IV Waste Heat Recovery

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IV.1 Diesel Engine Waste Heat Recovery Utilizing Electric Turbocompound Technology

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Objectives

- Configure laboratory engine that demonstrates technical feasibility
- Improve fuel economy with goal of 5% cycle improvement from exhaust energy recovery

Approach

Caterpillar's experienced research team has chosen the following approach to develop an electric turbocompound (ETC) system:

- Conceive turbocharger and system design from concept design to preliminary design and final design
- Analyze and test components
- Develop and test turbomachinery and electrical machinery
- Design, analyze and test control system
- Bench test overall ETC system on the engine

Accomplishments

- Gas stand results of the turbomachinery have been analyzed
- Detailed on-engine test procedure developed
- On-engine testing of ETC system conducted
- Post-test failure analysis completed
- Final report written

Future Directions

Caterpillar completed this project during FY 2005. Future work on electric turbocompound may continue as part of the Exhaust Waste Heat Recovery Program.

Introduction

Turbocompounding is a known technology for reducing fuel consumption. Research projects for truck-size diesel engines revealed a potential of 5% brake-specific fuel consumption (BSFC) improvement [1]. Diesel engines for ship propulsion and stationary power generation have shown BSFC improvements in the same order. However, those systems consisted of a turbocharger plus an additional power turbine, which was mechanically connected to the crankshaft.

Research efforts at Caterpillar are now focusing on the development of an electric turbocompound (ETC) system for heavy-duty on-highway truck engines. The efforts cover concept, design and test. A cooperative project between DOE and Caterpillar is aimed at demonstrating ETC technology on a Class 8 truck engine.

The goal is to demonstrate the technical feasibility and improve fuel economy. The system consists of a turbocharger with an electric motor/generator (M/G) integrated into the turboshaft. The generator extracts surplus power at the turbine, and the electricity it produces is used to run a motor mounted on the engine crankshaft, recovering otherwise wasted energy in the exhaust gases. 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 (A/F). The research work covered turbocharger design, system and component analysis, control system development, engine simulation, electrical machinery development and system and component testing.

Approach

A multi-disciplinary approach has been used in order to address the following key development areas: aero design, electrical machine design, engine performance, control system, structural analysis, and test.

The layout of the ETC turbocharger is a mid-mount configuration, i.e., the electrical machine is located between the compressor and the turbine wheel. For the compressor and turbine stages, high-performance machines were chosen.

The selection of the electrical machine was mainly driven by high shaft speeds and packaging constraints. Three basic machine types were compared: switched reluctance (SR), synchronous reluctance and brushless permanent-magnet (PM). The constraints of shaft speed, rotor outside diameter (OD), low centrifugal stresses, rotor inertia and cost lead to the choice of a SR machine.

The control system manages power flux and communication between the engine and the ETC controller. A schematic of the system is shown in Figure 1. When the power produced by the turbocharger turbine exceeds the power requirement of the compressor, this surplus power is converted into electrical power by the electrical machine located on the turbocharger shaft. Surplus power at the turbine can be recovered by the ETC system through an electric motor, mounted on the crankshaft, which assists the engine. The result is an increase in system efficiency. Alternatively, the surplus power can be used to drive other electrical on-board devices or it can be stored. To improve vehicle driveability, the system can be run in turbo assist mode, i.e., electrical power can be used to accelerate the turboshaft and increase engine intake air pressure.

Results

Gas stand test results have been completed and analyzed. Compressor efficiencies were approximately 3% lower than predicted – the cause was high clearances on the compressor end of the assembly. The clearance is controlled by a

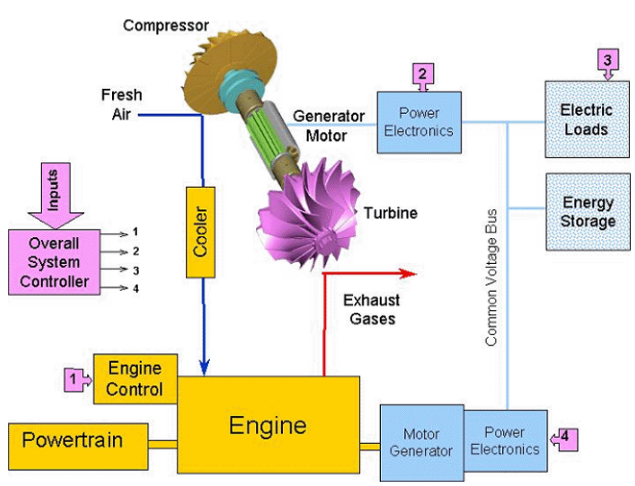

Figure 1. Electric Turbo Compound Schematic

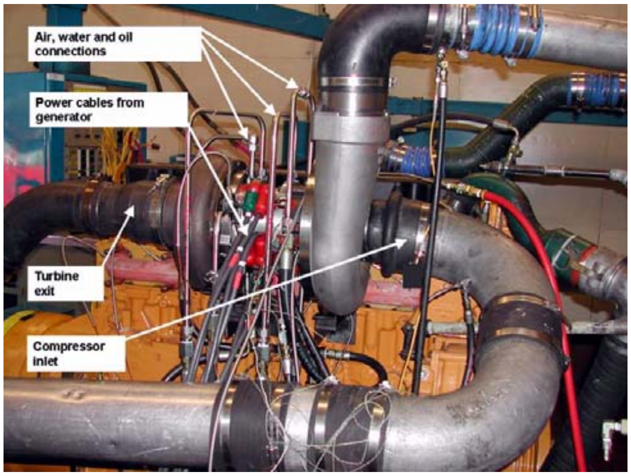

Figure 2. ETC Assembled On-Engine

complicated balance of spring and aerodynamic forces in the current design. Long-term this would be corrected with a shaft-system redesign, but for purposes of engine testing it was corrected with simple shimming.

Turbine efficiencies were very close to the target, while turbine swallowing capacity was 15% higher than predicted. The error in swallowing capacity is within the current predictive capacity of the turbo design codes and is easily corrected with a restaggering of the turbine nozzle ring.

A detailed plan for the on-engine testing was put together to try to minimize risk of hardware failures. The baseline C15 production engine was tested at 13 engine operating points, and then the engine was converted to the ETC configuration (see Figure 2). The engine was tested at an engine speed of 1,500 rpm and 25% and 50% load points. At these operating points, the engine ran in compounding mode and power was generated at the turbo shaft and recovered with the motor on the crankshaft. Since the focus was on debugging of the electronics and control system, no engine performance data was taken during this initial testing. Unfortunately, shortly after these points were tested the turbocharger suffered a bearing failure which prevented further testing.

The compressor-end bearing failure (see Figure 3) was caused by a rotor imbalance, likely due to a shifting in the rotor endplate, which was discovered upon disassembly.

Figure 3. Failed ETC Compressor Bearing

Conclusions

A turbocharger and ETC system have been designed and built. The system was tested on the gas stand, demonstrating excellent rotordynamic stability and aerodynamic efficiencies close to the target values. The turbo generator met the speed and power generation requirements; while its efficiency was lower than the target value, a technical path to improve the generator performance has been identified.

Compared to a mechanical system, Caterpillar's novel ETC system offers more flexible engine operation, e.g., A/F control and turbo assist mode. Performance predictions for the engine cycle indicate 3 to 5 percent improvement in fuel consumption. The system offers the potential for reduced emissions and improved driveabilty through improved air system response using the turbo assist capability.

FY 2005 Publications/Presentations

1. Algrain, M.: "Controlling an Electric Turbo Compound System for Exhaust Gas Energy Recovery in a Diesel Engine". IEEE Electro Information Technology Conference, 22-25 May, 2005, Lincoln, Nebraska

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1. Caterpillar Inc.: "LE55", internal research paper, 1982

IV.2 Thermoelectric Technology for Automotive Waste Heat Recovery

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Objectives

- Quantify the effect of reduced generator load and increased vehicle weight on the fuel economy of representative vehicles.
- Optimize superlattice-based and superlattice/bulk segmented/cascaded thermoelectric (TE) devices.
- Develop cost-effective, high-efficiency thermoelectric materials.

Approach

- Vehicle-level computer simulations of the effect of reduced generator load and increased vehicle weight on fuel economy of representative vehicles.
- Design, fabrication, and testing of superlattice-based and superlattice/bulk segmented/cascaded thermoelectric devices.
- Synthesis, structural analysis and transport property measurements of cost-effective, high-efficiency thermoelectric materials.
- Synthesis and structural analysis of new type I clathrates, filled skutterudites, and nano-structured bulk materials.

Accomplishments

- Quantified the effect of reduced generator load and increased vehicle weight on the fuel economy of representative vehicles, and evaluated suggestions for possible methods of achieving fuel economy gains using thermoelectric technology.
- Achieved ~2 W output power for superlattice-based TE devices and 13% energy conversion efficiency for superlattice/bulk segmented/cascaded TE devices.
- Demonstrated cost-effective, high-efficiency thermoelectric materials.

Future Directions

- Evaluation of thermoelectric properties of type I clathrates, solid solution-based skutterudites, and nano-structured bulk materials.
- Optimization of superlattice-based thermoelectric devices.
- Development of bulk material-based thermoelectric devices.
- Economic feasibility study of automotive thermoelectric waste heat recovery technology.

Introduction

The kickoff meeting of this project was held on May 23, 2005, in the DOE headquarters. In the past five months, the project has made progress in the following areas: vehicle-level simulations on the impact of generator load and weight on fuel economy of representative vehicles; development of superlattice-based thermoelectric devices consisting of 2x2 modular arrays, as well as some fine-tuning of the 4x4 modules; development of superlattice/bulk segmented/cascaded thermoelectric devices; synthesis and measurement of properties of cost-effective, high-efficiency TE materials; synthesis of doped type I clathrates, La-filled solid solution-based skutterudites, and nano-structured bulk materials; and development of high-temperature electrical resistivity and Seebeck coefficient measurement apparatus.

