IV. WASTE HEAT RECOVERY

IV.1 Developing Thermoelectric Technology for Automotive Waste Heat Recovery

Jihui Yang (Primary Contact), F. Seker, R. Venkatasubramanian, G. S. Nolas, C. Uher, and H. Wang
GM Research and Development Center
30500 Mound Road, MC 480-106-224
Warren, MI 48090

DOE Technology Development Manager: John Fairbanks

NETL Project Manager: Carl Maronde

Subcontractors:
- General Electric, Niskayuna, NY
- RTI International, Research Triangle Park, NC
- University of South Florida, Tampa, FL
- University of Michigan, Ann Arbor, MI
- Oak Ridge National Lab, Oak Ridge, TN

Objectives

- Develop cost-effective bulk thermoelectric materials for exhaust heat recovery.
- Develop high efficiency thin-film superlattice-based modules for radiator heat recovery.
- Complete manufacturability and cost assessment of bulk and thin-film modules.
- Validate the exhaust subsystem modeling.
- Select initial thermoelectric materials for the exhaust subsystem.

Accomplishments

- Demonstrated that the thermoelectric performance of misch-metal-filled skutterudites is comparable to that of single-rare-earth-element-filled skutterudites.
- Achieved ZT = 1.3 at 800 K in nano-composite n-type skutterudites, the highest reported ZT values for n-type skutterudites.
- Synthesized, and for the first time measured transport properties of novel antifluorite compounds.
- Achieved nearly 15 Watts electric output from large superlattice-based multi-module array with an external ΔT of 100 K.
- Established high temperature bulk material thermoelectric property measurement systems, and validated properties of many materials.
- Quantified the electric power requirements associated with the 10% fuel economy improvement target for the Federal Test Procedure city and highway cycles.
- Completed cost and manufacturability assessments for bulk and thin-film modules.
- Completed the initial exhaust waste heat recovery subsystem design and performance analysis.
- Initiated the initial radiator waste heat recovery subsystem design and performance analysis.

Future Directions

- Complete the initial radiator waste heat recovery subsystem design and performance analysis.
- Analyze subsystem cost for exhaust and radiator.
- Select thermoelectric materials for exhaust and radiator subsystems.
- Develop cost-effective thermoelectric materials and modules.

Introduction

In the past year, this project has been focused on several areas: economic feasibility of automotive thermoelectric waste heat recovery; initial thermoelectric material selections for exhaust and radiator heat recovery modules; design and performance analysis of the exhaust and radiator heat recovery subsystems; and the search for high performance and cost-effective thermoelectric materials and modules.

We have made significant progress in each of these focus areas. As part of the economic feasibility study, we have completed cost and manufacturability assessments for bulk and thin-film thermoelectric devices. The project electric power targets have been established for city and highway driving cycles. Critical vehicle level information for the two driving cycles, such as temperatures, heat flow rates, air flow rates, exhaust gas chemistries, etc., were obtained to enable the design and performance analysis of exhaust and radiator thermoelectric subsystems. A vehicle platform has been identified for the purpose of this analysis. The locations and geometric envelopes of thermoelectric subsystems have also been identified and established.

The discovery part of this project has demonstrated cost-effective skutterudite materials as potential material candidates. We have also established expertise in the area of nano-structured bulk materials, as evidenced by the development of the best n-type nano-composite skutterudites. We have synthesized and performed microscopic analysis of some novel nano-structured bulk materials. The structural data help us discern the fundamental mechanisms that determine the electron and phonon transport in these materials. Novel compositions of antifluorite compounds have been investigated for the first time by us. The preliminary data show that these materials' thermoelectric properties are tunable. One of the most interesting aspects of these materials is that they are very cost-competitive when compared with other potential materials.

As part of this project, Oak Ridge National Laboratory (ORNL) has installed and tested high temperature bulk material thermoelectric property measurement systems. Samples from various sources have been tested, compared, and validated in the past year. This continues to be a critical component of our project in terms of verifying material properties and providing material properties for subsystem design and modeling. ORNL is planning on expanding their capability into thin-film measurements next year.

Approach

The overall approach we use to achieve the project goal is to combine science and engineering. Existing and newly developed materials are carefully selected by the materials research partners of the project and supplied to the system engineers at General Electric (GE). Most of the material properties are also validated at ORNL to avoid potential pitfalls. System engineers work closely with vehicle engineers at General Motors (GM) to ensure that accurate vehicle level information is used for developing subsystem models and designs. Subsystem output is then analyzed by GM for potential fuel economy gains.

Our project incorporates material, module, subsystem, and integration costs into the material selection criteria. We use this approach not only as a guide for balancing technology options, but also for providing consumer benefits

Results

Installation of ULVAC ZEM-2 System

The ULVAC ZEM-2 (M8) system was installed at ORNL on April 13, 2006, as shown in Figure 1. The initial testing showed the system met the specs, and it was quickly used to characterize bulk thermoelectric materials in this project.

Type 1: Marlow Industries Elements

Specimens from the Marlow Industries Inc. were tested using the ULVAC system. Three types of elements, undoped, n-type and p-type, were tested, and the results are shown in Figures 2 and 3. Since the thermal power and resistivity values of these commercial elements are well known, we use them as a reference standard to calibrate/validate the high temperature results. The results are reproducible and matched the literature values very well.

Type 2: GM Skutterudite Materials

Bulk specimens from GM were tested from 50ºC to 500ºC using the ULVAC system. Four compositions of misch-metal filled skutterudites were measured. Figure 4 shows the Seebeck coefficient of the GM specimen. The material was characterized at GM using the PPMS from 0 K to 300 K. The ULVAC system carried out measurements from 300 K to 800 K. The two systems show very consistent Seebeck results, and the match at room temperature is nearly perfect.

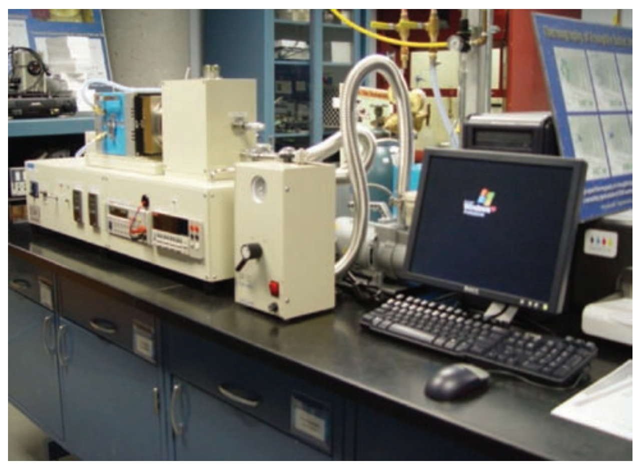

FIGURE 1. ULVAC ZEM-2 System at ORNL

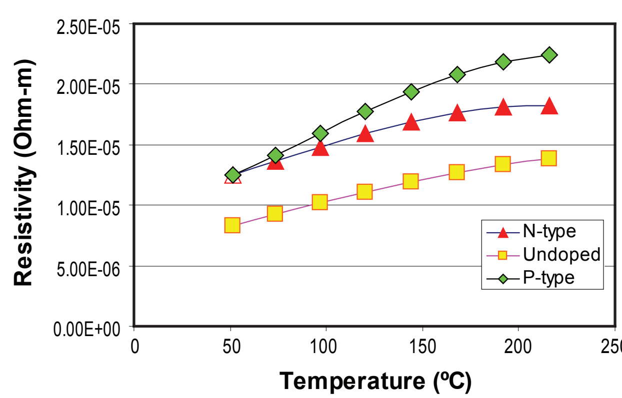

FIGURE 2. Electrical Resistivity of Marlow Elements

However, the match on electrical resistivity was not as perfect, as shown in Figure 5. A small, <5% drop was observed in the high temperature results. The specimens used in both measurements were from the same sintered rod, but cut from different locations. Considering the possible specimen-to-specimen variation in resistivity and the two completely differently measurement systems, the results are acceptably within the expected experimental error range.

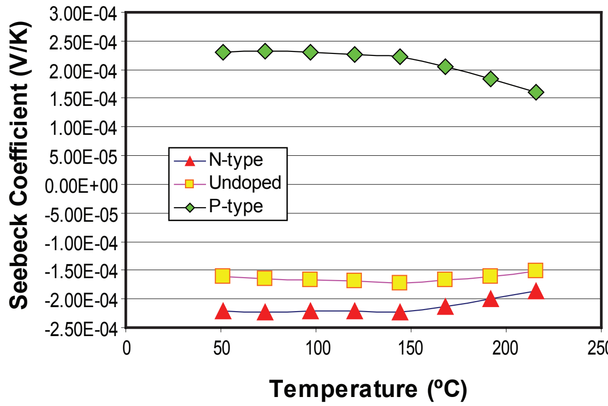

FIGURE 3. Seebeck Coefficient of Marlow Elements

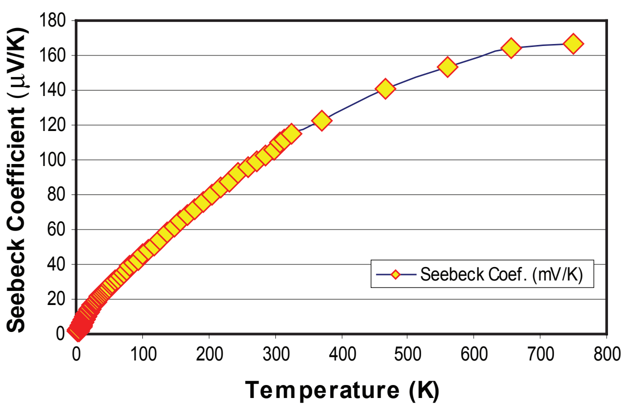

FIGURE 4. Seebeck Coefficient of GM Misch-Metal Sample

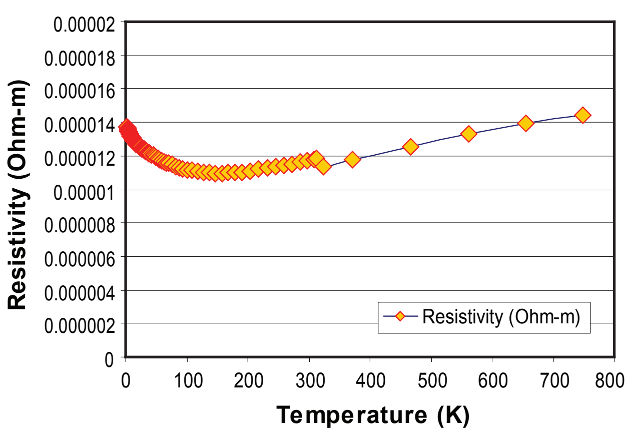

FIGURE 5. Electrical Resistivity of a GM Specimen

Type 3: Clathrates from University of South Florida

Five clathrate specimens from the University of South Florida (USF) were tested at ORNL. Figure 6 shows the electrical resistivity data obtained by the ULVAC system.

