Abstracts

SESSION 4 – Waste Heat Utilization

Chair: **John Fairbanks, U.S. Department of Energy**

Aaron Yocum, National Energy Technology Laboratory

Challenges and Opportunities in Thermoelectric Energy Conversion

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Thermoelectric devices are attractive for energy conversion because they are solid state containing no moving parts and, in particular for power generation, they are not fuel-specific, allowing them to be environmentally benign. Despite these advantages, a key drawback that has prevented them to be widely adopted is their performance – they generally operate below 10 percent of the Carnot limit, which makes them at least 2-3 times less efficient than macroscopic engines and refrigerators. At the heart of this issue is the lack of thermoelectric materials with sufficiently high figure-of-merit, ZT, which is defined as $ZT = S^2\sigma T/k$, where S is the thermopower or Seebeck coefficient, σ is the electrical conductivity, k is the thermal conductivity, and T is the absolute temperature. For the performance of thermoelectric devices to be about 30 percent of the Carnot limit, one must develop materials with $ZT > 3$. Five decades of research has increased room-temperature ZT of bulk semiconductors only marginally, from about 0.6 to 1. The challenge lies in the fact that S, σ, and k are interdependent – changing one alters the others, making optimization extremely difficult. The only way to reduce k without affecting S and σ in bulk materials is to use semiconductors of high atomic weight such as Bi_2Te_3 and its alloys with Sb, Sn and Pb. High atomic weight reduces the speed of sound in the material, and thereby decreases the thermal conductivity. Although it is possible in principle to develop bulk semiconductors with $ZT > 3$, there are no candidate materials in the horizon. Over the last few years, however, there has been a surge of interest in thermoelectricity driven primarily by discoveries of room-temperature $ZT > 1$, with claims even as high as 2.4. While there is debate over the exact values, producing materials with $ZT > 1$ can be considered a significant milestone. What has caused this sudden increase in ZT? The common feature in these studies is the use of nanostructures: the materials either contain superlattices or quantum dots. This talk will discuss the state of our understanding of how and why nanostructures increase ZT and if there is the possibility of developing materials with $ZT \approx 3$.

Development of an Underarmor 10 Kilowatt Thermoelectric Generator Waste Heat Recovery System for Military Vehicles

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Hi-Z Technology, Inc.

Hi-Z Technology describes the preliminary design and development of a 10 kilowatt quantum well thermoelectric generator waste heat recovery system for military vehicles. This work is performed under the Armies Tank-automotive & Armaments Command funding and builds on quantum well materials and generator development supported by the Department of Energy (DOE) and a gasoline Automobile Exhaust Thermoelectric Generator (AETEG) supported by New York State Energy Research and Development Authority (Clarkson University prime), DOE, and Hi-Z. A preliminary design of a quantum well thermoelectric generator has been developed that can convert waste heat of a Caterpillar 3126 Diesel into electricity while an Army Stryker vehicle is underway, and can also act as auxiliary power unit (APU) to provide quiet fuel efficient operation while a Stryker vehicle is parked. When parked the thermoelectric generator will use a logistic fuel burner and control system.

Hi-Z presents the preliminary design for the thermoelectric generator to fit into the extremely compact space under the armor of an Army Stryker vehicle. This design is based on predictions showing how quantum well material properties and module configuration can augment the performance of current experimental thermoelectric generators tested in the exhaust of Diesel and gasoline engines. This quantum well waste heat recovery thermoelectric generator is predicted to provide four to five times higher electrical output than conventional thermoelectric materials in the same Stryker vehicle exhaust stream and its available space. Data is presented for current generators ranging from 200 W to 1 kW. Predictions show how this quantum well thermoelectric electrical generator performs under load and APU conditions; and its dependence on module design, quantum well material properties and thickness, and hot side vehicle exhaust and cold side heat transfer.

Progress Report for Scale-up of Multilayer Thin Film Thermoelectric Materials for Vehicle Applications

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Thermoelectric devices offer significant promise for utilization of waste heat from lean burn engines and industrial processes. While these devices can convert waste heat directly into electrical energy, the same device can also be used for cooling with application of a direct current (Peltier effect). Multilayer thin film thermoelectric junctions have recently demonstrated promise by way of high conversion efficiency (>10%), but large scale cost-effective fabrication, high efficiency in arrays of junctions, as well as engineering of modules remain to be demonstrated. This project was specifically undertaken to determine the feasibility of fabricating large area multilayer thin film thermoelectric material with the desired thermoelectric properties.

We will report on the development of and recent progress in scale up of Si/ $Si_{0.8}Ge_{0.2}$ and B_4C/B_9C thin film multilayer structures for thermoelectric generator applications, and particularly, fabrication of large quantities of these materials. The scale up of the magnetron sputtering process is proceeding on two fronts: (1) deposition on standard and ultra thin Si wafers and (2) deposition on noncrystalline substrates. Doping with Ge is essential to obtain high conductivity B_4C/B_9C material. Multilayer films with up to 1000 layers were deposited onto substrate areas as large as 0.5 m^2. Initial studies showed that the power factor of these films was ~ 0.06 - high enough to produce a ZT significantly greater than 1. Deposition of TE thin films on noncrystalline substrates is critical for use in functional devices and low cost TEG. Initial progress on noncrystalline substrates is encouraging and will be reported, but an order of magnitude improvement in power factors is required to make them viable for TEG applications. To date, we have deposited Fe-Si/ Fe-$Si_{0.8}Ge_{0.2}$ multilayers with power factors of ~ 0.005 on glass and aluminum oxide substrates. The estimated costs of large area films will also be discussed.