The vehicle-level fuel economy studies are critical components of this initial stage of the project. They could help us to identify methods of improving fuel economy using TE waste heat recovery, to quantify the effect of reduced generator load and increased vehicle weight on fuel economy of representative vehicles, and therefore, to make initial selection of vehicle platforms for this technology development. The development of superlattice-based devices would form the basis for radiator (low temperature) TE waste heat recovery subsystems. The effort on development of high thermoelectric figure of merit (ZT) and low-cost bulk materials could lead to cost-effective and highly efficient exhaust (high temperature) TE waste heat recovery subsystems.

Approach

Vehicle-level fuel economy studies were carried out using the Overdrive simulation tool internally developed by General Motors (GM) [1]. Overdrive solves systems of ordinary differential equations that approximate the rigid body dynamics of the vehicle. The output from the simulation is a set of parameters that reflect vehicle performance, fuel economy, drive quality, and energy management [1]. These simulation tools have been used for many of GM's past and future vehicles.

Superlattice-based and superlattice/bulk segmented/cascaded TE modules are being developed to achieve high energy conversion efficiency and high output electric power by focusing on interface contact materials, fabrication methods, processes, etc. High ZT and low cost have been the focal points of bulk materials development. High-temperature TE property measurement validations were achieved by measuring standard Bi_2Te_3-based materials, and comparing data from low-temperature and high-temperature measurements.

Results

The overall objective is to achieve a 10% improvement in fuel economy. This can be accomplished by getting an additional 10% power from the TE generator at any given engine steady-state operating point (speed, torque). A typical vehicle electrical load according to the EPA Federal Test Procedures is about 300 W. Figure 1 shows the dependence of fuel economy (FE) on electrical load (EL) at the alternator for a group of representative cars and trucks in the 0 to 600 W load range. These results were generated by the Overdrive simulation tool [1]. These data illustrate that if the 10% fuel economy goal is to be achieved, then more electrical power will have to be produced than is consumed by the vehicle electrical system under most driving scenarios.

This leads to several choices: (1) reducing electrical accessory load on the alternator using thermoelectrically generated power; (2) shifting

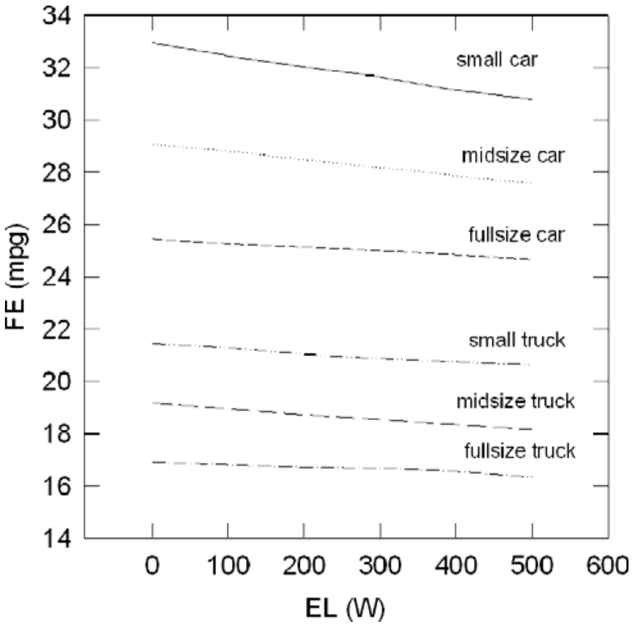

Figure 1. Dependence of Fuel Economy on Electrical Load at the Alternator for Representative Cars and Trucks

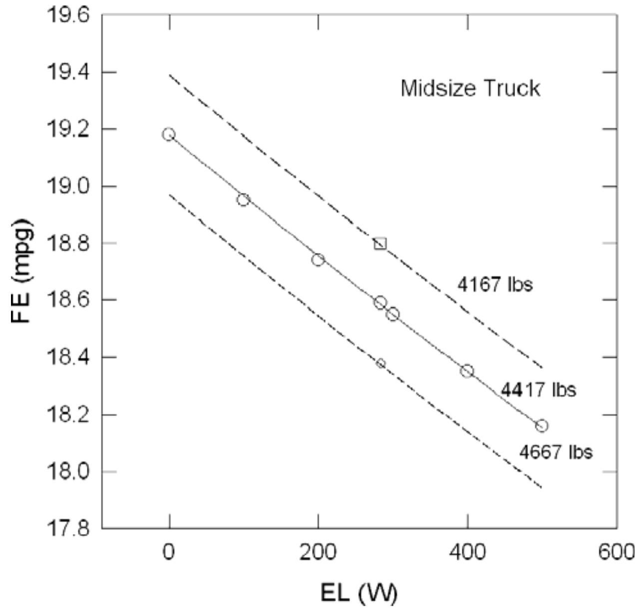

Figure 2. Dependence of Fuel Economy on Electrical Load at the Alternator for a Midsize Truck at Various Weights (The symbols are data simulated by Overdrive, and the lines are guides for the eye.)

some of the engine-driven accessories to electrical drive to raise the electrical accessory load consumption; or (3) attempting to use the excess electrical power for something other than the vehicle electrical load, such as propulsion. Examples of choice (2) include electric power steering, electric coolant pump, electric cooling fan, oil pump assist, electric valve actuation & timing, electric heating for catalytic converters, etc. The use of electric power steering or coolant pump alone, for example, could result in 2-3% or 3-5% fuel economy improvements, respectively [2]. It has also been determined through modeling and experiments that electric heating of catalysts could save energy relative to using additional fuel in an effort to bring the catalysts to their operation temperatures in a timely fashion. Choice (3) is easily adaptable for hybrid vehicles. It is difficult to estimate the fuel economy gains for a TE augmented hybrid before detailed information on packaging, electrical interface, mechanical interface, control interface, powertrain, etc, are available. Because the excess electrical power is used directly for vehicle propulsion, this choice potentially has the largest fuel economy gains amongst the three. In order to achieve the 10% fuel economy improvement goal, a combination of choices mentioned above should be used. It should be pointed out that fuel economy improvement technologies are not necessarily additive.

It is also important to keep in mind that the addition of a TE waste heat recovery unit would increase the overall vehicle weight and, therefore, reduce fuel economy. Figure 2 shows the dependence of fuel economy on electrical load at the alternator for a midsize truck at various weights. The truck weighs 4417 lbs with 18.6 mpg EPA composite rating; a 10% fuel economy improvement means 1.86 mpg improvement. Based on internal analysis, a benchmark target that the mass penalty should generally not exceed 5% of the 1.86 mpg gain was established. Data in Figure 2 indicate an 1190 lbs/ Δmpg mass penalty; the total mass of a TE generator for this truck should therefore be below ~111 lbs.

RTI has integrated 4x4 superlattice (SL) devices into multi-modular arrays (MMAs) for production of the power necessary to accomplish our deliverable goal. The MMA fabrication was undertaken, and an example of the completed device can be seen in Figure 3. The first 2x2 MMA constructed used SL devices based on 150 m contacts on the n-type elements and 100 m contacts on the p-type elements.

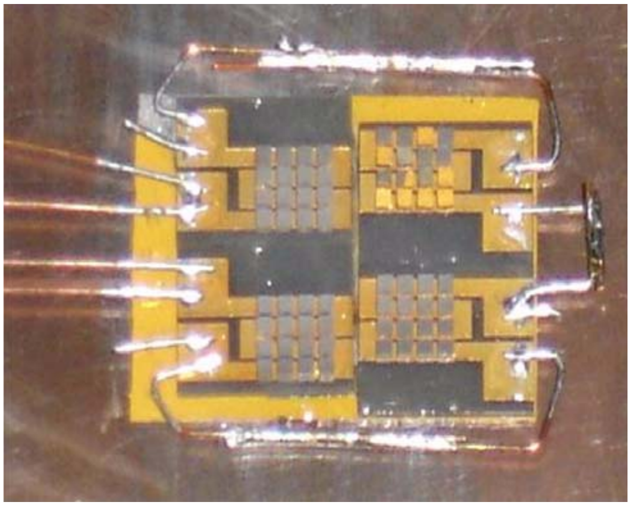

Figure 3. 2x2 Multi-Modular Array Consisting of Four 4x4 Superlattice Devices

The output power from an optimized MMA is close to 2 Watts. This is a tremendous step forward for our SL module power capabilities. Even with this grand result, we believe the performance could be further optimized.

RTI also began work on the bulk segmented devices by constructing multi-couple modules to build on the success of the single couples, with >500 mWatts per couple and with >13% energy conversion efficiency. It would necessitate only four couples to achieve a 2+ Watt device output. To this end, variations on achieving 2x2 arrays of bulk/segmented couples were undertaken. This type of bulk device is shown in Figure 4.

GM has synthesized a class of low-cost, high-efficiency thermoelectric materials. The structural and chemical analysis of these materials has indicated good homogeneity of the samples, and preliminary transport property data have shown that these materials have similar TE properties as those of the parent compounds. USF synthesized and characterized the structural and chemical properties of four type I clathrates based on a possible route for improving TE properties of type I clathrates [3]. The X-ray diffraction data of the specimens indicate they are phase-pure type I clathrates. Transport measurements and analysis are currently underway. UM completed synthesis of La-filled solid solution-based materials in an effort to further improve the TE properties of filled skutterudites. The transport

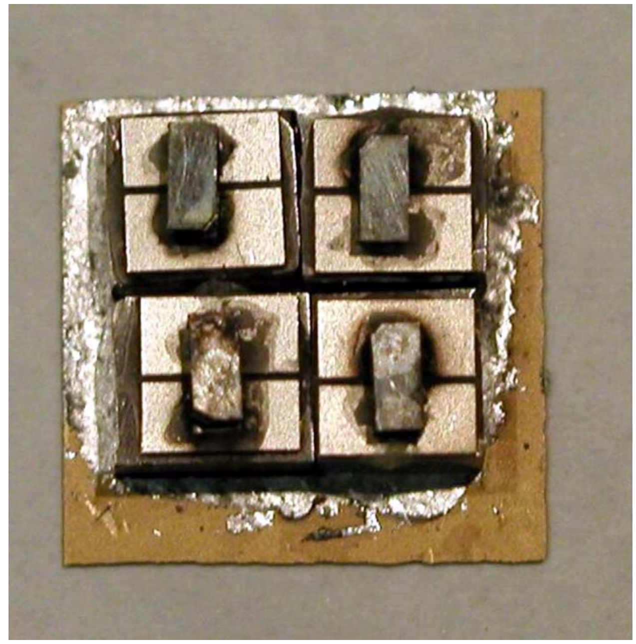

Figure 4. Bulk/Segmented 2x2 Device

properties of these materials are being measured. Synthesis of nano-structured bulk materials is underway at RTI.