Room temperature values provided by USF and measured using the ORNL Signatone Pro4 system were also plotted. The resistivity also showed very good match among the three systems. Figure 7 shows the Seebeck results of the same specimen. The USF data matched ULVAC data nicely. Complete low temperature data available at USF also confirmed the overall match of the two systems.

Novel Clathrates

From our previous work [1] it was found that the transport properties of $Ba_8Ga_{16}Si_xGe_{30-x}$ are sensitive to the Si concentration x. Previous work under this project involved the synthesis and characterization

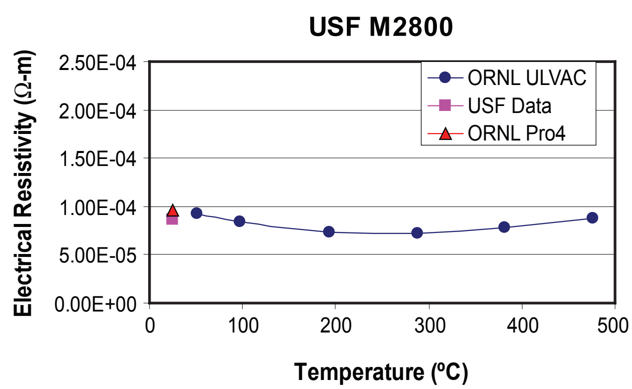

FIGURE 6. Electrical Resistivity of a University of South Florida Clathrate Specimen

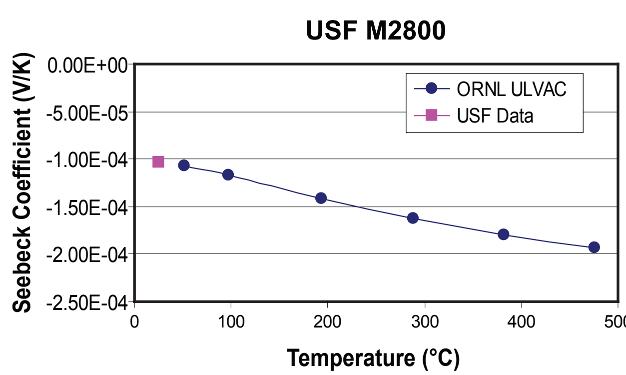

FIGURE 7. Seebeck Coefficient of a USF Clathrate Specimen

of compositions with higher Si content. The low temperature transport (12 - 300 K) was measured at USF and high temperature measurements (300 – 750 K) were conducted by Dr. Hsin Wang of the High Temperature Materials Laboratory at Oak Ridge National Laboratory. The data is shown in Figure 8. Note the excellent agreement (within experimental error) between the measurements from the different laboratories. The data also reveals that x ~ 6 may be of interest for optimization of these materials. The synthesis of more samples at x ~ 6 has begun and characterization of these specimens is currently underway.

Thin film Seebeck measurements on ceramic oxides were carried out. Initial testing suggested proper backing materials and electrical contacts are needed to establish a temperature gradient. It is expected that the ULVAC system can be used to measure Seebeck coefficient of thin films on insulating substrates. Thin film oxide materials were tested, and the results matched low temperature measurements performed at a university laboratory.

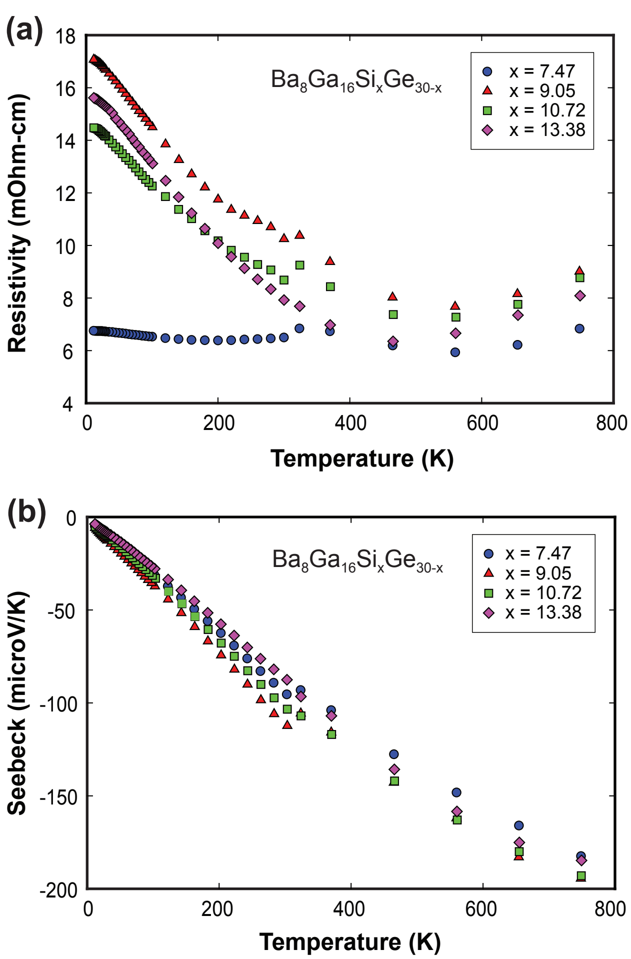

FIGURE 8. Low (<300 K) and High Temperature (>300 K) Transport Properties of $Ba_8Ga_{16}Si_xGe_{30-x}$

ORNL is in the process of acquiring the ULVAC LaserPit system. It will help to expand the measurement capability of thin film materials. In-plane thermal conductivity of many thermoelectric materials will be able to be tested at ORNL. The system is expected to arrive by the end of 2006.

Conclusions

The project has made significant progress in the areas of high efficiency cost-effective materials development, high power density thin-film superlattice-based modules, cost and manufacturability analysis for thin-film and bulk thermoelectric modules, exhaust heat recovery subsystem design and performance analysis, electric power output targets, and initial thermoelectric material selections. The next phase of our project will be focused on optimization of cost-effective bulk materials, final selection of thermoelectric materials for exhaust and radiator heat recovery devices, final design of exhaust and radiator waste heat recovery devices including estimated performance, and identification of volume capable and cost effective manufacturing processes for thermoelectric modules.

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IV.2 High-Efficiency Thermoelectric Waste Energy Recovery System for Passenger Vehicle Applications

J. LaGrandeur[1] (Primary Contact), D. Crane[1], L. Bell[1], S. Hung[2], B. Mazar[3], and A. Eder[3]
[1]BSST LLC
5462 Irwindale Avenue
Irwindale, CA 91706
[2]Visteon Corporation
One Village Center Drive
Van Buren Township, MI 48111
[3]BMW Technology Office
555 Hamilton Avenue, Suite 300
Palo Alto, CA 94301

DOE Technology Development Manager: John Fairbanks

NETL Project Manager: Aaron Yocum

Subcontractors:
- BMW, Palo Alto, CA
- Visteon, Van Buren Township, MI
- Marlow Inc., Dallas, TX

Objectives

Model, design and build the key subsystem equipment to achieve fuel efficiency and emissions objectives. Key equipment includes the primary heat exchanger (PHx), thermoelectric generator module (TGM) and power control subsystem (PCS)

- Achieve 10% fuel efficiency improvement by recovery and conversion of waste heat in a passenger automotive vehicle to electric energy
- Update the system model to reflect subsystem design, build and test results
- Maintain or reduce emissions levels
- Evaluate economic viability
- Show a path to commercialization

Accomplishments

- Subsystem equipment has been modeled, designed, built and tested including:
  - Primary heat exchangers made from stainless steel that transfer exhaust gas thermal energy to the secondary loop.
  - A PCS that converts TGM output electrical power to interface with the vehicle's electrical network that has tested at >90% conversion efficiency over the range of operating conditions.
  - Twenty-watt high temperature and 750-watt low temperature thermoelectric generators have been modeled and designed and are scheduled to be built and tested by end of December 2006.
- A bumper-to-bumper vehicle performance model used to predict fuel efficiency has been developed and validated in the GT Cool model
  - Preliminary system modeling results without operating algorithm optimization showed fuel efficiency improvement ranging up to 7.7%.

Future Directions

Phase 2 activities are scheduled to conclude at the end of 2006. An acceleration plan has been proposed to the DOE to speed commercialization by improving thermoelectric element contact interfaces. The acceleration plan activities are planned to occur in Q1 2007 and include the following objectives:

- Development of improved low resistivity electrical contacts to validate weight and cost reductions needed for the target vehicle application.
- Accelerated build of a 750-watt TGM using high efficiency high temperature materials.
- Build of a table top power generator that displays real time performance, including energy conversion efficiency.

The plan accelerates the commercialization of a high temperature TGM and provides timely integration hardware early in Phase 3.

Phase 3 activities include system integration and test and are planned to begin early January 2007.

Introduction

BSST began work to develop a high efficiency thermoelectric waste energy recovery system for passenger vehicle applications in November 2004 under a cost share contract[1] awarded by the U.S. Department of Energy Freedom Car Office.

[1] Contract number DE-FC26-04NT42279

In Phase 1, the team created a system architecture, developed a system model to predict performance and established system and subsystem design requirements. Phase 2 will be completed in December, 2006 in which key subsystem components will be built and tested and the system model updated to provide a new performance prediction.

