THERMOELECTRIC APPLICATIONS IN VEHICLES STATUS 2008

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INTRODUCTION

The direct conversion of heat to electricity was discovered, but not understood, by Thomas Johann Seebeck in 1821. He interpreted the phenomenon named after him (Seebeck effect) to be a magnetic rather than an electrical effect. He tested over 100 couples comprised of metals, oxides, minerals and several other compounds now referred to as semiconductors. Recent work with some of Seebeck's semiconductor couples were found to be about three (3) percent efficient in converting heat to electricity, which was about state of the art efficiency of steam engines during Seebeck's time. It would be another 50 years before electromagnetic generators driven by steam engines would emerge. Thus the opportunity for development of thermoelectrics in the early 19th Century was missed.

From Seebeck's day until the middle of the 20th Century, thermoelectrics were primarily used as thermocouples for measuring temperatures. In the early days of World War II Abram Ioffe developed thermoelectric semiconductor couples of roughly 3 percent efficiency when attached to the base of an operating oil lamp which produced enough power to operate a rudimentary radio. These systems were dispersed throughout rural Russia to maintain communications from Moscow.

In the latter half of the 20th Century, many major companies in the United States such as GE, Westinghouse, Texas Instruments, General Atomics, and the 3M Company, to name a few, initiated projects involving thermoelectrics. For years, the figure of merit (ZT), the measure of performance of a material for thermoelectric applications, has stayed below a value of 1. The inability to achieve commercially viable materials with ZT > 1 resulted in these organizations abandoning R&D in thermoelectrics.

Several small companies emerged for the thermoelectric niche market opportunities. Some were spin-offs from the larger organizations such as Marlow Industries from Texas Instruments and Hi-Z Technologies from General Atomics. These niche markets included power for interplanetary spacecraft to Antartica, submarines (for silent running), watches, water coolers, conversion of heat to electricity from household end heaters (primarily in remote locations), remote aids to navigation. cooling heat generating electronic devices , cooling computer chips to enable enhanced capacity, cooling/heating personal and others.

Up to the end of the century the best ZT was about 1 for Bismuth Telluride (BiTe), which translates to efficiencies of about 5 to 7 percent for most applications but falls off rapidly with hot side temperatures of over 230^{o}C. The thermoelectric ZT, which is directly related to electrical conductivity and inversely related to thermal conductivity, is limited for most bulk semiconductors because the ratio of their electrical conductivity to thermal conductivity as a function of temperature is essentially a constant.

Use of small particle size compacted material (nanocomposite approach) to reduce the lattice thermal conductivity by phonon-grain boundary scattering was postulated by D.M. Rowe in 1968 in his Ph.D. thesis [1]. Unfortunately, reductions in lattice thermal conductivity in small grain size compacts compared to large grain or single crystal material are in general accompanied by an unwanted reduction in electrical conductivity

Several nanoscale technology approaches, which broke through the "ZT<1 barrier", were analytically developed by a group at the Massachusetts Institute of Technology (MIT) led by Millie Dresselhauss [2] in the early 1990s. Shortly thereafter at least three organizations, MIT's Lincoln Laboratory, Research Triangle Institute (RTI), and Hi-Z Technologies reported thermoelectric materials developed in the laboratory [3, 4] with a nominal ZT>2. Progress in the ZT of thermoelectric materials is shown in Fig. 1, including public data reporting a ZT = 3.8 with a hot side temperature of 308^{o}C. This is an incredible advancement in roughly 10 years!

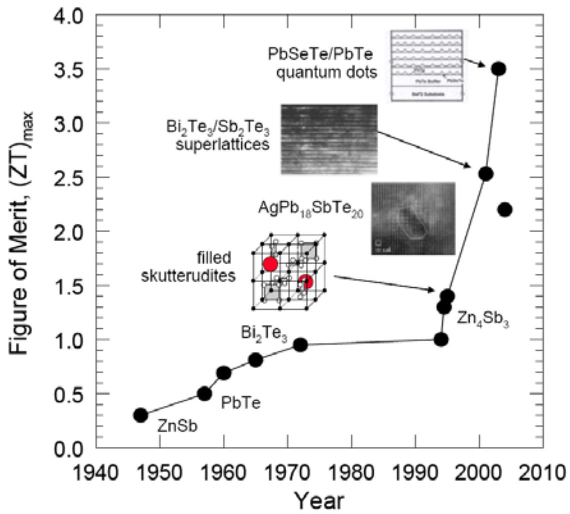

Figure 1. Progress in thermoelectric materials figure of merit, ZT.