One of the issues of thermoelectric material testing is that small specimens have to be prepared. While a small specimen is required for low-temperature testing, this is not the case for high-temperature measurements. To minimize heat loss, high-temperature thermal diffusivity testing requires a thin disk specimen, typically 0.5 inch in diameter and 1 mm thick. For electrical resistivity and Seebeck measurements, another small specimen is usually needed. One of our tasks for setting up standard testing procedures of bulk thermoelectrics is to make it possible to test all three properties on the same specimen. Using an existing Hot Chuck probing station, ORNL upgraded the system to perform 4-probe electrical resistivity measurements. The new system uses spring-loaded high-temperature probes and can be used to measure electrical resistivity from room temperature to 800 K. The system was installed and passed initial testing in October, 2005. The room-temperature resistivity measurements on GM specimens matched with the values obtained by the Physical Property Measurement System very well. The same high-temperature hot stage system is being tested for Seebeck coefficient measurements. Bulk

Figure 5. ORNL Room-Temperature (left) and High-Temperature (right) Testing Equipment

thermoelectric specimens from GM and USF have been undergoing testing for thermal diffusivity and specific heat at ORNL. Figure 5 shows pictures of room-temperature and high-temperature testing apparatuses.

Conclusions

We have made significant progress in the areas of assessing the impact of reduced generator load and increased weight on the fuel economy of several representative vehicles, fabrication and testing of superlattice-based and superlattice/bulk segmented/cascaded thermoelectric devices, and development of cost-effective TE materials. We have also initiated materials research efforts in new type I clathrates, solid solution-based skutterudites, and nano-structured bulk materials. High-temperature materials property measurement equipment has been set up at ORNL.

Special Recognitions & Awards/Patents Issued

1. J. Yang – elected to the board of directors of the International Thermoelectric Society, June, 2005.

FY 2005 Publications/Presentations

1. J. Yang, “Potential Applications of Thermoelectric Waste Heat Recovery in the Automotive Industry”, invited talk at the 24th International Conference on Thermoelectrics, June 2005, Clemson, SC, USA; also in Proceedings of 24th Intl. Conf. on Thermoelectrics (Pennington: IEEE, 2005), p. 155.
2. J. Yang, “Opportunities & Challenges of Thermoelectric Waste Heat Recovery in the Automotive Industry”, 2005 Diesel Engine Emissions Reduction (DEER) Conference, Chicago, IL, August 2005.

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2. www.pierburg.com.
3. J. Martin, S. Erickson, and G. S. Nolas, P. Alboni, T. Tritt, and J. Yang, “Structural and Transport Properties of Type I Silicon-Germanium Clathrates”, submitted to J. Appl. Phys.

IV.3 High-Efficiency Thermoelectric Waste Energy Recovery System for Passenger Vehicle Applications

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National Renewable Energy Laboratory, Golden, CO
Jet Propulsion Laboratory, Pasadena, CA
Purdue University, Purdue, IN

Objecives

The objectives of this project are as follows:

- Phase 1- Model a system architecture and subsystem equipment to demonstrate 10% fuel efficiency improvement
- Phase 2- Build and test subsystem equipment to validate performance models
- Phase 3- Iterate subsystem designs to optimize performance and integrate the system less the vehicle engine
- Phase 4- Integrate the subsystem equipment and vehicle engine and demonstrate performance on a dynamometer at the National Renewable Energy Laboratory's (NREL's) facilities in Golden, Colorado

Approach

- The BSST-led team selected BMW’s newest and most efficient gasoline internal combustion engine and a vehicle platform timeframe of 2010-2012 to provide a realistic environment coinciding with the timing of system readiness.
- Exhaust temperatures and mass flows were evaluated from BMW data over city and highway drive cycles to help develop subsystem equipment and the overall system architecture. It was determined that the most efficient system would be one that included a means for transporting and controlling the flow of thermal energy to the thermoelectric generator module (TGM) to manage wide variations in exhaust mass flow over typical driving conditions.
- The guiding principles for the project are:
  - First, to demonstrate technology viability, and second, to show a path to commercial feasibility.
  - To reasonably optimize each subsystem element to give the best practical performance without limitations due to system interfaces/constraints.
- Subsystem equipment is modeled (typically in MATLAB) to predict performance.
- Subsystem models are integrated into a “bumper to bumper” vehicle system model (AVL’s ADVISOR) to enable static and dynamic modeling of driving conditions, including Federal drive cycles used for fuel economy determination.

Accomplishments

- A system architecture was conceived and modeled using AVL's ADVISOR that features exhaust gas waste heat recovery via a primary heat exchanger (PHx), thermoelectric power generation in a thermoelectric generator module (TGM) and various liquid cooling loops to present a cold sink to the TGM and provide for engine preheating opportunities to further increase fuel efficiency (Figure 1). Power electronics were modeled featuring energy storage and DC/DC conversion to optimize system efficiency.
- In Phase 1, the vehicle simulation model predicted a reduction in fuel consumption of 8% to 12½% (depending on system configuration) and a corresponding reduction in emissions.

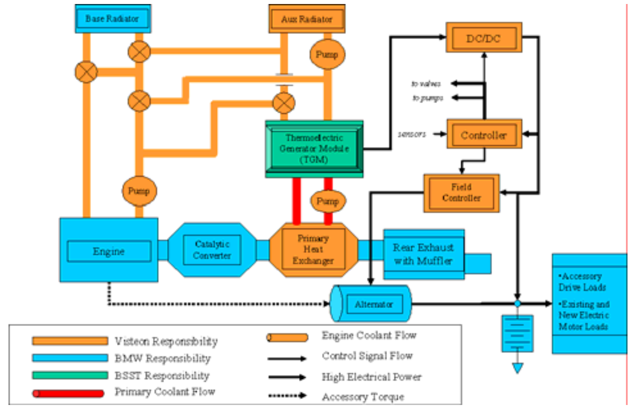

Figure 1. Waste Heat Recovery System Architecture

- Opportunities for further improvement were recognized, including downsizing the vehicle alternator to reflect the benefit of TGM, engine preheating using the TGM, and integration of the muffler and PHx to reallocate back pressure and acoustic noise management.

Future Directions

In Phase 2, the following equipment will be designed, modeled, built and tested:

- Primary Heat Exchanger
- Thermoelectric Generator Module
- Power Electronics (load balancing and DC/DC conversion)

Subsystem equipment will be tested over typical drive conditions, and models will be updated and validated. These results will be used to update the overall system performance model, yielding a new set of performance predictions based on the test results of subsystem equipment operating in a laboratory environment.

In Phase 3, the subsystem equipment designs will be iterated as required and equipment will be built, integrated and tested as a system.

In Phase 4, the system will be integrated with a BMW engine and tested at NREL's facility in Golden, Colorado, as a final demonstration of system performance.

Introduction

The objective of this project is to increase fuel efficiency and reduce exhaust emissions, key goals within the DOE's FreedomCar Program. The gain in fuel efficiency is achieved by replacing electrical power required by the vehicle with power produced by a TGM.

The TGM utilizes thermal energy from the hot exhaust gas, normally wasted via discharge through the muffler to the environment, and converts it to electric energy using thermoelectric material and power conversion principles. In doing so, the TGM offloads the vehicle alternator, which is powered by the engine, to provide required electrical power. Phase 1 system simulations have shown that a gain of up to twelve percent in fuel economy can be realized through this means.

Approach

Energy flow from the exhaust gas over typical driving conditions was analyzed to trace the flow of energy through the system. This data was used to establish nominal design parameters for the PHx and TGM that achieved optimum efficiency over the various conditions. The nominal designs were modeled and incorporated into a vehicle level "bumper to bumper" model so the system behavior could be analyzed and adjusted. (The system model also included power conversion and load balancing models that interacted with the vehicle alternator.) It was discovered that a point of diminishing system performance vs. PHx and TGM sizing and performance existed at approximately 25 grams per second of exhaust gas mass flow (Figure 2). This finding established a baseline for subsequent equipment design and build in Phase 2.

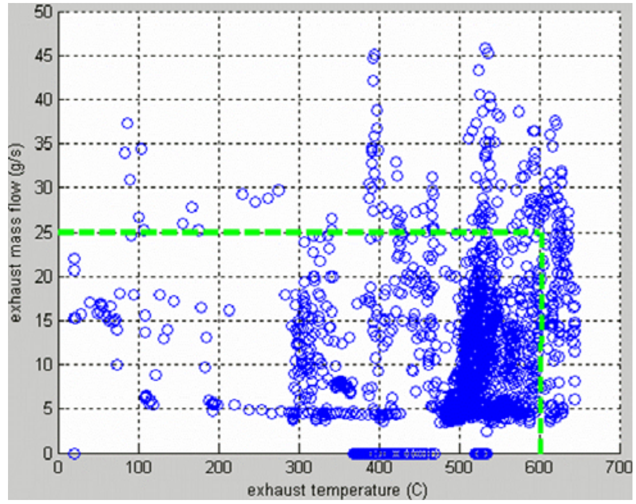

Figure 2. Exhaust Gas Mass Flow and Temperature Plotted over the FTP-75 Cycle (Each circle represents mass flow at temp for a one-second interval. Green limits suggest an efficiently sized PHx design point.)

Results

Overall results for Phase 1 (fuel and emissions reduction percentages) are reported in Table 1.