Engine exhaust gas passes through a shell and tube heat exchanger (Primary Heat Exchanger, or PHx) downstream from the catalytic converter where thermal energy is extracted and transferred to a gaseous working fluid (preliminarily designated as 75% He, 25% Xe). Wide variations in exhaust gas mass flow, which result in correspondingly wide variations in thermal flux, are managed by means of a pump which circulates the working fluid between the PHx and the TGM's hot side. The use of this working fluid loop enables optimal usage of the thermoelectric material in the TGM as well as providing a dense, minimally sized hermetic enclosure for the thermoelectric (TE) material. Heat rejection from the cold side of the TGM can be facilitated by either the vehicle's powertrain cooling system or a supplemental cold-side cooling loop. TGM electrical power is linked to the vehicle electrical bus via a load matching DC/DC converter in the Power Conditioning System (PCS). Fuel efficiency is increased by offloading the vehicle alternator by use of power generated in the TGM. The TGM is using segmented elements comprised of Skutterudites, TAGS, PbTe and BiTe.

Approach

Early in the project a key architectural decision was made to use a secondary loop to transfer exhaust gas waste heat to the thermoelectric generator (See Figure 1). The benefits of this approach include:

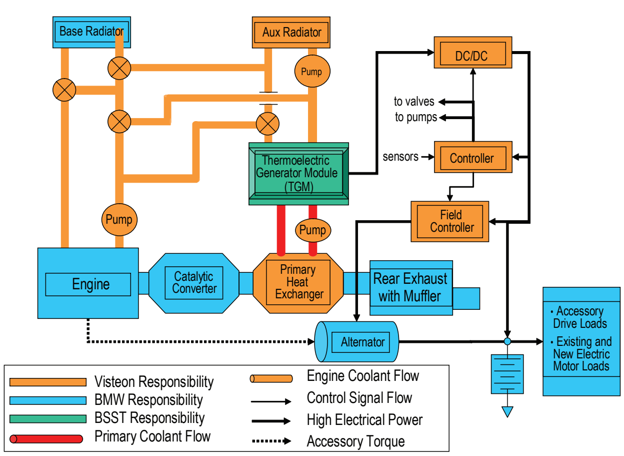

FIGURE 1. System Architecture

- Localization and hermetic packaging of thermoelectric material to mitigate potential environmental impacts
- Control of the thermal flux to the TGM through the secondary loop by means of a pump with the following important benefits:
  - Maximizing generator performance
  - Reducing thermoelectric material usage, and therefore cost

Results

The GT Cool model was integrated with the PHx, TGM and PCS models to predict system performance. The base model without the thermoelectric subsystems was validated with steady-state operating points and standard drive cycles, including FTP75 and the New European Drive Cycle (NEDC). A comparison of measured data to the simulation results for the NEDC driving cycle is shown in Figure 2.

The simulation results correspond well with the measurement results. The variations in the temperature profile have a minor influence on the power output of the TGM and are acceptable. This tool will provide accurate input parameters for the PHX/TGM subsystems from a vehicle perspective. Figure 3 shows modeling results for the TGM electrical power output.

PHX Design

Design of the PHX involved trade-offs between thermal exchange efficiency and the resulting effect on exhaust gas flow. Flow path restriction for optimization of exchange efficiency can result in exhaust back-pressures that can compromise vehicle-level fuel economy. An initial PHX prototype currently in test at Visteon is shown in Figure 4.

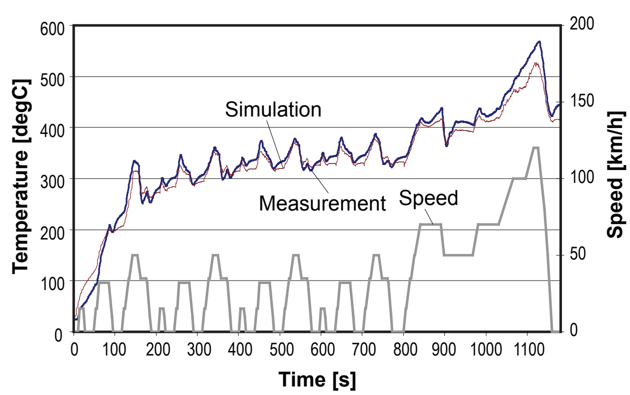

FIGURE 2. Temperature Profile of the Exhaust Gas

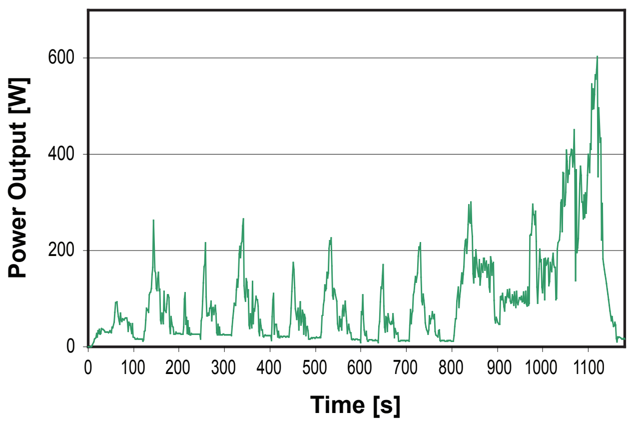

FIGURE 3. Modeling Results for TGM Electrical Power Output

FIGURE 4. Primary Heat Exchanger (PHX)

The inlet to the PHX is at lower left and includes two ports compatible with the dual pipes extending rearward from the catalytic converters. The PHX outlet section is at upper right, with a single, large port that feeds the mid-vehicle muffler.

In order to minimize direct backpressure and to maintain exhaust gas velocity for exhaust gas scavenging, the exhaust path in the tube-&-shell section is long and narrow, as opposed to being short and wide. Preliminary analyses show that, even with the use of smooth bore tubes, the PHX should be able to provide hot-side working fluid at the target temperature ranges while presenting no more than a 100 mbar incremental increase in exhaust backpressure across all operating conditions. Spiral tubes (to enhance exhaust gas contact with the interior surfaces of the tubes in the tube-&-shell heat exchanger) are an available option, should there arise a need for greater heat exchange efficiency.

Power Conditioning Subsystem

The PCS serves two functions: drawing of maximal electrical power from the TGM across a 0 V-25 V range, and conversion of TGM electrical output to supply the vehicle electrical power bus across a 12.3 V-16.5 V range. Virginia Polytechnic Institute & State University (Virginia Tech) and Visteon are developing a high-efficiency PCS for the project. The TGM acts as a Thevenin source comprised of a temperature-dependent voltage source, V_{TGM}, and source resistance, R_{TGM}. The TGM output voltage seen by the PCS is V_{in}.

A straight-forward strategy for vehicle electrical bus interaction is planned:

In conditions where the TGM/PCS cannot supply all the electrical power needed by the vehicle (e.g., cold-start), the alternator will provide electrical bus voltage regulation, under the supervision of the vehicle electrical bus controller (usually the powertrain control module, or PCM), and the PCS will act as a current source to the vehicle electrical bus. In this mode of operation, the PCS electrical output voltage floats to that established by the alternator.

In conditions where the TGM is able to supply all the electrical power needed by the vehicle, the PCS switches control modes to act as the electrical bus voltage regulator. It regulates the electrical bus voltage in a fashion that is optimal with respect to the battery at an output voltage that is slightly higher than the alternator output voltage regulation target. Under this condition, the vehicle electrical bus controller automatically and naturally shuts off the alternator as an electrical power source, thus allowing the PCS to act as the sole electrical power source for the vehicle.

The prototype Visteon PCS and test results are shown in Figure 5. Since PCS efficiencies decrease as V_{in} decreases, Visteon will implement a TGM switch network in Phase 3 that will switch the series/parallel arrangement of thermoelectric substrings in the TGM and keep V_{in} optimally high.

Thermoelectric Generator Module

A prototype device was built of six Bi_2Te_3 elements sandwiched between seven copper connectors as shown in Figure 6. Bi_2Te_3 elements were used because the tests were conducted at lower temperatures with materials that have well defined properties. These tests were conducted to better isolate problem areas in the integration of TE material into a device.

The copper connectors are placed on a liquid heat exchanger constructed from an aluminum tube. Many of the same type of liquid heat exchangers are intended to be used for the full-scale TGM device. The tube is anodized to provide electrical isolation from the copper connectors. A layer of thermal grease covers the anodized layer to help minimize thermal resistance. Two 100 W cartridge heaters provide the heat source for the device. An anodized aluminum housing encloses the heat source. Thermal grease is used as the thermal