With these advancements in ZT, there appears to be a great opportunity for thermoelectrics in the early part of this century for low grade waste heat recovery as well as for heating, ventilating, and air conditioning (HVAC).

VEHICULAR THERMOELECTRIC GENERATORS (TEGs)

Major impetuses for thermoelectric applications in vehicles are improved fuel economy (particularly in light of the recent rapid increase in fuel prices), and reduced regulated and greenhouse gas emissions. The roughly 17 million cars sold annually in United States alone presents an opportunity to establish a large-scale production base needed to make thermoelectrics cost-competitive. For example, Amerigon introduced their thermoelectric “Climate Controlled Seat” in 2001 and have sold over 5.4 million units to the auto industry. It is important to note that a thermoelectric device manufacturer is a qualified Tier 1 supplier to the automotive industry. Currently, there are other lower volume vehicular applications of thermoelectrics such as Peltier cooling in collision avoidance systems and cooling/heating of drink holders.

At about 1995 the U.S. Department of Energy (USDOE) initiated a project with Hi-Z Technologies to develop a thermoelectric generator (TEG) demonstrator to convert the waste heat from a heavy-duty Class 7-8 diesel engine directly to electricity. This unit used Bismuth Telluride cells and provided a nominal 1 Kw. This TEG was integrated with the muffler and was installed in a heavy-duty truck. Radiator cooling water (~110^{o}C) was used to extract the heat from the cold side of the TEG. The TEG was run for the equivalent of 550,000 miles on the PACCAR test tract. These data coupled with a first approximation analysis justified initiation of a competitive procurement to develop Thermoelectric Generators (TEG’s) for transportation vehicles, to either augment or replace the alternator.

Awards were made to three (3) teams in 2004 to develop TEGs. The teams developing automotive TEGs are: BSST with BMW, Visteon, Marlow, Virginia Tech, Cal Tech, University of Texas – Dallas, and Ford; GM is teamed with GE, the Oak Ridge National Laboratory, Brookhaven National Laboratory, University of Michigan, University of South Florida, and Virginia Tech. The team working with waste heat from a heavy-duty Class 7-8 truck diesel engine is headed by Michigan State and teamed with the Cummins Engine Company, NASA-JPL, Iowa State, and Tellurex. The objective of these projects is to provide a 10 percent improvement in fuel economy [5]. This is the same objective for the engine waste heat recovery projects developing bottoming cycles and electric turbocompounding, which involves adding a motor/alternator to the turbocharger shaft.

Since thermoelectric generators operate across a temperature difference, or “Delta T”, a commercial or pleasure boat with a thermoelectric hybrid propulsion system could trickle-charge the battery pack while the boat is moored or tied up dockside 24/7. Only a small circulating pump would be necessary. Underway this TEG would convert engine exhaust waste heat to electricity. In fact, Professors Paul Wlodkowski and Richard Kimball along with a group of students are pursuing this concept at the Maine Maritime Academy in Castine, Maine. This boat with the location of the TEG is shown in Fig. 2.

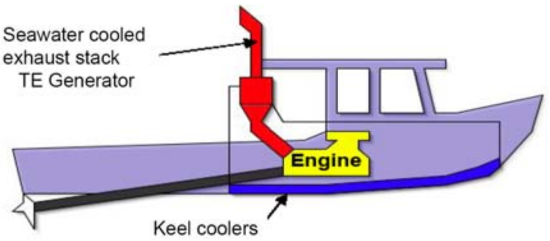

Figure 2. Exhaust heat recovery thermoelectric generator on a boat.

As the thermoelectric figure of merit, ZT, or better yet, ZT average over the temperature range of interest is significantly increased with modules available at commercially viable cost and in large quantities, there will be a second generation of vehicular TEGs. While the 1st generation TEGs augmented or minimized the size and/or time of operation of the alternator, the 2nd generation TEGs will replace the alternator. They will not only be in the engine exhaust but also on the radiator or on a single radiator combining the cooling requirements of the engine and the lube oil cooler. The exhaust gas recirculation (EGR) loop is an additional candidate.