Representative city and highway drive cycles (FTP-75 and the Highway Fuel Economy Test, HWFET, respectively) were used to evaluate system performance. As shown in Table 1, the system provides a range of fuel consumption reduction of 8 to 12½ percent and decreases emissions.

The results are grouped to reflect present system capability (2005) and capabilities projected and targeted for 2008 dynamometer testing. It should be noted that the values used for thermoelectric material performance, or ZT (figure of merit), reflect values for materials reported by researchers and in applications currently in use.

Table 1. System Performance Results

	Present (2005) System Capability			**Projected for Dyno Test, 2008**			**Target for Dyno Test, 2008**		
Drive cycle	FTP-75	HWFET	Combined (1)	FTP-75	HWFET	Combined (1)	FTP-75	HWFET	Combined (1)
Average alternator load (W)	1000	1000	1000	2000 (2)	2000 (2)	2000 (2)	2000 (2)	2000 (2)	2000 (2)
Average ZT	0.85	0.85	0.85	1.00	1.00	1.00	1.25	1.25	1.25
% improvement - mpg	8.36	8.25	8.28	9.60	10.50	10.03	11.64	12.61	12.10
% change - HC (3)	-1.67	0.19	-1.03	-2.19	0.58	-1.26	-2.77	0.58	-1.65
% change - CO (3)	-1.86	-1.75	-1.82	-2.07	-2.65	-2.27	-2.53	-3.16	-2.75
% change - NOx (3)	-2.99	-1.75	-2.53	-3.77	-1.48	-3.09	-4.25	-2.22	-3.64

(1) Combined drive cycle weighted 60% FTP-75 and 40% HWFET
(2) Increase in average alternator load is due to the estimated increase in electrification of vehicles by the year 2012
(3) Emissions results do NOT included significant reduction in emissions due to faster coolant warm-up

Conclusions

A viable technology path to 10% fuel economy improvement exists for application of TGMs to light-duty vehicles. A review of other technology options for achieving double digit fuel economy improvements indicates that the thermoelectric-based systems are economically competitive.

Special Recognitions & Awards/Patents Issued

1. Patent application filed by BSST and Visteon pending.

FY 2005 Publications/Presentations

1. Phase 1 Final Report under Contract Number DE-FC26-04NT42279, July 1, 2005
2. "Diesel Engine Efficiency Improvement through Waste Heat Recovery and Thermoelectric Power Generation", John LaGrandeur and Doug Crane, BSST, and Andreas Eder, BMW, presented at the 2005 DEER Conference, Chicago IL.

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3. Crane, D. T., "Optimizing Thermoelectric Waste Heat Recovery from an Automotive Cooling System": Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 2003

IV.4 Cost-Effective Fabrication Routes for the Production of Quantum Well Structures and Recovery of Waste Heat from Heavy-Duty Trucks

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[5]Pratt & Whitney, East Hartford, CT

Objective

- Develop a thermoelectric technology which improves diesel engine efficiency for heavy-duty on-highway trucks by 10%, thereby reducing fuel consumption by 9.3%.

Approach

- Develop cost-effective fabrication routes for the production of quantum well (QW)-type thermoelectric (TE) materials, enabling commercialization of high-efficiency thermoelectric devices.
- Demonstrate this technology in the form of an integrated ~500 Watt prototype thermoelectric generator on a Caterpillar More Electric Truck (MET)* initiative Class 8 heavy-duty truck.
- Develop a viable commercialization path for this technology in the diesel engine industry.

Accomplishments

To date, Phase I of the project has been completed and Phase II has begun. The main objectives of Phase I were met: carry out cost, performance and system-level modeling to assess the technical and economic viability of the thermoelectric technology being proposed for the application of interest.

- Process flow sheets were created to project manufacturing and selling costs for the three proposed fabrication routes, at the material, device and system level.
- TE parameters along with heat transfer models were used to evaluate the expected power output of the proposed thermoelectric (QW-type) materials.
- Market acceptance criteria were determined and compared to deduce selling price at the system level.
- A first-generation thermoelectric generator (TEG) was designed and its performance determined.

Future Directions

A three-pronged approach to materials development will be pursued during Phase II as a future direction.

*A Caterpillar initiative to power engine auxiliaries using electric power.

- Employment of cathodic arc deposition as a fast deposition process to make quantum well multilayer films. (Pratt & Whitney)
- Scaling up, via sputtering, quantum well multilayer films for the purpose of comparison in a 2 W mini-module. (PNNL, Hi-Z)
- Exploration of various routes to quantum well-type structures, as heterogeneous nanocomposites. (United Technologies Research Center)

Initial activities, as part of Phase II, will include base technology qualification and verification at the material level, proof-of-concept experiments using cathodic arc as a deposition process as well as non-deposition processes for heterogeneous nanocomposites, and method development for the enhancement of techniques that are used to measure thermoelectric performance and conversion efficiency at the material and device level.

Introduction

The trucking industry today faces several challenges related to high operating expenses due to increased fuel costs and more stringent Environmental Protection Agency regulations. Driver comfort is also being challenged by new regulations that are restricting truck idling in certain locations. A typical truck consuming 100 units of fuel energy loses 25% in heat transfer for engine cooling and 35% in exhaust heat, leaving only 40% for useful shaft energy. To maintain a competitive advantage, automotive manufacturers as well as producers of light- and heavy-duty trucks must deliver continuous engine efficiency improvements and reductions in emissions. DOE research suggests that electrification of heavy vehicles can improve fuel economy up to 20% in certain applications. Technologies supporting this notion are strategically important because they lower fuel consumption, decrease gaseous emissions, reduce noise, and enable substantial reduction of main engine idling. A direct thermal-to-electrical conversion system utilizing thermoelectrics is one of these technologies worth supporting and is the focus of this project.

As part of Phase I, five tasks were conducted: (1) thermoelectric material/device thermal and performance modeling, (2) waste heat generator concept development, (3) waste heat generator system analysis (truck modeling), (4) cost modeling, and (5) Phase II preparation. Task 2 contained five subtasks – (i) TEG requirements definition; (ii) exhaust flow characterization; (iii) TEG sizing, location and generic design; (iv) TEG concept generation; and (v) TEG system analysis and downselection. Task 4 contained three subtasks – (i) material cost modeling, comparing sputtering, cathodic arc, and heterogeneous nanocomposite; (ii) device cost modeling; and (iii) TEG system cost modeling, including a marketing study. The outcomes of this work were a first-generation TEG design, relative costs for each fabrication process as well as recognition of the cost drivers for each process, a maximum acceptable cost/watt value as a function of time, and a realistic assessment of what is achievable in terms of fuel economy improvement, alone and in conjunction with technology being developed under the More Electric Truck initiative.

Approach

The overall approach that was taken to fulfilling Phase I objectives was as follows:

- Carry out cost, performance and system-level models.
- Quantify the cost benefits of cathodic arc and heterogeneous nanocomposites over sputtered material.
- Evaluate the expected power output of the proposed thermoelectric materials and predict the efficiency and power output of an integrated TE device.
- Define market acceptance criteria by engaging Caterpillar's truck original equipment manufacturers (OEMs), potential customers and dealers, and identify high-level criteria for a waste heat TEG.
- Identify potential TEG concepts.
- Establish cost/kW targets as well as a breakdown of subsystem component cost targets for the commercially viable TEG.

Results

The Phase I study led the team to many technical accomplishments and experiences. Engine conditions were defined for a Class 8 heavy-duty truck using data from a Caterpillar C15 engine. These data consisted of the engine speed and load, the exhaust temperatures, the thermal flux delivered to the thermoelectric devices, and the expected power output. Application-specific conditions were defined for the thermoelectric devices. These consisted of the overall footprints, thicknesses, and geometries of the devices, as well as the expected thermal flux through the devices (Figures1 and Table 1).

Application-specific conditions were also defined for the thermoelectric materials, both P and N, as quantum well films and nanocomposites. These conditions included target ZT values based on projected seebeck (S), electrical resistivity (ρ) and thermal conductivity (κ) values, as well as specific power (Watt/g) and conversion efficiencies. Various locations across an engine were evaluated for placement of the TEG. Based on exhaust flow characteristics, projected power output, pressure drop requirements and conversion efficiencies, the best location was downselected. A generic design for the TEG was developed in order to estimate volume requirements (Figure 2).

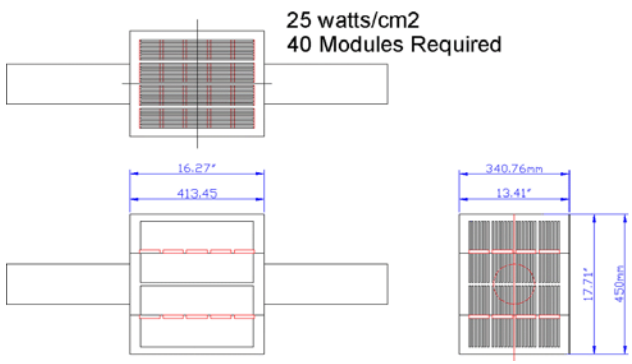

Figure 1. Schematic of a Generic TEG at a TE Material Heat Flux of 25 Watt/cm

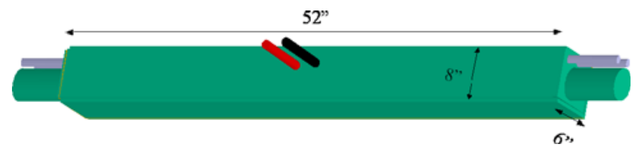

Figure 2. Layout and Dimensions of the Downselected Thermoelectric Generator

Several concepts for the cold side heat exchanger were developed. Based on size constraints, heat flow analysis, and pressure drop requirements, the best concept was downselected and a detailed design was generated. Thermal analysis on the hot side of the TEG was completed, resulting in a best-in-class design for the heat and sink. Truck modeling was completed on the downselected TEG configuration, giving an estimate for the overall fuel efficiency improvement (Table 2).