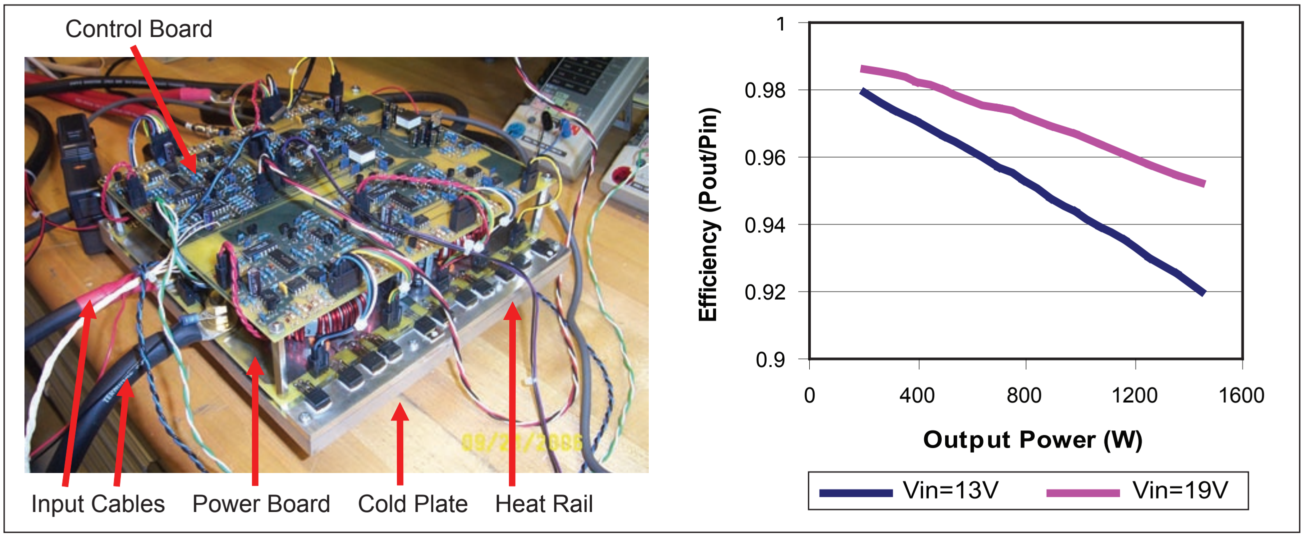

FIGURE 5. Visteon Power Converter and Test Results

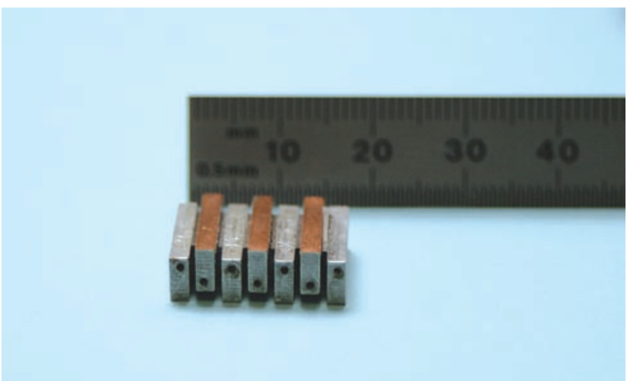

FIGURE 6. Six Bi_2Te_3 Element Device

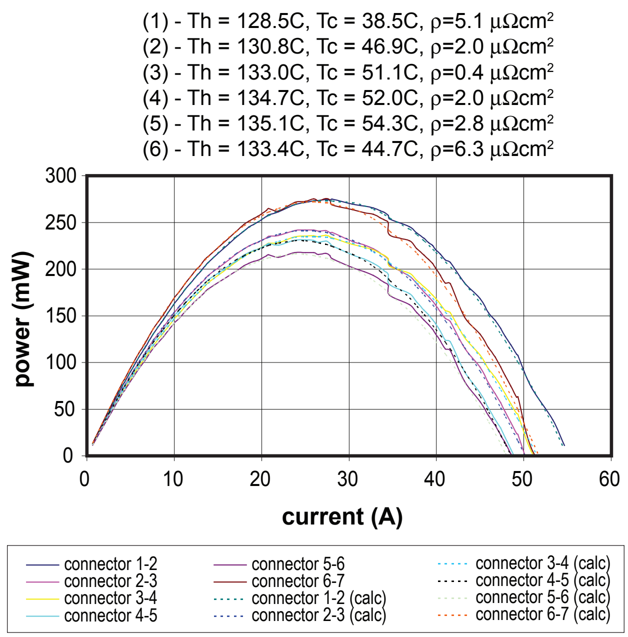

FIGURE 7. Graph Showing Power Generation Curves for Individual Bi_2Te_3 Elements

interface material between the aluminum housing and the TE connectors. A prototype test fixture was constructed to test the device described.

Figure 7 shows power generation curves for the six individual Bi_2Te_3 elements. Using the measured data along with standard TE equations to derive current-independent temperature offsets and temperature-independent electrical interfacial resistivities, the power generation curves that were experimentally determined were duplicated numerically. The dotted lines in the graph represent the calculated power curves compared to the measured power curves represented by the solid lines. It can be seen from the figure that this method of estimation can be very accurate for all six elements.

Lessons learned from these tests on Bi_2Te_3 elements will be carried over to the tests and device design for the higher temperature materials. Interfacial resistances and temperature drops across connector interfaces should be similar for these elements.

Figure 8 shows experimental results for initial testing of high temperature segmented elements. Two n-type elements were tested with dimensions and materials used listed in the figure. The same prototype fixture and device configuration to those described above were used on this test as well. Temperatures of the cold-side, hot-side heater settings and the measured TE surface temperatures are also listed in the figure. Curves are different due to the difference in element and layer thickness, as well as the slightly different temperature drops. It can be seen from the figure that the amount of power recovered increases with

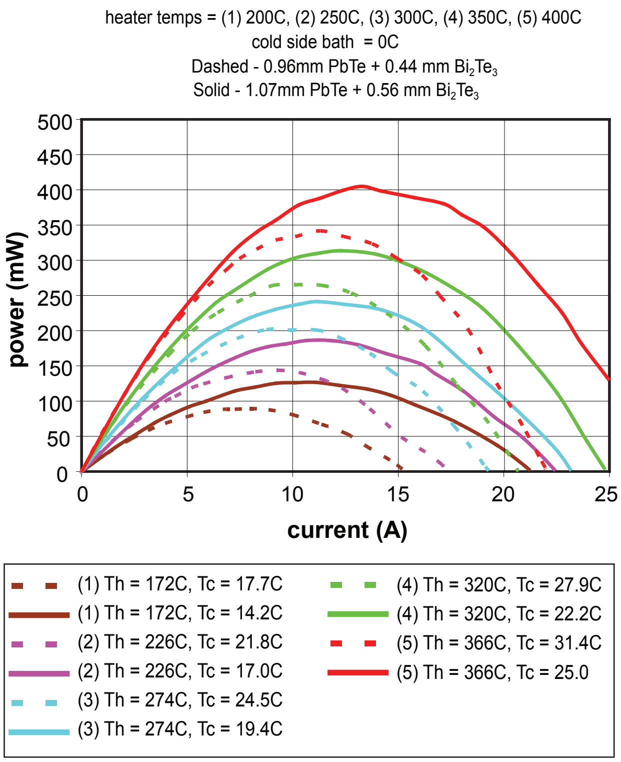

FIGURE 8. Power Generation Curves for Two N-Type Segmented Elements at Different Temperature Differences

increasing hot-side temperature. Optimal current also increases slightly with increasing temperature. Element 1 produces maximum power at 8 amperes at a hot side temperature of 172°C and at 11.3 amperes at 366°C. Further testing and analysis is necessary on these and other similar p- and n-type segmented elements to determine the same level of predictability as the tests on the Bi_2Te_3.

Using a combination of segmented elements, a fractional device will be constructed that produces 20 W of power. Once tested and analyzed, a full-scale TGM will be constructed from multiple fractional devices that will produce a nominal power output of 750 W.

Conclusions

With Phase 2 nearing completion, the design, build and test of key subsystem equipment has been accomplished (or is on track to be accomplished) per the stated objectives. An acceleration plan has been proposed to speed the commercialization of the TGM by developing improved thermoelectric material contact interfaces.

FY 2006 Publications/Presentations

1. ICT 2006
2. 2006 DEER Conference
3. 2006 DTEC Conference

IV.3 Cost-Effective Fabrication Routes for the Production of Quantum Well Structures and Recovery of Waste Heat from Heavy Duty Trucks

Rhonda R. Willigan (Primary Contact)[1], Donald Hautman[1], Dan Krommenhoek[2], and Peter Martin[3]
United Technologies Research Center (UTRC)
411 Silver Lane, MS 129-30
East Hartford, CT 06108

DOE Technology Development Manager: John Fairbanks

NETL Project Manager: Aaron Yocum

Subcontractors:
[1] United Technologies Research Center, East Hartford, CT
[2] Hi-Z Technology, San Diego, CA
[3] Pacific Northwest National Laboratory, Richland, WA

Objectives

The primary objectives of Phase II were to:

- Demonstrate high ZT performance of quantum well (QW) films on Kapton® at the size required for the designed waste heat recovery generator.
- Demonstrate, as verified and accepted by an independent group of experts, using the materials proposed in the application, a demo couple consisting of both a P-leg and N-leg at greater than 5% efficiency.
- Fabricate quantum well-type materials as heterogeneous nanocomposites and report a first set of ZT measurements.

Accomplishments

A summary of the accomplishments are given as follows:

- A new thermoelectric generator (TEG) design was developed that resulted in a 6.5–7.0% fuel economy improvement, versus the earlier reported 4–4.5% (both taking into consideration benefits from the More Electric Truck [MET] design)
- A thermoelectric (TE) conversion efficiency rig was designed, fabricated, and validated using a Bi_2Te_3 couple. The design, instrumentation, operating procedures, calculation assumptions and approaches were reviewed by the Jet Propulsion Laboratory (JPL). The agreement between measured and standard data was excellent (+/- 2–7%).
- Two QW film couples were assembled using two different QW-type film compositions. Data for Seebeck coefficient, electrical resistivity, and conversion efficiency were acquired for each. The conversion efficiencies for both couples were lower than needed.
- Two routes for bulk silicon germanium nanocomposites were identified. A series of materials were prepared from each route. The materials were characterized, and TE property measurements were acquired for each material up to 400°C. The ZT values obtained were comparable only to bulk.
- A series of bulk boron carbide nanocomposites were fabricated, characterized, and TE property measurements acquired up to 400°C. The ZT values obtained were comparable only to bulk.

Future Directions

As of yet, the primary objectives of this period have not been met. In particular the go/no-go milestone, consisting of demonstrating either high ZT performance of quantum well (QW) films on Kapton® at the size required for the waste heat recovery generator or 5% conversion efficiency using a QW film couple consisting of both P-leg and N-leg, has gone unfulfilled. Consequently, United Technologies Research Center and the Department of Energy have decided to terminate the project as it exists. There are no open items left and no additional work has been planned.

Introduction

The trucking industry today faces several challenges related to high operating expenses due to increased fuel costs and more stringent Environmental Protection Agency (EPA) regulations. Driver comfort is also being challenged by new regulations that are restricting truck idling to 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 TE is one of these technologies worth supporting and is the focus of this project. The primary objective of this project is to develop a TE-based technology which improves diesel engine efficiency for heavy-duty on-highway trucks by 10%, thereby reducing the fuel economy 9.3%. During Phase I of this project, a system level analysis was carried out which yielded a TEG design with a projected fuel economy improvement of 2.2% (4–4.5% taking into consideration benefits from the MET design).

As part of Phase II, seven tasks were carried out: (1) reevaluation and modification of the existing TEG design to yield greater projected improvement in fuel economy, (2) design, fabrication and assembly of a conversion efficiency rig for the testing of QW film couples, (3) QW film fabrication, (4) QW couple assembly, (5) QW couple testing, (6) qualification of ZT testing equipment at UTRC and (7) fabrication of heterogeneous nanocomposites. Task 1 contained two subtasks – (a) reevaluation of the TEG location (b) reevaluation of the TEG cold side rejection strategy. Task 2 contained four subtasks – (a) heater design and fabrication, (b) rig instrumentation, (c) documentation of test procedure for raw data collection and (d) documentation of test procedure for the efficiency calculation. Task 3 contained three subtasks – (a) buffer layer development, (b) development of a laser annealing technique, and (c) design and fabrication of a new heater/deposition assembly. Task 4 contained three subtasks – (a) film deposition, (b) laser cutting development and (c) contact deposition development. Task 5 contained two subtasks – (a) bismuth telluride and (b) silicon germanium qualification testing. Task 6 contained two subtasks – fabrication of (a) silicon germanium and (b) boron carbide type bulk nanocomposites.

