerator. Typical operation is to run 8 h to 12 h a day with daily start-up and shut down in order to clean out ash from solid waste combustion. On some larger installations, more continuous operation is common. Normally,
the incinerators are dimensioned with excess
capacity to allow sludge produced in waters or ports where incineration is prohibited to be incinerated later. Ships have a seawater heat sink with average temperature of 5℃ to 30℃, depending on where they sail, readily available. The high combustion temperatures and efficient heat sink make incinerators ideal for TE-based waste heat recovery. An efficient steam turbine design would have a higher efficiency, but add significant man-hours to the ship because of daily start-up and shut down of incinerator and hence the steam system. As the cost of additional personnel is prohibitive on board a ship, the low-maintenance aspect of TE makes TEG attractive. TE incinerator design may be used for other incinerator applications such as land-based garbage
incineration or other high-temperature waste heat sources. However, if the hot gas is cleaner than the flue from marine incinerators, the heat exchanger can be made more efficient and cost and weight can
be reduced (Fig. 13).

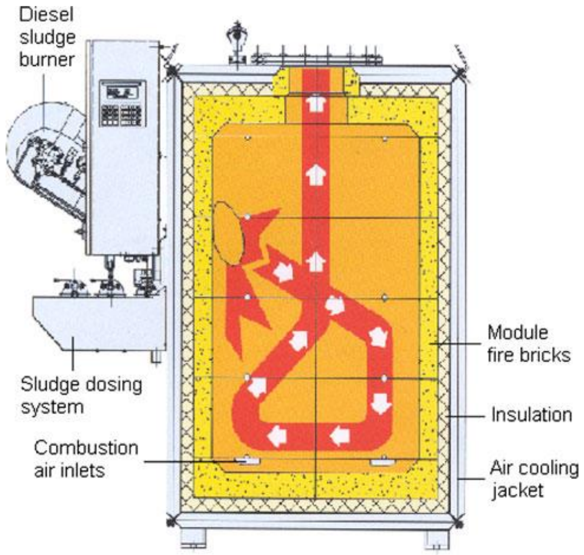

Fig.1. Diagram of a typical shipboard incinerator (13)

10. TEG COMPONENTS [14]

1. Thermoelectric Module

2. Thermoelectric shield

3. Thermal Fin

4. Copper electrode

1. Thermoelectric Module:It is semiconductor which is highly doped by pollutants to increase the electric conductivity of the semiconductor. Good semiconductor has electric conductivity in between 200µV/K - 300µV/K. When choosing semiconductor it has to withstand that much high operating temperature.

2. Thermoelectric Shield:It is a material which protects the modules damage due to high Temperature. Mostly Ceramics material for this which is Al_2O_3. It also transfer temperature to the modules from hot side. It should be thick.

3. Thermal Fin:It is used here for increase the thermal gradient value. When we increase the Thermal gradient value it increase the seebeck voltage generated by TEG.

This FIN also transfers the heat from Thermoelectric Module. It is made by Aluminum metal. When we include Thermal fin it increase the efficiency of the TEG

11. THERMOELECTRICSYSTEM DESIGN

This section discusses the TEG system requirements by focusing on the technical challenges and barriers to their use in the application. The discussion is intended to address and/or quantify the following [2]:

- 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

12. TEG SYSTEM ENGINEERING NEEDS AND 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 technical issues identified in this scoping analysis are as follows [2]:

• ZT ~ 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 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 ~ 2 properties that have recently been developed and characterized and new advanced TE materials with ZT ~ 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 ~ 1000°K.

• Manufacturing techniques for low-cost high-volume production of TE devices that incorporate the new, advanced TE materials (ZT ~ 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 ~ 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 ~ 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 ~ 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 [2]:

- Advanced TE materials development and manufacturing techniques to achieve ZT ~ 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.

13. CONCLUSION

Thermoelectric generator provides an opportunity for waste heat recovery from exhaust gas with higher temperature and flow rate. Still provision for waste heat recovery from steam power plant. Possibility for recovery of solar energy which is unavailable for photovoltaic conversion. By increasing ZT ~3 in future there is possible for commercial application for waste heat recovery from I C engine.

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