Cost modeling was completed at the material and device level for three fabrication routes (sputtering, cathodic arc and heterogeneous nanocomposite). Two market cases and two heat flux conditions were evaluated. Process improvements were included over a commercialization timeline to reduce costs with time, and a proforma/economic analysis was completed to distinguish between cost to make and

Table 1. Size Estimates for the TEG at Three Different Heat Fluxes

Heat Flux (W/cm	Power Output (kW)	T_{cold} (°C)	T_{hot} (°C)	Delta T	Thermal Power Into TE Devices (kW)	Conversion Efficiency	Thermal Power Out of TE Devices	TE Material Area Required (cm^2)	Number of TE Modules	Power Per Module (Watts)	TEG Width (m)	TEG Length (m)	TEG Height (m)
10	5	100	275	175	39.7	12.58%	34.7	3975	100	50	0.7	0.7	0.45
25	5	100	275	175	39.7	12.58%	34.7	1590	40	125	0.4	0.4	0.45
50	5	100	275	175	39.7	12.58%	34.7	795	20	250	0.28	0.28	0.45

Table 2. Truck TEG Model Simulation Results

	0° (0%) Grade			0.2° (0.35%) Grade			1.14° (2%) Grade		
	Base-line MET	MET with 0 kg TEG	MET with 105 kg TEG	Base-line MET	MET with 0 kg TEG	MET with 105 kg TEG	Base-line MET	MET with 0 kg TEG	MET with 105 kg TEG
Engine Power (kW)	148.4	144.9	145.1	184.1	179.7	180.0	348.7	341.2	342.4
TEG Power (kW)	0	4.33	4.34	0	5.54	5.55	0	11.8	11.8
Fuel Savings (%)	---	2.4	2.1	---	2.4	2.2	---	1.9	1.6

price to sell. Cost modeling was completed at the system level using both a heat exchanger model and a discounted cash flow model to estimate the total price of the thermoelectric generator. A marketing study was completed that determined the maximum acceptable cost/watt. Acceptable cost/watt numbers were compared to the projected improvement in fuel efficiency, and an overall assessment of feasibility/viability was made.

Comparing the minimum selling price of the TEG system to the maximum acceptable price, based on the market analysis, indicates that the TEG system is commercially viable for the on-highway truck market (Figure 3). It is worth noting that the expected increase in the cost of diesel fuel was not factored into this analysis. Additionally, the payback period was assumed to be two years. The acceptable payback period for customers can and does vary. Both of these factors would increase the maximum acceptable market price considerably. A marketing strategy should focus on targeting customers that log a higher number of miles per year and/or customers who own their trucks longer than average and, therefore, are willing to accept a longer payback period.

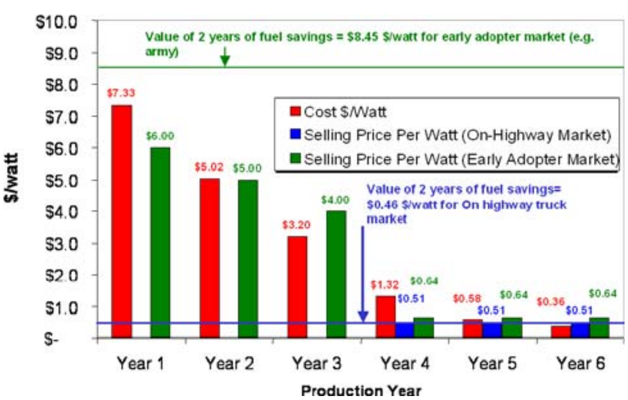

Figure 3. Comparison of the Maximum Acceptable Purchase $/Watt to the Minimum Acceptable Selling $/Watt for the TEG System for Both the On-Highway Truck Market Segment and an Early Adopter Market Segment

Risks at each level (material, device, system) were identified. Plans to mitigate each risk were also detailed.

Conclusions

- A fuel economy improvement of 2.2% was determined for the first configuration. This fuel economy improvement and the requirement for a two-year payback resulted in a market price of $0.46/watt.
- The TEG selling price was determined to be $0.51/watt. Based on these numbers, the generation of power using diesel exhaust was deemed economically viable.
- Moving the TEG upstream to a hotter location in the exhaust and including a dedicated cooling loop resulted in a 4.4% fuel economy improvement. Taking into account future identified improvements in heat exchanger technology (including heat exchanger materials), up to 7% fuel economy improvement can be achieved.
- To achieve the 10% fuel economy improvement goal, more than 80% of the waste thermal energy needs to be transferred through the TEG. This level of energy transfer will require currently undefined improvements in heat exchanger technology (including heat exchanger materials) and an engine redesign. Active monitoring and

adoption, if appropriate, of advanced heat exchanger and heat exchanger material technology will be one focus of the project moving forward.

- The More Electric Truck platform provided by Caterpillar is expected to give another 2 – 2.5% fuel economy improvement due to better utilization of electrical energy, resulting in a total fuel economy savings of up to 9.5%.
- Critical customer requirements for fuel economy savings were determined to be 2 – 9%. Therefore, based on the TEG design and the assumptions made in the cost modeling, the technology proposed was deemed as technically feasible.

FY 2005 Publications/Presentations

1. 2005 Diesel Engine Emissions Reduction Conference, Chicago, Illinois, August 2005.

Patents Issued

1. Caterpillar patent (File number 05-336); date of conception: March 14, 2005; Title: A Waste Heat Thermoelectric Generator Using Heat Pipes for Heat Extraction and Cooling; Inventors: Mahmoud Taher, Ronald L. Dupree, and Doug Fei.

IV.5 Thermoelectric Conversion of Waste Heat to Electricity in an IC Engine Powered Vehicle

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Objectives

- Quantify the potential benefits of alternative thermoelectric generator (TEG) designs in converting waste heat from internal combustion (IC) engines to work.
- Evaluate various TEG-engine configurations for an over-the-road Class 8 diesel powerplant operating at a mid-load condition.
- Evaluate the importance of heat transfer enhancements in the design of the TEG.
- Develop modeling techniques to determine the optimal relative dimensions of individual legs in the thermoelectric (TE) module and quantify the efficiency of the TE material selected.
- Characterize the mechanical properties of the selected TE material for incorporation into finite element analysis (FEA) to determine TEG model stresses.
- Develop a preliminary system design for utilization of the recovered waste heat.

Approach

- Analyze alternative TEG configurations incorporated into the exhaust system of a Class 8 truck engine using engine performance simulation (WAVE) software.
- Evaluate the heat transfer coefficients needed to maintain appropriate temperature gradients across the TEG devices by assessing heat transfer with and without enhancements.
- Determine the optimal relative dimensions of individual legs in a TE module by using an iterative technique based on Domenicali's energy balance equation.
- Calculate the thermoelectric efficiency of the generator utilizing formulas given by Cobble and inputs from the WAVE analysis.
- Determine the mechanical properties of cast ingots from calculations using the measured hardness, elastic modulus, fracture toughness and fracture strength.
- Design an electrical energy utilization system that will recover the waste heat using a TEG and immediately deliver the energy to the vehicle wheels.

Accomplishments

- A detailed WAVE analysis of the 6-cylinder Cummins ISX engine shows that a one TEG per cylinder configuration permits an energy extraction level which is 90% greater per cylinder compared to the three-into-one design.

- Heat transfer evaluations showed that ribbed and dimpled surfaces can increase heat transfer about 3 to 4 times over the original value.
- The maximum module efficiency increased from 9.1% to 11.0% when the wall temperatures increased from T_{cold} = 338 K and T_{hot} = 644 K to T_{cold} = 341 K and T_{hot} = 726 K.
- A power output analysis shows that increasing the temperature difference between the cold and hot side by 80 K will reduce the number of unicouples needed to produce 16.5 kW by 28.5%.
- The range of mechanical properties of the cast TE material agrees with previous data collected by other researchers. Literature indicates that by using hot pressing techniques, the fracture strength can be increased by fivefold or more.
- A preliminary design of the electrical-energy-to-mechanical-work system indicates that a thermal power split hybrid operating at a nominal potential of 144 Vdc has the potential to be a cost feasible system.

Future Directions

- Model the full 6-cylinder ISX engine with integrated TEG units and include the turbocharger and exhaust gas recirculation (EGR) bypass systems. This is necessary to study the tradeoffs in TEG exhaust energy extraction and turbocharger efficiency, as these tradeoffs particularly affect the engine output and NOx emissions.
- Explore additional ways to increase heat input to the TEG such as valve timing, decreasing compression ratio and alternate EGR bypass strategies.
- Couple WAVE to a detailed TEG computer model that includes heat transfer optimization.
- Optimize both the n-type and p-type TE materials by further reducing the thermal conductivity and raising the power factor.
- Conduct detailed FEA analysis of various TE modules and TEG structures.
- Develop powder processing techniques to reduce the grain size and increase the mechanical strength of the TE materials.
- Analyze the thermal and mechanical properties of the TE hot pressed materials.
- Conduct a detailed analysis of the electrical system components for the thermal split hybrid design.
- Construct and bring to operational status a single-cylinder test system for the purpose of confirming heat transfer and TEG performance models.

Introduction

The objective of this work is to quantify the potential benefits of alternate thermoelectric generator (TEG) designs in converting waste heat from IC engines to useful work. The Phase I effort provided evaluation of various TEG design concepts and of new thermoelectric materials implemented in a direct energy conversion device to extract electrical energy from the exhaust gases of an over-the-road Class 8 diesel powerplant. Currently, thermoelectric devices are commonly used in a variety of cooling and power generation applications. The best current IC engines have a nominal brake efficiency of 40%, with 35% of the fuel energy going to exhaust and 25% to other losses. Thus, in the best IC engines, nearly 60% of the energy content in the fuel is rejected as heat. The Phase I effort evaluates the technology barriers to overcome for successful implementation of thermoelectric technology in this application.