Vehicles will be “more electric” with more of the current belt driven off the engine accessories operated with electric motors. Electrical requirements will increase with stability control, collision avoidance, steer-by-wire, electronic braking, electronic entertainment systems, enhanced computer controls, and additional electrical systems undefined at this time.

When ZT average materials > 3.0 become available, we can think of replacing the internal combustion engine with a thermoelectric hybrid with a dedicated combustor. Thermoelectric cells would be mounted concentrically around this combustor and a coolant loop concentric to the thermoelectric modules. Cells would be selected for the temperature gradient in the combustor surface. Combustion temperatures would be < 1,000°C so formation of oxides of Nitrogen (NO_x) would be minimal. This combustor could be configured to burn any liquid fuel, gaseous, or pulverized solid (coal, corn, wood, etc.) fuel (see Fig. 3). It would probably need a particulate trap. .

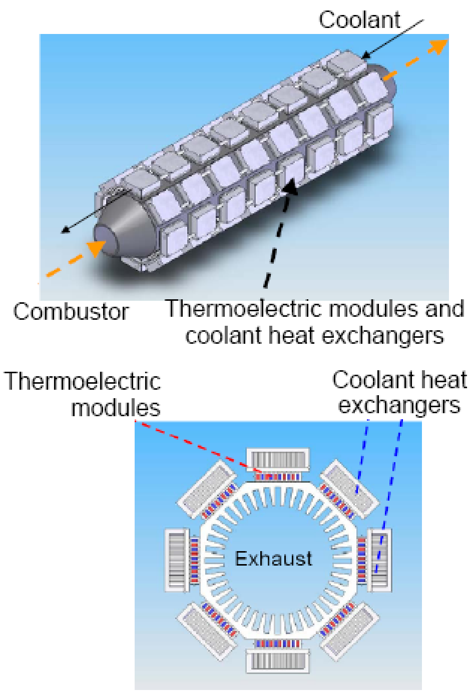

Fig.3 Possible Multi TEG Fuel

In the long term, towards the 22nd

Century after post peak petroleum use, radioisotope power generation with ZT > 5.0 thermoelectric modules might make an automotive radioisotope thermoelectric generator (RTEG) hybrid powertrain a reality. As these systems are successfully operating in deep space exploring spacecraft for 35 years, we might anticipate similar service life. They will be expensive but the vehicle body, be it a bus or personal vehicle, could be replaced over the powertrain every 5 years or so.

TEG PROJECT STATUS

The U.S. DOE TEG projects have been underway since 2004. The design challenges include the wide range of excursions of the engine exhaust gas temperature, from ambient to 800°C, maintaining optimal thermal conductivity with the TE modules while accommodating the thermal and mechanical stresses as well as long cycle fatigue.

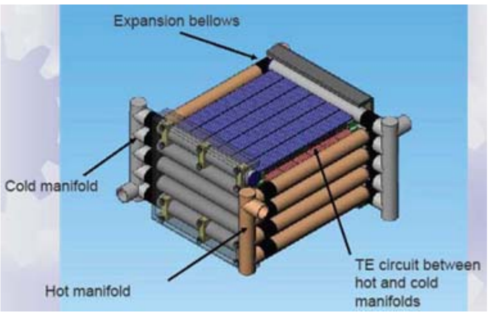

Figure 4. TEG system packaging.

Design engineers need to know the modules current-voltage output as a function of the applications thermal excursions. The assembled TEG must meet the mechanical and thermal stresses anticipated in the application. Maintaining maximum electrical contact throughout the service life is vital. Performance models had to be developed. The initial approach for the BMW Series 5 employed a heat transfer fluid to ameliorate the exhaust gas thermal variations. While this system had packaging advantages, it was cost effective to place the TEG in direct thermal contact with the exhaust gas and a counterflow liquid cooling loop connected to a dedicated radiator. A low temperature advanced Bi_2Te_3 subassembly is shown in Fig. 4.