Approach

The first focus was to revise the project's TEG design to yield a greater benefit. The system level analysis carried out during Phase I of this project yielded a TEG design with a projected fuel economy improvement of 2.2% (4–4.5% taking into consideration benefits from the MET design). In an effort to achieve a higher projection for fuel economy improvement, efforts were dedicated this period to reevaluating the assumptions supporting the Phase I TEG design.

The second focus was to obtain measured values for thermal-to-electrical conversion efficiency for QW films on Kapton® at the size required for the designed waste heat recovery generator. In order to satisfy this goal, a new TE conversion efficiency test rig was needed. Efforts were therefore dedicated to design, fabricate, assemble, baseline test and document test procedures for such a rig. The test sample required for this rig was notably larger than the single, flat P-N couple demonstrated in the past by Hi-Z to give 12% conversion efficiency. The test sample also needed to be made consistent with the device design selected as part of Phase I. It was recognized that this larger test sample will have more thermal and electrical losses, when built for the first time, than the previous, single P-N couple. Consequently, a lower conversion efficiency milestone of 5% was set.

The third focus was to obtain high quality QW films on Kapton®, at the size required for the designed waste heat recovery generator, and assemble these films into a P-N couple for the purpose of conversion efficiency testing. In order to satisfy this goal, the fundamental process for fabricating QW films on Kapton® needed optimization and the process for assembling the QW films into P-N couples needed development. Efforts were therefore dedicated to achieving these goals.

The fourth focus was to evaluate, as a potential cost-reduction pathway, methods to fabricate the QW-type materials as bulk heterogeneous nanocomposites. The approach taken to achieving this goal was to first downselect one or two fabrication methods for the each of the type of nanocomposites (silicon germanium and boron carbide), develop a fabrication process by systematically varying to optimum each processing step, and produce a first set of test specimens for ZT testing.

Results

Accomplishments made included an improved TEG design yielding 4.4% fuel economy improvement (6.5–7.0% taking into consideration benefits from the MET design), a fully-functional, qualified and externally reviewed conversion efficiency rig, identification of buffer layer crystallinity as the critical parameter in achieving high quality QW films on Kapton®, development of an assembly process for the production of QW couples, conversion efficiency test results from two different fabricated film couples, fully-functional, qualified ZT testing equipment at UTRC, techniques developed for the fabrication of silicon germanium and boron carbide type nanocomposites and ZT test results from three series of fabricated nanocomposites.

After considering all system level parameters in the TEG design, the TEG was moved upstream to a hotter location in the exhaust and a dedicated cooling loop was

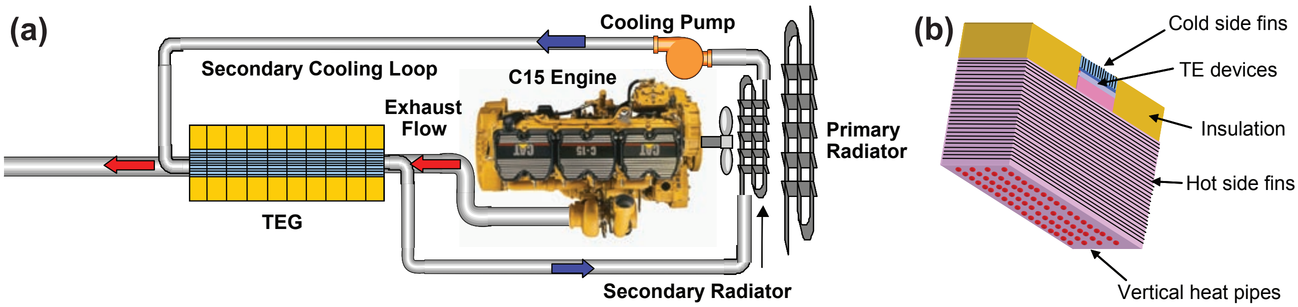

FIGURE 1. (A) System-level engine design, integrating a thermoelectric generator (TEG) for the purpose of waste heat recovery, with a Caterpillar C16 Engine. (B) Detailed design of the thermoelectric integrated heat exchanger (single segment).

included, resulted in a 4.4% fuel economy improvement (6.5–7.0% taking into consideration benefits from the MET design) as shown in Figure 1. Considering future identified improvements in heat exchanger technology (including heat exchanger materials), up to 7% fuel economy improvement is now projected as achievable (9–9.5% taking into consideration benefits from the MET design).

Figure 2 shows the conversion efficiency rig that was designed, fabricated and assembled as new this budget period, including the test sample and heater assembly. Supporting this test capability is a test procedure for the conduction of experiments (heat and current flow in plane with QW films) and collection of raw data.

Extensive instrumentation and 3-D finite element analysis was used to calculate conversion efficiency from the measured quantities. A test procedure was developed for the processing of raw data into conversion efficiency and validated against a Bi_2Te_3 test sample. The agreement between measured electric resistivity, Seebeck coefficient and conversion efficiency, and standard data, was excellent (±2–7%). The design, instrumentation, operating procedures and calculation assumptions were further reviewed by JPL and no major issues uncovered. Areas of improvement were identified and implemented to reduce uncertainties.

A process was further developed to fabricate and assemble the QW films into a P-N couple for conversion efficiency testing. The process involves three steps: (1) film deposition, (2) laser cutting, and (3) contact deposition. The films were deposited at PNNL using the larger scale sputtering machines. The films were deposited on both sides of a Kapton® substrate to a total thickness of 12 microns. The films were sectioned into approximately 12 subsections using a laser micromachining system. The films were stacked and contacts were sputtered on each end. Figure 3 illustrates how the individual films are assembled into the P-N couples, including the location for the contacts.

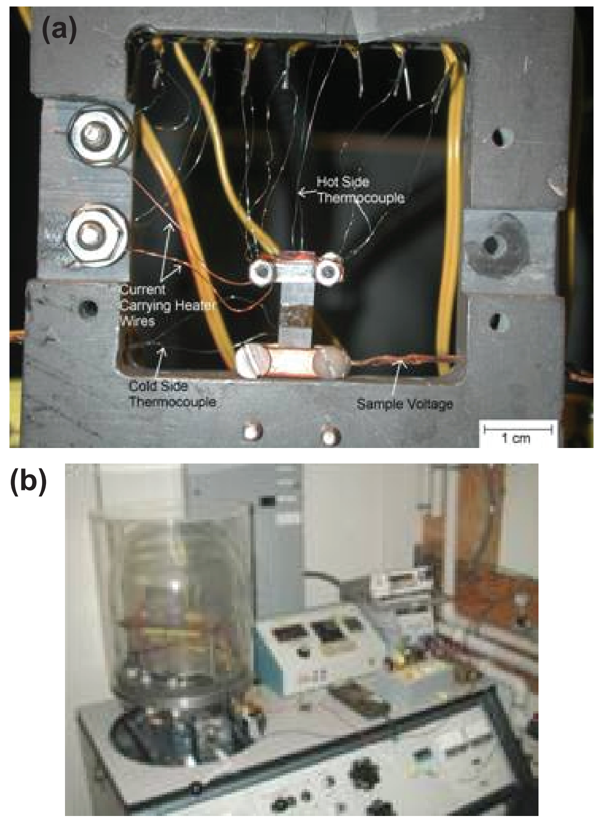

FIGURE 2. (A) Front view of the thermoelectric sample (P-N couple) clamped in the thermoelectric conversion efficiency rig.
(B) Thermoelectric conversion efficiency rig positioned inside the vacuum chamber.

Figure 4 shows the first of two TE couples fabricated. The 1st couple - Kapton®/Si/$Si_{0.8}Ge_{0.2}$ - exhibited very high electrical resistivity and gave a Seebeck coefficient that was low for QW films, but consistent with bulk values. The measured conversion efficiency was very low (<1%). The 2nd couple, consisting of an alternate material (not Si/SiGe) on

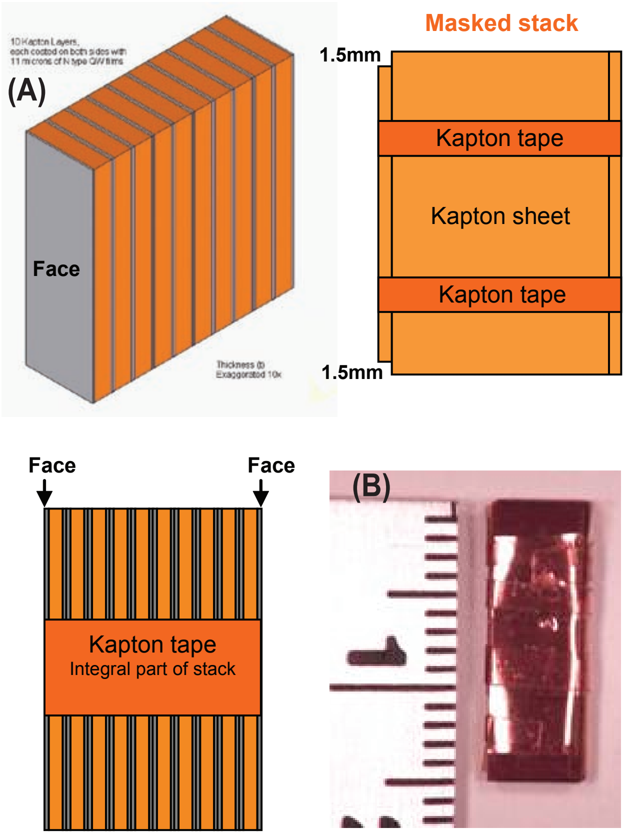

FIGURE 3. (A) Assembly and masking schematic. (B) Practice piece assembled at PNNL.