Approach

Although the potential exists for substantial energy recovery at full power engine output, realistic duty cycles must be examined to evaluate critically the potential energy recovery. In the Phase I effort, we considered a relatively conservative operating condition and conducted a detailed analysis of the potential benefits of implementation of this technology for the Class 8 truck application. A significant issue which must be resolved if thermoelectric devices of practical utility are to be implemented in powertrain systems is determining the configuration of the heat exchanger-thermoelectric energy conversion system that will offer sufficient energy recovery to justify the cost. Having established a representative operating condition, we conducted a detailed engine energy analysis to evaluate the temperature gradients and heat fluxes available for energy conversion using a thermoelectric generator. In the Phase I effort, the Michigan State University team has established the viability of the power conditioning and energy conversion configuration needed to utilize effectively the electrical energy generated.

Results

Table 1 summarizes the overall results of this Phase I analytical study of the potential viability and benefits of the application of TEG technology to the ISX engine. The results are for a cruising mode for Class 8 trucks.

The results indicate that the most energy is extracted per cylinder for the single cylinder per TEG configuration. This follows primarily from the fact that the total wetted gas-side surface heat transfer area of the TEG per cylinder is three and six times greater, respectively, than for the three- and six-cylinder configurations. Also, the lower frequency of exhaust "events" per engine cycle for the single-cylinder case allows the interior walls more time to cool off between pulses and, thereby, provides a larger average temperature gradient to "drive" the transfer of energy from the exhaust gases to the TEG

Table 1. Summary of WAVE Analysis of ISX/TEG Engine Configuration

Configuration (Optimized Geometry)	TEG Energy Input Rate [kW]	Energy Input per Cylinder [kW/cylinder]	Total TEG Energy Input [kW/engine]
1 Cylinder per TEG	31.9	31.9	191.4
3 Cylinders per TEG	50.2	16.7	100.4
6 Cylinders per TEG	64.5	10.8	64.5

structure. Table 2 shows the time-average wall and exhaust gas temperatures at the inlet and exit of the TEG for each configuration. Both temperature values increase as the number of cylinders feeding the TEG increases.

Table 2. Average TEG Gas and Wall Temperatures

Configuration	TEG Inlet Wall Temp, K	TEG Inlet Gas Temp, K	TEG Outlet Wall Temp, K	TEG Outlet Gas Temp, K
1 Cylinder per TEG	708	856	597	634
3 Cylinders per TEG	798	884	662	711
6 Cylinders per TEG	831	898	731	785

In order to produce compact and efficient TEG systems, we evaluated heat transfer enhancement concepts which can be used to maintain temperature gradients on hot/cold plates of TE devices. Results show that surfaces which have been properly designed can increase the heat transfer approximately 3 times over the original value.

Using the data obtained from the WAVE analysis, two cases of temperature conditions were used to calculate the module efficiency using an iterative modeling technique. The modules were modeled using cascaded legs of Bi_2Te_3-LAST and Bi_2Te_3-LASTT. Figure 1 shows that the maximum module efficiency increases from 9.1% to 11.0% when the wall temperatures increase from T_{cold} = 338 K and T_{hot} = 644 K to T_{cold} = 341 K and T_{hot} = 726 K.

The results from mechanical tests involving hardness and elastic modulus are shown in Figures 2 and 3, respectively. The Vickers hardness measurements for the LAST and LASTT materials ranged from 481 MPa to 1050 MPa as a function of composition. The range of Young's modulus values obtained was consistent with modulus values measured by Kosuga et al. [1] for sintered specimens of $Ag_{1-x}Pb_{18}SbTe_{20}$. Thus, for PbTe-based TE materials, both in the literature and in this study, the elastic modulus is a strong function of the chemical composition.

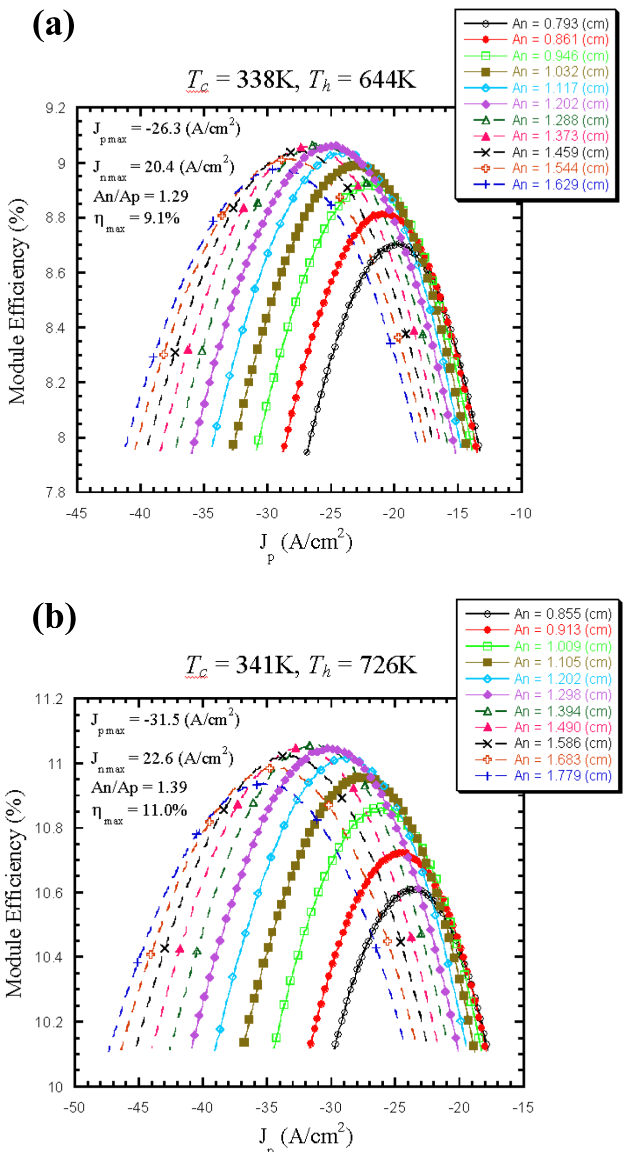

Figure 1. Results of the Iterative Technique for Cases 1 and 2, Using Cascaded Legs of Bi_2Te_3-LAST and Bi_2Te_3-LASTT

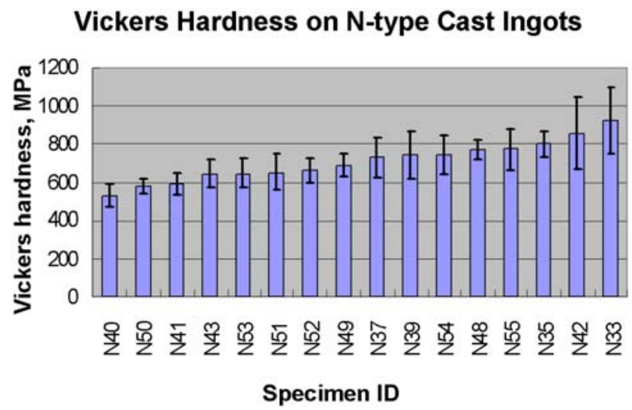

Figure 2. Vickers Hardness of LAST and LASTT Specimens Cut from Cast Ingots

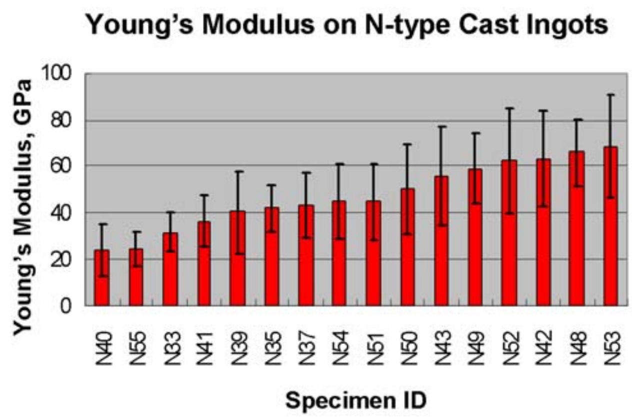

Figure 3. Young's Modulus of LAST and LASTT Specimens Cut from Cast Ingots

An initial design of the recovery of the waste heat and utilization of the electrical energy was analyzed, and the overall architecture is shown in Figure 4. In the system, a fraction of the heat rejected via the engine exhaust will be returned to the engine induction port via an exhaust gas recirculation, EGR, loop. Opportunity for energy scavenging exists in the EGR loop because a conventional EGR system incorporates a cooler. Rather than reject this heat through the radiator, the thermoelectric generator converts a fraction of this rejected heat directly into electrical power as shown. The remainder of the engine-rejected heat is delivered in the conventional manner to the turbine side of the turbocharger and from there to the exhaust system. As shown in Figure 4, other opportunities exist for generating electricity from waste heat.

Conclusions

- A greater amount of exhaust energy can be extracted through the TEG when each cylinder of the six-cylinder engine has its own separate TEG passage, as opposed to alternate designs having three or six cylinders "feeding" a single TEG unit.