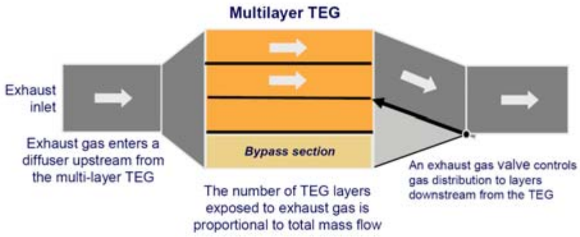

Figure 5. New system architecture.

The TEG was divided into 3 banks installed in parallel to the exhaust flow. Each bank has TE modules selected to for their best match to the temperature range. A downstream exhaust gas valve controls the exhaust gas distribution (see Fig. 5). Thus at start up, or low power, this valve would divert all the exhaust to the layer with the highest TE efficiency at the low temperature diverted exhaust.

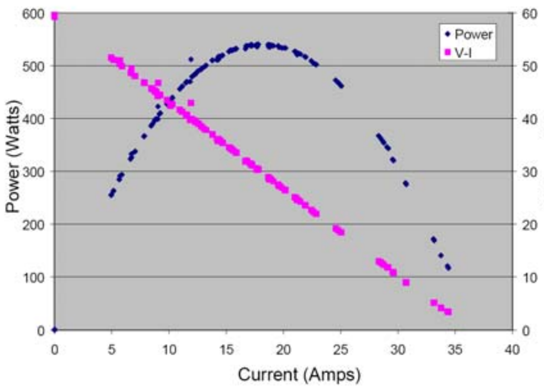

Figure 6. Performance of 500W TEG

The performance of the 500 W TEG with a Delta T = 207°C is shown as Fig. 6. The installation of the TEG in the BMW is shown in Fig. 7.

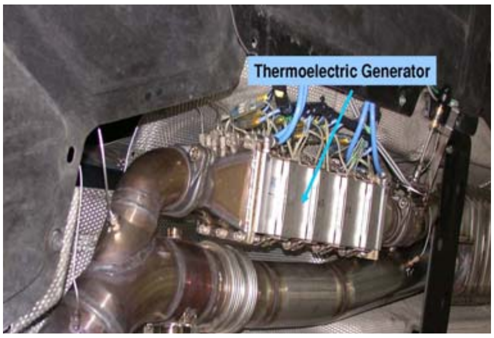

Figure 7. Installation of TEG in the BMW

VEHICULAR THERMOELECTRIC HVAC SYSTEMS

There has been a recent surge in interest in thermoelectric heating, ventilation and air conditioning (TE HVAC) for all vehicles but especially for the plug-in hybrid electric vehicles. Consider the Chevy Volt as representative of these emerging vehicles. The Volt can be fully charged by plugging into a household 110 volt socket for about 6 hours. It can then run for 40 miles before it has to kick in its small 3-cylinder engine which will directly charge the battery pack.

Maintaining occupant comfort during hot or cold weather using a minimal amount of energy is a problem for hybrid vehicles. Heating can be done with the effective but very inefficient resistive heaters. Conventional air conditioning requires an electrically driven compressor using a refrigerant gas which would run off the battery. This approach would seriously reduce the battery only operating range.

There is also concern about the global warming contribution of conventional mobile air conditioners [6]. The dominant refrigerant gas used in vehicles since the early 90s is R-134a which replaced the Freon gas that adversely affected the ozone layer. However, R-134a has 1,300 times the global warming potential of carbon dioxide (CO_2). The European Union (EU) is proscribing R-134a from new model cars in 2010 and all new cars in 2017.

Cooling/heating using currently available thermoelectric materials could provide significant advantages compared with current systems for improved fuel economy, reduced toxic and greenhouse gas emissions. TE HVAC systems could be designed to take best advantages of thermoelectrics. Compact thermoelectric units can be installed in the seats, dashboard and overhead for the driver and the front seat occupant. Units can be installed in the back of the front seats, the overhead, seats and floor. These units can be devised to only cool or heat the person, not the whole cabin. The driver can be cooled with less than 700 watts of cooling whereas current air conditioners provide up to 3,500 to 4,000 watts. TE HVAC can be converted from air conditioning to heating by simply changing the polarity of the DC power. The TE HVAC system can be remotely activated 50 meters or so from the vehicle. The thermoelectric modules are silent with no moving parts. However, the TE HVAC system would have fans and a coolant loop circulating pump to remove the heat from the modules and to a heat exchanger to disburse the heat. It is anticipated that the TE HVAC systems will require far less maintenance than current compressed refrigerant gas systems.