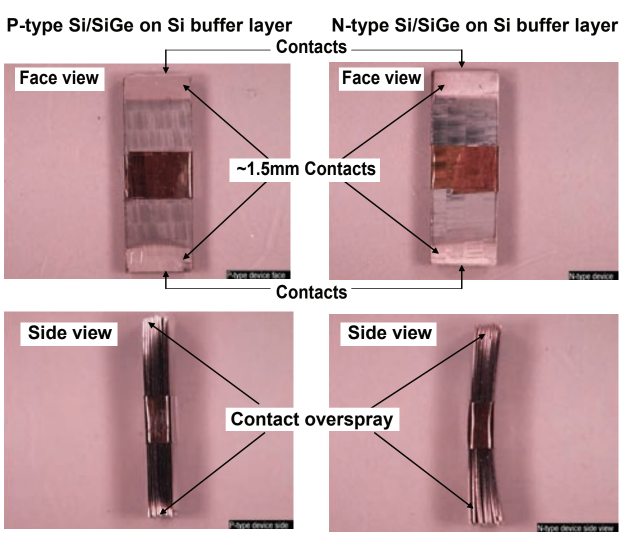

FIGURE 4. Pictures of the final, assembled P-N couple ready for conversion efficiency testing.

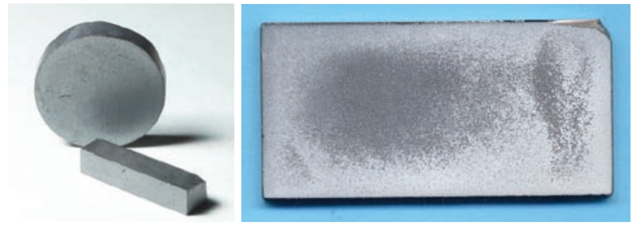

FIGURE 5. Representative bulk heterogeneous nanocomposite samples fabricated at UTRC. (A) silicon germanium, and (B) boron carbide.

Kapton®, was evaluated as a risk reduction measure. This couple also exhibited very high electrical resistivity and gave a Seebeck coefficient that was low for QW films, but consistent with bulk values. The measured conversion efficiency was also very low (<1%).

Figure 5 shows examples of the heterogenous bulk nanocomposite materials fabricated as part of this budget period. For the silicon germanium system, two methods were evaluated: (i) hot isostatic pressing of Si nanoparticles into a coarse $Si_{0.8}Ge_{0.2}$ powder mixture to form $(Si)_x/(Si_{0.8}Ge_{0.2})_{1-x}$ and (ii) arc melting of a uniformly mixed, pre-consolidated powder mixture of Si, Ge, and an insoluble additive phase, A, to form $(A)_x(Si_{0.8}Ge_{0.2})_{1x}$. The hot isostatic pressing method yielded samples that had densities ranging from 90–95% of theoretical, while arc melting yielded samples that had densities ranging from 85–100 % of theoretical. TE property measurements were acquired for the nanocomposites produced from both routes. ZT values for the $(Si)_x/(Si_{0.8}Ge_{0.2})_{1-x}$ nanocomposites formed by the hot isostatic pressing ranged from 0.17–0.21 at 175°C. These values are comparable to bulk silicon germanium. ZT values for undoped $(A)_x(Si_{0.8}Ge_{0.2})_{1-x}$ nanocomposites, formed by hot isostatic pressing, ranged from 0.01–0.04 at 175°C. These values are significantly lower than fully doped, bulk silicon germanium, but are comparable to the undoped, bulk silicon germanium sample prepared for the purpose of baseline comparison.

For the boron carbide system, one fabrication route was evaluated. Within this route, phenolic resin was demonstrated as a suitable carbon source to generate nanostructured boron carbide in-situ via reaction with amorphous boron powder. Formation of boron-rich boron carbide was demonstrated via direct reaction of B_4C with additional amorphous boron. Hot pressed boron carbide heterogeneous nanocomposites exhibited densities that ranged from 77–97% of theoretical, with retained nanocrystallinity between 45–100 nm. TE property measurements were acquired for the fabricated boron carbide nanocomposites up to 400°C. Results were comparable with bulk TE properties.

Conclusions

- Moving the TEG upstream to a hotter location in the exhaust and dedicating a cooling loop to the system design resulted in an additional 2.2% improvement in fuel economy.
- QW films on Kapton® were unable to produce high ZT needed for TEG design.
- The bulk heterogeneous nanocomposite routes evaluated, for both silicon germanium and boron carbide, produced ZT values comparable only to bulk. If performance benefits exist in these materials, they would likely be observed at higher temperatures.

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FY 2006 Publications/Presentations

Presentations

1. 12th Annual Diesel Engine Emission Reduction (DEER) conference, August 24th, 2006, Detroit, MI.

2. Phase II, Budget Period 2 Program Review, Oct. 10th, 2006, Washington, D.C.

IV.4 Thermoelectric Conversion of Waste Heat to Electricity in an IC Engine Powered Vehicle

Harold Schock (Primary Contact),
Eldon Case, Adam Downey, Tim Hogan,
Mercouri Kanatzidis, James Novak, John Miller,
Fang Peng, Fei Ren, Ed Timm
Michigan State University
East Lansing, MI 48864

DOE Technology Development Manager:
John Fairbanks

NETL Project Manager: Sam Taylor

Subcontractors:
- Jeff Sakamoto, NASA Jet Propulsion Laboratory
- Tom Shih, Iowa State University, Ames, Iowa
- Todd Sheridan, Cummins Engine Company, Columbus, Indiana
- Charles Cauchy, Tellurex, Traverse City, Michigan

Objectives – Phase II (30 months)

- Using thermoelectric energy recovery from the exhaust system, determine material performance needed to produce a 10% improvement in brake specific fuel consumption for an over-the-road (OTR) truck operating under cruise conditions.
- Evaluate currently available thermoelectric materials to determine engineering developments required for their implementation in a thermoelectric generator (TEG) for an OTR truck, to be demonstrated within five years.
- Determine requirements for a heat exchanger needed in this application.
- Determine power electronic and control requirements for this application.
- Assemble the equipment needed to conduct the necessary material synthesis, fabrication and hardware necessary for a scaled demonstration.
- Determine if Phase II results warrant a prototype engine – TEG final design in Phase III.

Accomplishments in Phase II

- Systems for material synthesis, powder processing, hot pressing, leg preparation, material mechanical and thermoelectric property characterization, and couple fabrication have been demonstrated. In addition to the facilities at Michigan State University, this includes the use of facilities at the Jet Propulsion Laboratory (JPL) and DOE's Oak Ridge National Laboratory (ORNL). Upon completion of Phase II we expect to meet the objectives of being able to successfully fabricate the modules required for the TEG.
- Using the measured properties of known materials for the temperature range of operation we estimate that a segmented couple can provide a 12.3% conversion efficiency.
- Analytical studies were performed to obtain operating points and efficiencies of various TEG configurations using materials that have been developed. Calculations show estimated improvement of up to 6.2% in fuel economy for a Class 8 OTR truck operating at cruise conditions.

Future Directions for Phase II

- Conduct design and analysis of the power conditioning system to optimize thermoelectric system performance including fault remediation.
- Explore leg fabrication methods (e.g. wet milling/dry milling, hot pressing) for improving mechanical properties and microstructural characteristics.
- Develop fabrication techniques for scaleable couple/TE modules.
- Improve results of analytical studies on the full engine system by coupling current simulations to the 3-D heat transfer studies performed at Iowa State University.
- Improve the coefficient of performance (ZT) by exploring several more promising thermoelectric material compositions, with emphasis this period on PbTe systems with Eu doping.
- Extensive mechanical, thermal cycling and thermoelectric property testing of segmented hot-pressed legs including Bi_2Te_3 and LAST/(T).
- Continue development of module fabrication methods.

Introduction

At peak efficiency, current diesel engines are capable of converting 40 percent of fuel energy to useful energy. When a Class 8 diesel truck is loaded, the engine might deliver 300 kilowatts of power to drive the wheels, while at the same time, another 300-400 kilowatts of energy goes out through the exhaust stack as wasted energy. This research project is attempting to find ways to capture that wasted energy and convert it to back into useful energy. A reasonable long term goal would be to increase the diesel power plant efficiency to greater than 50%!

This unique project requires input from a number of researcher collaborators and experts inside and outside of the College of Engineering at Michigan State University (MSU). The aim of the research is to use a direct conversion device--fabricated out of thermoelectric materials--to recover waste heat from the exhaust of internal combustion engines and turn it into useful electricity. The team is working with thermoelectric materials that have already been developed and is assessing them to see if they can be implemented in a powertrain in a cost-effective manner. The team is also developing new high efficiency thermoelectric materials that will permit a 10% improvement in fuel economy of OTR Class 8 trucks. We expect that completion of the project through Phase 4 will result in a scaled demonstration of the engine and thermoelectric energy recovery system.

Approach

This MSU-led multidisciplinary research effort is to evaluate the entire system and identify the required processes needed to bring thermoelectric technology to a cost-effective commercial product for an OTR truck. The Phase II effort is 30 months in duration involving an exploratory analysis and feasibility study which includes system design, new TE material synthesis, power electronics design, material thermoelectric and mechanical property characterization, heat exchanger design, TE material fabrication methods, module fabrication and evaluation of system performance.

Results

1. Couple and Module Design

An important part of this effort includes transport measurements of the thermoelectric materials, design, assembly, and testing of the thermoelectric modules, which includes the investigations of protective coatings and contacts to the materials. From software developed in the LabView® programming environment, the expected efficiency is calculated for various module loading conditions and module leg geometries to determine the optimal ratio of cross-sectional areas for the *n*-type and *p*-type legs. This iterative modeling procedure was used for the following boundary conditions which were provided by the engine analysis of Novak, Hartsig, and Schock as shown in Table 1. Results for the six conditions are given in Table 2.