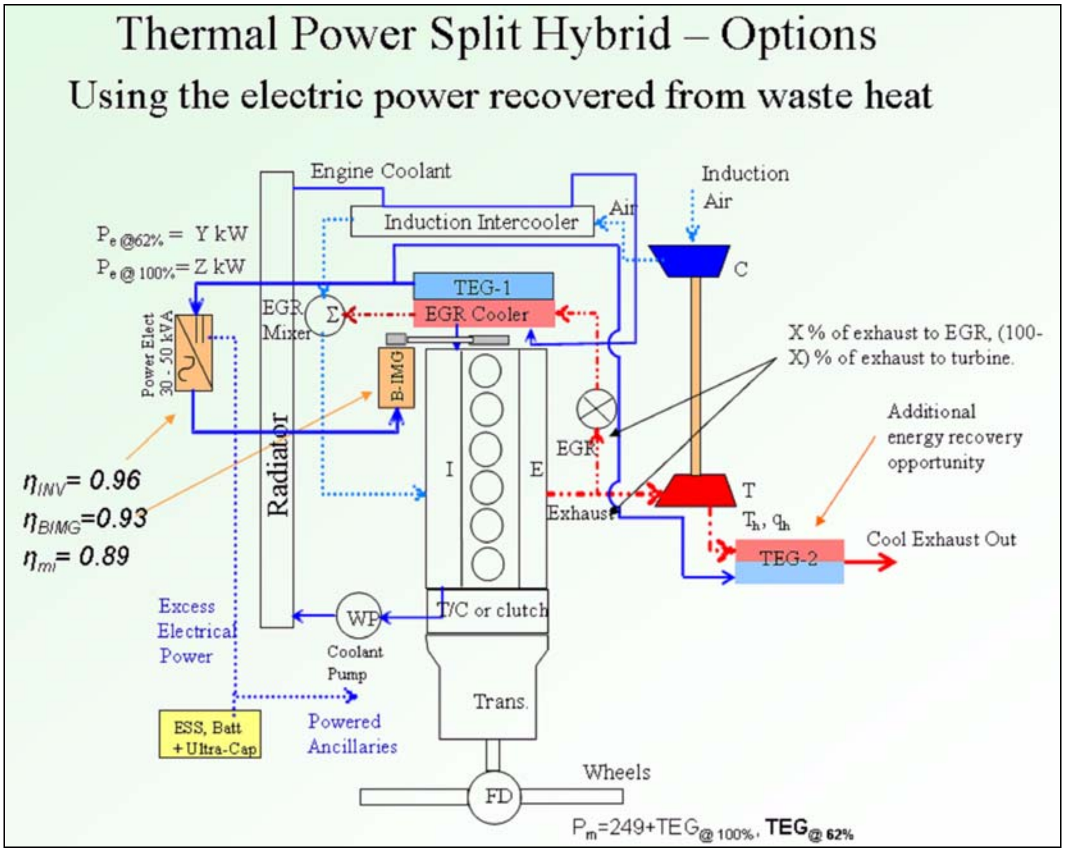

Figure 4. Potential Architecture of the Thermal Power Split System

- Heat transfer enhancements and optimization will be critical in designing a cost-effective TEG.
- The importance of increasing the wall temperature differential between the hot and cold sides of the TEG suggests that engine operating load optimizations should be conducted.
- Powder processing and hot pressing the thermoelectric material are necessary to optimize the mechanical properties. This is critical for long-term stability during thermal and mechanical fatigue cycling.
- Development of a detailed power electronics system will need to occur along with the evaluation of the dynamic response of the system as temperatures change.
- A scale model demonstration unit with an efficiency gain of 5% is a reasonable 5-year goal.

FY 2005 Publications/Presentations

1. DEER Conference, Thermoelectric Conversion of Waste Heat to Electricity in an IC Engine Powered Vehicle, Chicago, Illinois, August, 2005.

References

1. Cobble, M. H., "Calculations of Generator Performance." Chapter 39, *CRC Handbook of Thermoelectrics,* Editor: D. M. Rowe, CRC Press, 1995.
2. Kosuga, A., M. Uno, K. Kurosaki and S. Yamanaka, *J. Alloys and Compounds 387* (2005): 52-55.

IV.6 Diesel Truck Thermoelectric Generator

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Subcontractor:
PACCAR Technical Center

Objectives

- To develop a cost-effective thermoelectric generator (TEG), powered by diesel engine exhaust heat, in sizes from 1 kW to 10 kW.
- The TEG, by generating required electrical power from waste heat, will reduce fuel consumption and corresponding emissions.
- Greater onboard generation of electricity could power exhaust cleanup devices being developed to further reduce emissions.
- Development of the next generation of thermoelectric technology called multi-layer quantum well films (MLQWF) should improve the thermoelectric conversion from the 5% to 6% available today to 20% to 30%.

Approach

- Design, build and test a 2 W quantum well (QW) module, followed by a 20 W QW module, as building blocks leading ultimately to 80 W modules suitable for installation in a 5 to 10 kW diesel truck thermoelectric generator (DTTEG).
- Develop advanced sputtering techniques to join 1000 layers of QW P-type film with 1000 layers of QW N-type film to form QW couples, which then are joined together to form QW modules.
- Complete the design of the 10 kW DTTEG with QW modules.

Accomplishments

- Achieved >530,000 equivalent miles in road tests of the 1 kW DTTEG.
- Achieved successful laboratory and test cell tests on a 300 Watt automobile exhaust thermoelectric generator (AETEG).
- Developed operating capabilities on a 34" inside diameter (ID) sputtering machine (200 to 360 square inch deposition area), scaled up from an 18" laboratory machine (2 square inch).
- Designed, constructed and operated a Hot Wall QW Deposition apparatus.
- Obtained 14% efficiency on multiple QW couples.
- Developed QW couples with Mo contacts for 500°C operation.

Future Directions

- Accelerate QW development with the utilization of the 34-inch ID machine.

- Continue to work with Pacific Northwest National Laboratory (PNNL) to produce improved QW film for QW modules.
- Test 2 W and 20 W modules as building blocks for larger QW modules.
- Improve high temperature limits and reduce parasitic losses for QW film to approach the predicted 25% efficiency.

Introduction

Hi-Z Technology, Inc. (Hi-Z) is currently developing four different auxiliary generator designs for the conversion of waste heat from the truck engine exhaust directly to electricity. The first is a 1 kW generator for heavy-duty diesel trucks. The second is a 300 W generator to be used on light-duty gasoline engine trucks or automobiles. The third is a 200 W generator to be used on a light-duty diesel hybrid truck. The fourth is a 10 kW generator for Army Stryker trucks.

The 1 kW generator activity [1] has been ongoing for several years and has completed testing for its response to over-the-road shock and vibration in a Class VIII Kenworth truck, logging in excess of 530,000 equivalent miles on PACCAR's test track.

The current focus of the 1 kW activity has shifted from generator testing to the development of quantum well thermoelectric modules to replace the currently used bulk thermoelectric modules in the generator so that its output can be increased to about 4 kW, and ultimately to 10 kW.

Approach

The 1 kW DTTEG was completed through DOE-funded work as of March 31, 2005, with corporate participation from PACCAR and Hi-Z, and is shown mounted underneath the truck in Figure 1. The 300 W AETEG is being funded by the New York State Energy Research & Development Authority and DOE, and the work is being done for Clarkson University with corporate support from General Motors and Delphi. This generator is shown in Figure 2. The 200 W generator rework is being funded by DOE, and the work is being done for Ohio State University. The preliminary design 10 kW TEG for the Army's Stryker vehicle is shown in Figure 3.

Figure 1. 1 kW DTTEG on PACCAR Truck

Figure 2. Photograph of a 300 Watt Generator Without Case

Three of the above-mentioned generators (the exception being the 10 kW TEG for the Army's Stryker vehicle) currently use conventional Bi_2Te_3 alloy thermoelectric modules. The material in these modules has a value of ZT [figure of merit (Z) times its mean absolute operation temperature (T)] of about 1. The value of ZT has hovered around 1 since the mid-1950s, when semiconductor materials were

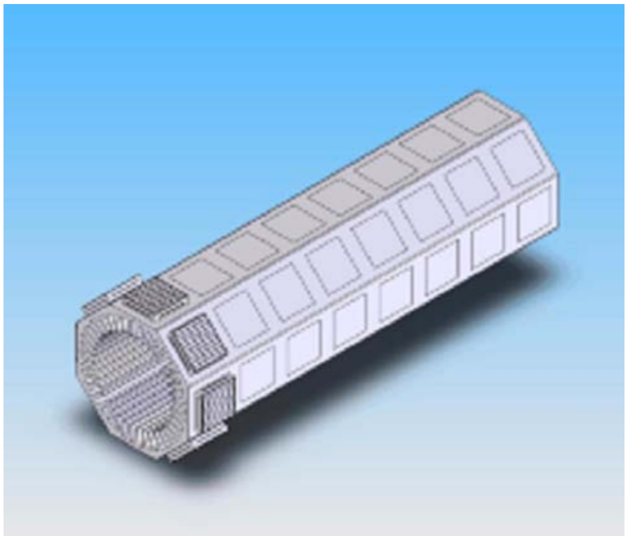

Figure 3. Preliminary Design of the 10 kW TEG for the Army's Stryker Program

introduced into thermoelectric conversion. In the late 1990s, new materials, including quantum well materials, started to increase the value of ZT to about 4 with some promise that even higher values can be obtained as development continues.

Results

Hi-Z has completed Phase I involving concept design of a 10 kW TEG for underarmor installation in a Stryker vehicle. The concept design resulted in two 5 kW TEGs arranged in series to fit the underarmor space. Each of the 5 kW TEGs contains 64 QW modules arranged on the octagonal flats of the exhaust gas heat exchanger. The inside diameter (5.5") and fin structure of the exhaust gas heat exchanger are sized to optimize heat transfer and match the pressure drop of the muffler which the 10 kW TEG replaces. The cold side of the TEG is cooled with the engine coolant. Each 5 kW quantum well generator occupies a region that is only 27 inches long and 10 inches in diameter. In the same volume, a generator with today's Bismuth Telluride thermoelectric materials will produce only 1 kW.

Hi-Z has started Phase II to develop the key quantum well thermoelectric module for the 10 kW quantum well TEG. This multi-year project will establish first the 2 W, and then 20 W, building block quantum well modules. This represents the first large-scale set-up, application and film deposition on the new 34" sputtering machine at Hi-Z. Initially, both N and P type Si/SiGe films will be deposited on both sides of the Kapton substrate. A one-micron Si buffer layer will first be deposited on each side of the Kapton prior to deposition of the 100-Angstrom Si and SiGe films. It is expected that the process (including time at temperature, deposition rate, anneal temperature, target source, etc.) will require substantial adjustment for the scale-up from the current 18" machine (2 sq. in.) to the 34" machine (200 to 360 sq. in).