ADDITIONAL POTENTIAL THERMOELECTRIC APPLICATIONS

As the TEGs and TE HVAC systems are introduced in vehicles, the volume should result in lower cost and greater availability of thermoelectrics for an extended range of applications. This should also significantly enhance support for development of more efficient thermoelectrics and commercially viable fabrication. TEGs should be next considered as candidates for buses, off-highway vehicles, and locomotives. A near term opportunity is for an auxiliary power unit (APU) for heavy-duty trucks as 78,000 of them in the U.S. use power lift off-loaders which run off battery power. Anti-idling ordinances prevent running the propulsion engine to charge the battery. A small space heater with thermoelectric modules could keep the battery charged sufficiently for this operation. A battery typically at its thermal "sweet spot" for optimized efficiency and service life; this could readily be maintained in hybrid vehicles with thermoelectrics. A candidate concept for battery thermal management is shown in Fig. 8.

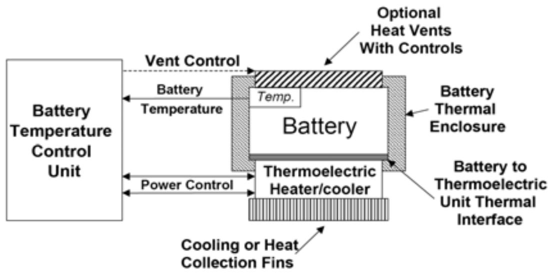

Figure 8. Schematic of a battery temperature control system.

Thermoelectric household refrigerators will gain an ever increasing market share as Peltier thermoelectric modules exceed a coefficient of performance (COP) of 2.0 with competitive costs. Thermoelectrics would allow compartments within the refrigerator to be held at a temperature that would optimize the life of the commodity. For example, fruit such as bananas maintained at 52^{o}F could be kept fresh for 3 weeks.

Solar concentrators focused on thermoelectric arrays could provide electric power at parking lots for plug-in hybrids. High ZT thermoelectrics could challenge photovoltaics for a wide range of household and commercial applications. Thin film high efficiency thermoelectrics could bonded to the back of solar cells and either air or liquid cooling could be applied to the thermoelectric cold side. Solar cell efficiency is typically an inverse function of temperature so the thermoelectric thin film converting conducted heat to electricity would be concurrently reducing the solar cell temperature.

Many homes use solar energy to heat water in rooftop coils. This activity could be enhanced with solar concentrators. Flat plate thermoelectric modules could be installed such that the exiting hot water provides the T_{hot} and the cooled water would be routed through the TEG back to the solar heater. In colder climes the solar heating coils could be encapsulated in a greenhouse effect structure to optimize solar energy and minimize convective heat transfer losses. Thermoelectrics may become the most effective approach for geothermal energy conversion to electricity.

Thermoelectrics present possibilities of recovering electricity from energy intensive industrial processes. Converting waste heat to electricity in the aluminum process should reduce the cost of aluminum such that it could be considered for mass market vehicles. Currently Jaguar, Aston Martin and Audi A-8 have aluminum frames and bodies which reduce vehicle weight by about 500 pounds. Oak Ridge National Laboratory has empirically developed a rule of thumb that a 10 percent reduction in vehicle weight improves fuel economy by 5 to 7 percent.

SUMMARY

As we are completing the first decade of the 21st Century the world is beginning to understand the ramifications of the finite limit of fossil fuels. Thermoelectrics Generators and HVAC can significantly improve fuel economy. The role of thermoelectrics in reducing greenhouse gases could well be very important in the global climate scheme of things. As module efficiency improvements are achieved, thermoelectrics will challenge photovoltaics in many applications or possibly be combined with them. Thermoelectrics will have an expanding range of both commercial and household applications as efficiencies improve and costs are reduced Let’s not overlook the possibilities with thermoelectrics in the early 21st Century as Seebeck’s peers did in the early 19th Century.

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