TABLE 1. Temperature and Heat Flow Conditions from the Engine Analysis

	T2	T2'	T3	T3'	q (calc)
6-1	731	**727**	524	**342**	50493.822
6-1	781	**777**	546	**338**	57445.870
6-1	831	**826**	567	**334**	64397.918
EGR Cooler	495	**493**	408	**331**	21222.041
EGR Cooler	636	**633**	474	**331**	39516.904
EGR Cooler	834	**829**	568	**334**	64885.781

TABLE 2. Results for 4 mm and 7 mm Leg Modeling for the Given Engine Conditions

Leg length	T_c (K)	T_h (K)	η (%)	R (mΩ)	V (V)	P (W)	#/kW
4 mm	342	727	11.0	6.1	0.142	0.73	1,370
4 mm	338	777	12.3	6.75	0.165	0.90	1,112
4 mm	334	826	13.4	7.3	0.188	1.10	910
4 mm	331	493	5.48	4.76	0.067	0.21	4,762
4 mm	331	633	9.05	5.26	0.110	0.52	1,924
4 mm	334	829	13.5	7.32	0.189	1.12	893
7 mm	331	493	5.48	8.32	0.067	0.12	8,333
7 mm	331	633	9.05	9.20	0.110	0.30	3,333
7 mm	334	829	13.5	12.8	0.189	0.62	1,612

2. Design of Power Electronics and its Control

Using commercially available 5.7 W TE modules from Tellurex Corp. it has been calculated that at least 200 modules are required to generate a reference power target of 1 kW. Although an all-in-series module configuration would make the power conditioning circuit easier and more efficient and an all-in-parallel module would result in a more reliable circuit with higher power output, a combination of series and parallel (Figure 1) is preferred as it will alleviate some inherent operating and robustness problems. The smart power electronic circuit would provide load matching to maximize output power, bypass failed modules to continue operating, protect each module from thermal and electrical stresses and it would enable each TE module to be operated at different heat flux and ΔT conditions.

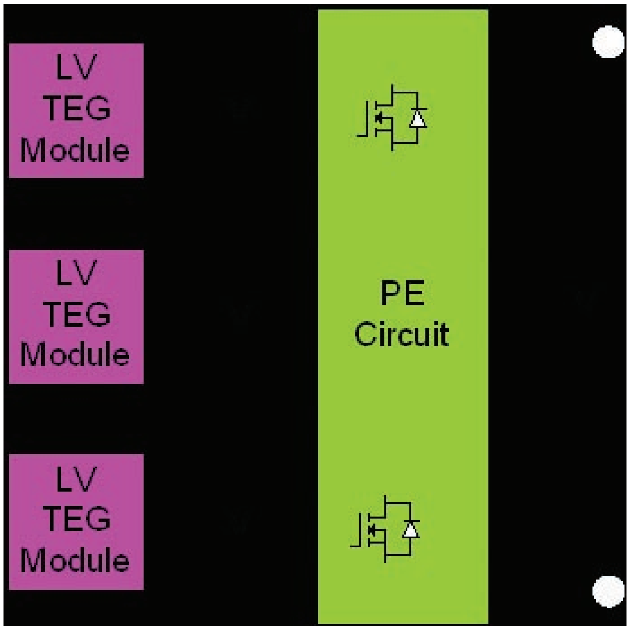

FIGURE 1. Using Power Electronic Circuits to Improve TEG reliability, Provide Load Matching, and Protection

3. Production and Property Characterization of TE Materials

Over the last 12 months a major effort related to production, powder processing and material characterization of LAST/T material has been underway. Powder processing by wet and dry milling has been explored. The particle size and distribution of these powders were analyzed using Coulter counters and scanning electron microscope micrographs. Powder was hot pressed at the University of Michigan and ORNL. Over 90 LAST/T ingots of various stoichiometries were synthesized during the past year. Material property characterization was performed on these ingots by studying hardness, elastic modulus, fracture toughness and internal strain.

4. Leg Segmentation

JPL assisted MSU in their efforts to mature LAST-based thermoelectric technology to quantify the thermoelectric and electrical properties of this material as well as helping to develop hot pressing methods for the LAST material. A puck of LAST ETN121 was metallized using JPL's *in situ* hot pressing technique (Figure 2). JPL has also been involved with designing and developing Skutterudite/PbTe/BiTe technology for the waste heat application.

5. Engine-Thermoelectric Systems Performance

The analytical study continues with the objective of a more accurate prediction of the potential benefits of TEG design alternatives for converting exhaust gas heat into electrical energy. The WAVE engine system model simulates the complete engine system. Contrary to the Phase I model, the TEG now functions as the exhaust gas recirculation (EGR) cooler and resides within the EGR bypass subsystem.

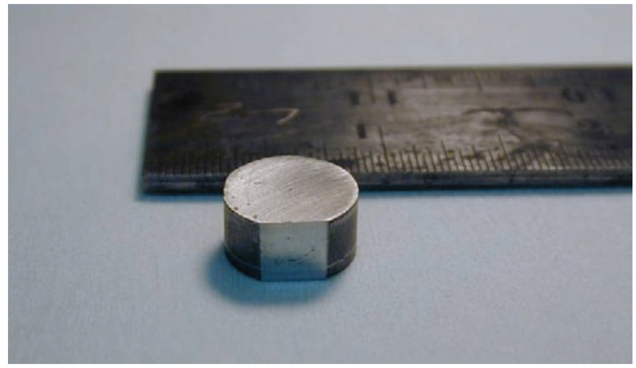

FIGURE 2. A 0.5″ LAST ETN 121 Puck Metallized with Ni on One End and Fe on the other

One of the primary objectives of this analysis is to better understand and quantify the balance of exhaust gas mass flows between the TEG (EGR cooler) and the exhaust turbine. The temperature variation along the length of the TEG at this instant in the engine cycle spans over 300 K. Calculated improvements in fuel economy are shown in Table 3.

TABLE 3. Improvement in BSFC for Different TEG Configurations

TEG configuration	% Improvement in BSFC
1 Cylinder into 1 TEG (6 TEGs)	6.2%
3 Cylinders into 1 TEG (2 TEGs)	4.0%
6 Cylinders into 1 TEG (1 TEG)	2.8%
TEG used as EGR Cooler (1 TEG)	1.5%

6. Heat Transfer Enhancement

As part of the proposed efforts on heat transfer enhancement, literature on gas-turbine thermal management was reviewed to identify heat transfer enhancements techniques for the hot-gas side. Some examples of heat-transfer enhancement techniques are shown in Figure 3, which involve ribs in various arrangements. This survey indicates that the maximum heat transfer enhancement is approximately three to four on the average at best. However, it was noted that locally the heat transfer enhancement can be higher.

7. ZT Amplification

By the end of Phase 2 our goal is to achieve not only a doubling of our current ZT of 1.4-1.7 but also close matching of the temperature profiles of the ZT to the temperature profile available from the diesel engine

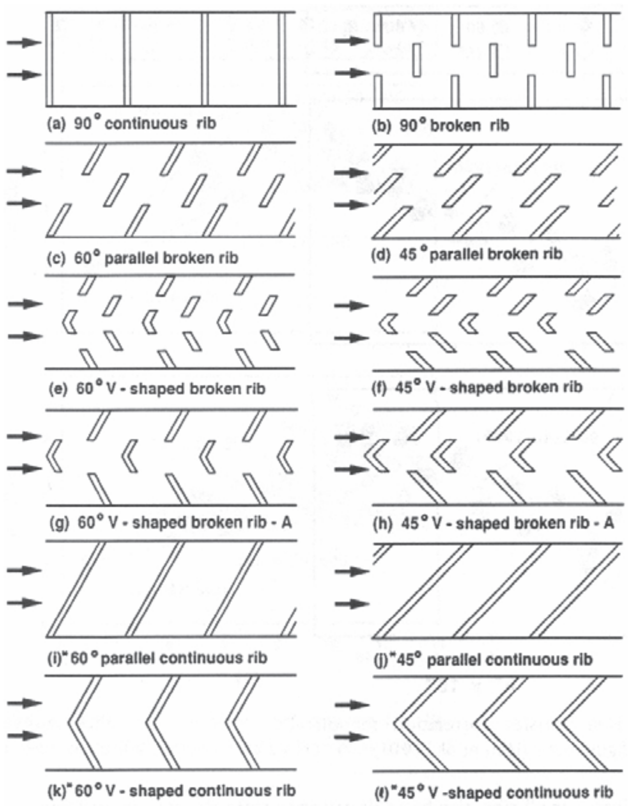

FIGURE 3. Examples of Heat-Transfer Enhancement Methods Involving Ribs

selected for the project. Emphasis will be on long-term material stability and cost.

We are focusing on the $AgPb_{18}SbTe_{20}$ class of materials but also on KPb_mSbTe_{2+m} and PbTe derivatives which show good promise for high efficiency. We expect materials with lower Pb content such as $KPb_{16}SbTe_{20}$ and $KPb_{14}SbTe_{20}$ to have lower thermal conductivity which should help reach higher ZTs. We have investigated the PbTe systems containing Eu nanoparticles. Preliminary data for these samples have been obtained and they are promising. Details of this work can be found in our Septembr 30, 2006 quarterly report to DOE.

Conclusions

Completion of the Phase II effort will provide the following results:

- Preliminary TEG design will be completed using material properties that have been measured.
- Demonstrate the viability of a module which can produce between 20 and 40 watts of power with a temperature difference of less than 800 K on the hot side and 300 K on the cold side.
- Accurately quantify the bulk mechanical properties for the LAST/T material for use in the FEA studies of the thermoelectric generator.
- Complete selection of appropriate metallization for segmented couples, voltage insulators and required sublimation suppression.
- Couple detailed heat transfer models of Iowa State University to WAVE and FEA models of thermoelectric generator. Perform comparison of system efficiency for various options.
- Estimate of possible performance gains using demonstrated materials with known mechanical and thermoelectric properties will be provided.

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2. A. L. Pilchak, F. Ren, E. D. Case, E. J. Timm and H. J. Schock, “The effect of milling time and grinding media upon the particle size distribution for LAST (Lead-Antimony-Silver-Tellurium) powders,” to be submitted, Materials Science and Engineering.

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IV.5 Exhaust Energy Recovery

Christopher R. Nelson
Cummins Inc.
1900 McKinley Ave.
Columbus, IN 47203

DOE Technology Development Manager:
Roland Gravel

NETL Project Manager: Ralph Nine

Objectives

- Improve engine fuel efficiency by 10% through the recovery of waste heat energy
- Reduce the need for additional cooling capacity in Class 8 trucks
- Provide conditioning (cooling) for combustion charge air

Accomplishments

- Identified the prime path working fluid for the Rankine cycle system. Honeywell Genetron R245fa has been identified as the most appropriate working fluid for use as it is available, has good environmental and thermal performance properties, and is expected to be a cost-effective choice.
- Performed thermodynamic cycle analysis to predict performance across engine duty cycle. Basic thermodynamic analysis has been conducted to determine the amount of power recoverable from the Rankine cycle system. Analysis has identified the optimum arrangement of heat exchangers and system components within planned engine system architectures to provide the maximum amount of power recovery with a minimum of system complexity and expense.
- Identified supporting technologies to enhance the recovery of waste heat energy using common electric power engineering components. Recovered waste heat energy will be converted to electricity. This electricity is most efficiently handled at higher voltages (approximately 340 VDC, common with hybrid electric vehicle technology). The presence of a high-voltage bus and its associated components creates a power system which can accommodate high-voltage power producing and consuming devices. More efficient electrically driven parasitics (such as coolant pumps, fans, etc.) will be explored to most effectively utilize the recovered electric power.