In addition, P type B4C/B9C will be deposited on SiGe and Kapton substrates. To successfully join the multilayer film at the junction of the N and P legs to form couples, the parallel work funded by DOE will develop critical quantum well film joining technology. These quantum well joining and film development techniques are under evaluation in parallel under DOE- and Army-funded projects for exhaust environments with maximum thermoelectric material temperatures of 300 degrees C. The goal of the Army project is to demonstrate application of one or more quantum well modules in an auxiliary power unit for the Stryker vehicle.

Figure 4 shows a recently developed quantum well device with two couples of N and P type Si/SiGe deposited on both sides of a Kapton substrate. This nanotechnology device, which has 26 QW couples built into a circular array, is being fabricated for the U.S. Navy milliwatt energy harvesting/sensor powering applications. Of particular significance for this project, three achievements are noteworthy: (1) Kapton, which has a low thermal k, was used as the substrate instead of single-crystal silicon, eliminating a major heat leak obstruction to higher efficiency; (2) an improved sputtering process was successfully developed to deposit the Mo metal contacts that exhibit the negligible contact resistance necessary for the high efficiency performance of the QW module; and (3) initial power measurements, as shown in Table 1, are very close to the 5 milliwatt predicted values at 40 degrees C, and when extended to 200 degrees C, are calculated to produce 9.24 Watts, a very significant advancement to achieving the project objectives.

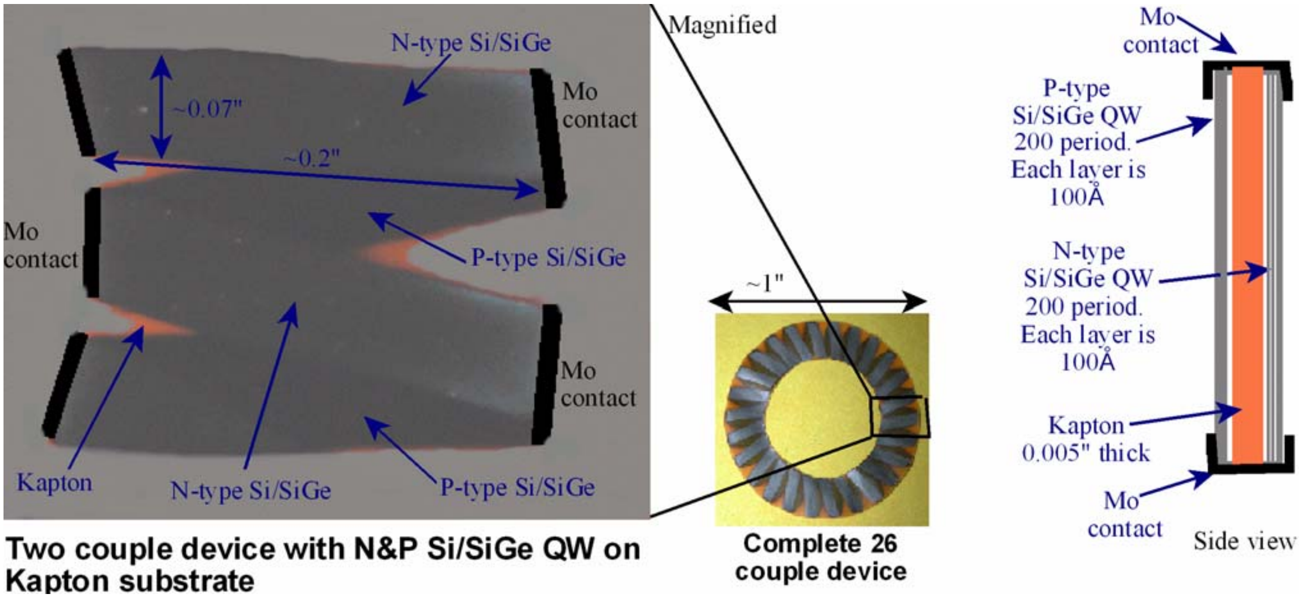

Figure 4. QW N and P type Si/SiGe Two-Couple Device on Kapton

Table 1. Thermoelectric Properties of QW Device on Kapton

T_{Cold} = 26E C T_{Hot} = 66E C	2 Couples Measured at T = 40E C	Results 2 Couples Measurements Extrapolated to 26 Couples at T = 40E C	Calculated 26 Couples at T = 40E C	Calculated 26 Couples at T = 200E C
Voltage (V_L)	225 Milli V	2.93 V	3 V	14.6 V
Power	0.371 Milli W	4.82 Milli W	5 Milli W	121 Milli W

An earlier single-couple device fabricated with N-type Si/SiGe and P-type B4C/B9C is shown in Figure 5. It also has Mo contacts. However, the substrate was single-crystal Si, and alumina was used to electrically insulate the N and P legs. It has operated for more than 2,500 hours with no degradation.

During this period, the hot-wall deposition system was used to evaluate deposition of Si-Ge alloys, and the e-beam deposition system (without the hot wall) was used for test deposition of molybdenum and titanium onto silicon to evaluate this process for deposition of electrodes on quantum-well couples.

Both N-type (81 at% Si, 19 at% Ge) and P-type (87 at% Si, 13 at% Ge) Si-Ge were used as source materials. Water-cooled copper, graphite and boron nitride crucibles were used to contain the source material. HPP Kapton substrates were held in the range of 125 to 185°C, and excellent adherence was obtained for all deposits. Deposition thicknesses were in the range of 1 to 2 µm. Hot-wall temperatures between 250 and 500°C were evaluated. Alloy composition could not be reliably controlled for any combination of deposition rate, substrate temperature and hot-wall temperature, and it was concluded that the hot-wall deposition process alone cannot control the composition of alloy films of Si-Ge. The source of this problem was traced to change in the composition of the source material during evaporation, with the source becoming significantly more germanium-rich. It is believed that this problem can be overcome by using a flash-evaporation process in conjunction with the hot wall in which powder or small pellets of the Si-Ge alloy are dropped into an e-beam-heated crucible at a

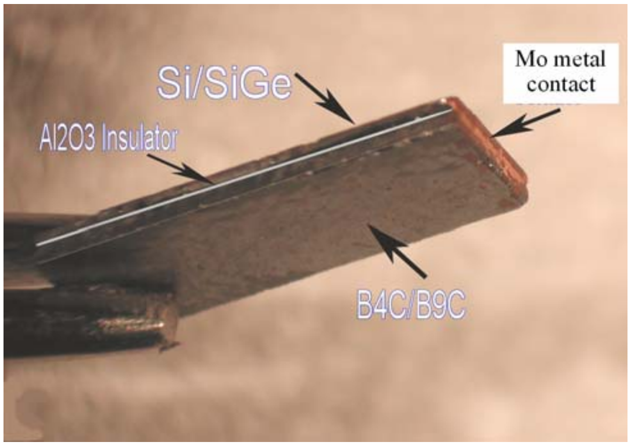

Figure 5. QW Si/SiGe-B_4C/B_9C Couple for Thermal Stability Test

temperature at which they evaporate almost instantaneously. The flash evaporation would assure that the desired alloy composition is evaporated, and the hot wall would assure that both constituents of the alloy reach the substrate. This process has not yet been evaluated experimentally.

Titanium and molybdenum have been deposited onto single-crystal silicon using an e-beam source. Titanium yielded continuous, adherent deposits with thicknesses between 1.2 and 2.3 µm at substrate temperatures between 150 and 250°C. Adherence of molybdenum could not be attained at lower substrate temperatures but was achieved at substrate temperature of 425°C.

Conclusions

An advanced 10 kW TEG is achievable with 80 W QW modules (which need to be developed in steps using building blocks of 2 W and 20 W QW modules).

- QW test couples achieved 14% conversion efficiency to confirm a point on the theoretical curve. Techniques are being developed for joining the 1,000 layers of the N and P legs into a low-resistance junction to form high-efficiency QW couples, components of a QW module.
- QW modules can be developed for higher temperatures and greater efficiencies using improved materials and techniques now under development.
- QW couples are being fabricated with Mo contacts and exhibit stable performance.
- QW couples of Si/SiGe deposited on both sides of a Kapton substrate have been demonstrated and show great potential.
- Hot wall deposition continues to show promise for QW film preparation.

Special Recognitions & Awards/Patents Issued

1. Hi-Z has been awarded 16 patents: five apply to QW material, two apply to TEGs.

FY 2005 Publications/Presentations

1. Final Report DTTEG, March 16, 2005.
2. "Predicted Performance of Quantum Well Thermoelectrics for Waste Heat Recovery Power Generation", Krommenhoek, D.J., Ghamaty, S., Bass, J.C., Elsner, N.B. and Jovanovic, V., presented at the IECEC meeting, San Francisco, 2005.
3. "Quantum Well Thermoelectric Devices", Ghamaty, S. and Elsner, N.B., proceedings of InterPack 2005: ASME Technical Conference on Packaging of MEMS, NEMS and Electric Systems, July 17-22, 2005, San Francisco, CA.
4. "Design and Fabrication of Quantum Well Thermoelectric Energy-Harvesting Power Supply for Navy Wireless Sensors", Jovanovic, V., Ghamaty, S. and Bass, J.C., proceedings of InterPack 2005: ASME Technical Conference on Packaging of MEMS, NEMS and Electric Systems, July 17-22, 2005, San Francisco, CA.

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1. Kushch, A.S., Bass, J.C., Ghamaty, S., Elsner, N.B., Bergstrand, R.A., Furrow, D. and Melvin, M., 2001, "Thermoelectric Development of Hi-Z Technology", Proceedings, 7th DEER Conference, Office of Scientific and Technical Information, Portsmouth, VA.
2. "Proof-of-Principle Test for the Thermoelectric Generator for Diesel Engines", 1991, Final Report, Hi-Z Technology, Inc., HZ 72691-1.
3. Elsner, N.B., Ghamaty, S., Norman, J.H., Farmer, J.C., Foreman, R.J., Summers, L.J., Olsen, M.L., Thompson, P.E. and Wang, K., 1994, "Thermoelectric Performance of $Si_{0.8}Ge_{0.2}$/Si Heterostructures by MBE and Sputtering", Proceedings, 13th International Conference on Thermoelectrics, AIP Press, Kansas City, MO.