The Effects of an Exhaust Thermoelectric Generator on a GM Sierra Pick-up Truck

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Madhav Karri, Brian Helenbrook, and Eric Thacher
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Clayton J. Richter
Delphi Corporation

A liquid-cooled, exhaust-driven thermoelectric generator (TEG) for use with a 1999 GM Sierra pick-up truck has been designed and built. The TEG consists of an exhaust gas heat exchanger that is surrounded on both sides by 8 HZ-20 thermoelectric modules (developed by Hi-Z Technology Inc.) and two coolant heat exchangers. The modules are connected in series and provide their output to a power-conditioning unit that is connected to the truck's electrical bus. The TEG system is designed to provide 330 Watts to the bus thus reducing the electrical load on the alternator and improving the fuel efficiency of the truck.

In cooperation with Delphi Corporation, extensive testing has been performed on the modified truck. The data from these tests will be presented at the conference. In the tests, data have been taken from both the baseline truck and the modified truck that allow the following to be assessed:

- the net increase in fuel efficiency provided by the TEG
- the additional power consumed in the coolant pumping loop
- the importance of insulating the exhaust to maintain exhaust temperatures
- the effect of coolant temperature on the TEG power
- the efficiency of the power conditioning unit
- back-pressure effects of the TEG on the truck
- the effect of the vehicle's electrical load
- the effect of ambient conditions
- the environment seen by the TEG during operation
- temperatures and pressures throughout the system

Using this information important factors will be discussed for improving the TEG system performance.

Status of the Application of Thermoelectric Technology in Vehicles

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Amerigon Incorporated

Over the last four years, Amerigon's climate control thermoelectric (TE) cooling/heating system has come into broad usage in the automobile and light truck markets. This is the first large-scale, consumer-driven, application of TE systems to the global vehicle market. Over 2,000,000 TE modules (4 per vehicle system) are installed in passenger cars and light trucks. The control climate system (CCS) system has proven to be reliable and durable in the field, and exhibits stable operation after exposure to the environments associated with use in cars and light trucks. Tests in both the laboratory and direct field experience confirm the capability of the CCS system to meet the requirements of the vehicle industry.

Focus group studies by vehicle manufacturers and Amerigon show that performance is superior to that of other competitive technologies, such as pure ventilation (without active cooling), heating alone (heated seat systems) or systems that duct air from the vehicle's HVAC system into the seat. Field experience to date also has been very favorable, with the installation take rate 50 to 100 percent higher than comparable seat heater installation rates. Consumers have determined that the added value of the cooling feature is both important as a benefit, and the cost increment over heated seats is worth the added cost of the combined cooling/heating system. The technology is becoming available on an increasing number of vehicle lines. The associated installation and demographic growth trends are presented.

Prospects for additional applications of advanced TE systems for cooling/heating, other temperature control usage, and waste power generation are discussed briefly in light of the present state of TE material technology and the impact of new developments in the field. Long-term societal needs for emission reduction and greater fuel efficiency, are opening opportunities for solid-state TE systems since they interface well with other advanced components including electronic fuel controls, power management systems, and electrical power storage systems. The trend toward further electrification of passenger vehicles offers additional opportunities for TE systems because of their ability to interface directly with other electronic subsystems. Thereby avoiding the energy conversion losses associated with the power conversion to mechanical work associated with subsystems that employ electric motors, actuators, or pumps for operation. Finally, the opportunity for use in newer vehicle types (such as hybrid, fuel cell, and electric powered vehicles) is discussed. These long-term trends match well with the properties of TE systems, and thus TE usage can be expected to continue to increase as larger numbers of advanced vehicles come to market.

Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

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A cooperative program between the Department of Energy Office of Heavy Vehicle Technology and Caterpillar is aimed at demonstrating fuel consumption reduction using electric turbocompound (ETC) technology on a Class 8 truck engine. The goal is to demonstrate a 5 percent reduction in fuel consumption. Electric turbocompounding (ETC) is a way to recover exhaust heat energy and return it to the driveline. The system consists of a turbocharger with an incorporated electric motor/generator on the turbo shaft. The generator extracts the surplus power at the turbine and feeds it back to a crankshaft mounted electrical motor. The electric turbocompound system also provides more control flexibility in that the amount of power extracted can be varied. This allows for control of engine boost and thus air/fuel ratio.

This presentation will report progress to date on the technology demonstration program. Design and analysis of components, control system, and the ETC system will be reviewed. Design features and test results of the motor/generator will be shown. Results of turbocharger gas stand testing will be shown as well as test results of the complete ETC system on a heavy-duty Caterpillar on-highway truck engine.

Regulated 2-Stage (R2S™) Charging System for High Specific Power Engines

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The proportion of turbocharged engines is increasing from year to year. Passenger car Diesel engines are virtually all operated with an exhaust-gas turbocharger. While the boom in turbocharged engines is chiefly attributable to the lower pollutant emissions which must be complied with for current and future emission legislation, it is also attributable to the clear consumption advantages and thus, reduction in carbon dioxide emissions which the European auto industry has obligated itself to comply with. In addition, vehicles with modern turbocharged engines provide a great deal of driving enjoyment due to a very advantageous torque curve.

Now that the exhaust-gas turbocharger with variable turbine geometry (VTG) has become established as the state of the art for the Diesel engine, it is evident that certain limits to the charging system exist. Higher starting torques at lower engine speeds and, simultaneously, increasing rated power output lead to a more aggravated conflict of goals.

Regulated 2-stage turbocharging (R2S™) is an obvious choice for solving this conflict of goals. It offers the option of increasing both starting torque and rated power output. This article compares engines using VTG and R2S™ with respect to their performance potential. Along with the engine's rated power output and the starting torque, differences in transient engine operation will also be investigated.

Special importance is attached to the system design owing to the use of two turbochargers instead of one turbocharger with VTG. This article will also discuss control of the complex charging system with at least two anticipated bypasses.