Future Directions

Continuing effort is planned in the pursuit of an effective and efficient Rankine cycle waste heat recovery system. The past activities have identified key components and have defined their performance for a successful, integrated system. Based on this analysis we expect to:

- Create specifications for prototype hardware and control software. Suppliers were identified during FY 2006 and we will be working with them to design, fabricate, and test their prototype devices prior to their delivery for laboratory, engine-system level testing.
- Perform subcomponent testing of prototypes and verify model predictions for their performance.
- Perform model-based simulation of integrated systems for vehicle-level performance prediction across operating duty cycles.
- Define expected hardware performance in-vehicle.
- Start laboratory-based, integrated system testing.

Also, we will continue pursuit of an electric-assist turbocharger which will use the high-voltage power electronics introduced in support of the energy recovery system. This development also supports potential significant emissions improvement and engine performance (responsiveness for improved driveability). Towards this goal we expect to:

- Create an appropriate turbocharger model for the target engine application (Cummins' ISX, 15-liter, 6-cylinder engine)
- Perform modeling exercises to determine the potential performance improvement this technology may offer to exhaust gas recirculation (EGR) engines.
- Pursue hardware for testing should modeling results indicate significant benefit.

Introduction

With the advent of low-NOx combustion techniques using cooled EGR, heat rejection has increased driving cooling package space claims 'in vehicle' to their limits.

A means to mitigate this increased heat rejection is desired to avoid extensive revisions to vehicle cooling packages. A solution which serves this purpose while providing operating efficiency benefits would be ideal.

The Rankine cycle is essentially a steam-turbine thermodynamic cycle wherein a working fluid (akin to water or steam) is heated to boiling and superheated (heated beyond boiling). Thereafter, the fluid is passed to an expansion device (in this case a turbine) where it releases its heating-induced energy and momentum to create mechanical work. This work is used to turn a generator which then provides additional power above what the diesel engine produces for the same amount of fuel burned. Using the Rankine cycle to extract energy (or to thereby provide cooling) from waste heat streams serves to reduce the amount of heat which must be rejected while simultaneously providing extra power. Reducing heat rejection and minimizing cooling package size serves to provide vehicle manufacturers with continued opportunities to minimize vehicle frontal area, reducing aerodynamic drag, and improving fuel economy.

The Exhaust Energy Recovery program at Cummins Inc. was initiated by experiments conducted under the Heavy Duty Truck Engine program. During this testing, a Rankine cycle was employed in support of that Program's high engine efficiency demonstration. In the current work, Rankine cycle heat recovery is being focused on the heavy-duty diesel engine's EGR and fresh, compressed charge air streams as these sources of waste heat drive the most significant performance increase to the vehicle's cooling package. Also, in combination to this recovery work, electric-assist turbocharging will be pursued to add to and use power provided by the Rankine cycle energy recovery system.

Approach

Cummins' approach to the Program objectives emphasizes analysis-led-design in nearly all aspects of the research. An emphasis is placed on modeling and simulation results to lead the way into feasible solutions.

With the advent of cooled EGR-based combustion technology, the need to provide an effective cooling system for combustion charge conditioning has become vital. The additional cooling required for additional EGR and fresh charge air to thereby achieve low intake manifold temperatures (in pursuit of clean combustion) drives an increase in vehicle cooling system performance.

A Rankine cycle extracting heat energy from the engine's EGR and fresh, compressed charge air streams reduces the heat load on the cooling package and simultaneously provides extra power from the engine system. The cycle's turbine-driven electric generator provides power which may be used for a number of different on-vehicle applications including:

- Traditional alternator load (alternator may be removed)
- Supplemental power to engine output (through the use of a driveline-coupled motor)
- More efficient parasitics in the form of coolant pumps, fans, etc.

To efficiently accommodate power from the Rankine cycle generator and to minimize its size, higher voltage than what is traditionally used on heavy-duty vehicles (12 VDC) is required. The recommended voltage level of approximately 340 VDC creates opportunities to use efficient and cost-effective power electronics developed for use in other industries (rectifiers, power conditioners, motor drives, etc.) and components and techniques common with hybrid electric vehicles. High-speed, permanent-magnet or switched-reluctance generators and motors are also compatible with this higher-voltage environment. This compatibility leads to further applications of these devices with subsequent efficiency benefits to the engine and vehicle. The electric-assist turbocharger is one example of this. Efficient coolant pumps, fans, etc. are others.

Results

Research has been focused on identifying the most effective techniques and tools for Rankine cycle application to a heavy-duty diesel engine installed in a Class 8 tractor.

Simulation Analysis

A simple Recuperated Rankine Cycle is schematically presented in Figure 1. Saturated liquid working fluid (blue) comes from the system condenser and first passes through a Recuperator which transfers energy left over after turbine energy extraction. The fluid then passes to the engine heat exchangers (charge

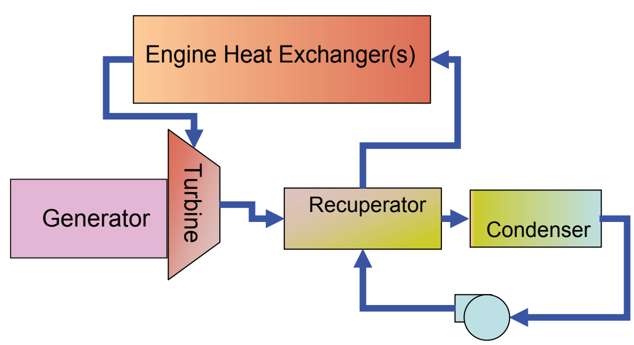

FIGURE 1. Simple Recuperated Rankine Cycle

air cooler, CAC, and EGR cooler) where it reaches a superheated state. The superheated vapor is then passed through the turbine to generate electricity. The fluid then passes through the recuperator and then the condenser.

A performance analysis using R245fa in a recuperated Rankine cycle extracting energy only from EGR and charge air resulted in a maximum brake thermal efficiency (BTE) improvement of 10.6% over the base engine alone at the B100 operating condition. Heat rejection out of the engine system from the EGR and compressed, fresh charge air was reduced by 16.3% (or by the Rankine cycle efficiency). The table below summarizes results from this study.

TABLE 1. R245FA Recuperated Rankine Cycle Analysis using only CAC and EGR Heat

Condition	Engine Power (kW)	Total Heat Rejection (kW)	Net WHR (kWe)	%BTE Improvement
C100 – Max Power	338	234.9	35.68	10.55
B100 – High speed, high torque	336	235.4	35.8	10.64
B50 – cruise	170	96.7	14.7	8.62
A100 – low speed, high torque	283	151.8	23.1	8.2

The optimum configuration for energy recovery from the ISX engine has continued beyond this analysis and has considered a Rankine cycle architecture which best fits within the expected engine architecture for future diesel engines. The recovery of heat energy from only EGR flow offers a simpler packaging challenge with acceptable performance results.

Hardware Design

An initial design study (see Figure 2) of a turbine generator for this application has been made. The turbine for this application will be either a variable nozzle turbine (VNT) or variable admission turbine (VAT) to increase Rankine cycle efficiency over the base engine operating map as much as possible. Also, this design includes a reaction-type turbine wheel (similar to existing turbocharger compressor wheels) and hydrodynamic bearings for good performance in-vehicle against shock and vibration (again, similar to turbocharger technology).

Generator output voltage for this system is expected to be 340 VDC in order to be compatible with currently available heavy hybrid transmission and driveline equipment. This higher voltage also minimizes the physical size of the generator.

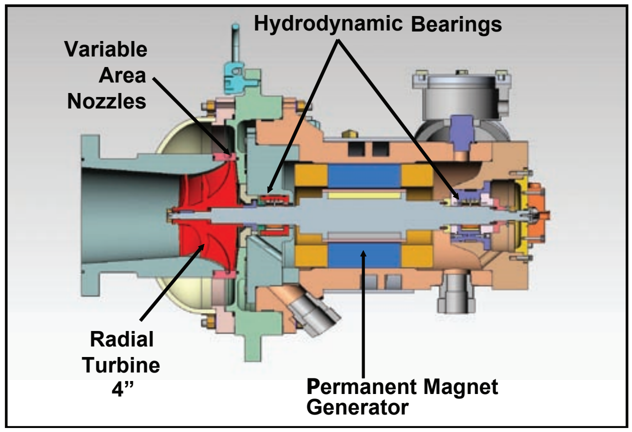

FIGURE 2. Proposed Turbine/Generator Design

Heat exchangers for the system are being pursued through outside suppliers who are providing design, fabrication, modeling, analysis, and performance testing of their components prior to integrated system testing at Cummins. The work is similar to the effort made for typical EGR coolers and CACs. Of critical concern is the maintenance of a temperate operating environment for the working fluid as over-temperature conditions will lead to fluid breakdown.

The system’s driveline motor and high voltage power electronics are being designed and developed by Cummins Power Generation and Generating Technologies groups. Typical efficiencies for the major components in the power electronics architecture are expected to be approximately 96%, resulting in very little loss due to power conditioning.

Conclusions

Modeling and analysis performed to date, supported by the previous experiments with Rankine cycle systems on the Heavy Duty Truck Engine Program leads us to expect significant efficiency improvement from the heavy-duty diesel engine through the incorporation of this concept. The synergistic opportunities offered by the presence of additional electric power with subsequent efficiency gains and improved parasitic load characteristics indicate that this concept has significant potential to improve real, in-use fuel economy.

- The 10% efficiency improvement goal is technically feasible and appropriate components (working fluid, turbine/generator, flywheel motor-generator) for the Rankine cycle concept are being developed.
- Significant cooling system benefit is possible from this concept and will therefore provide benefits beyond base engine fuel efficiency to the vehicle original equipment manufacturer customer.

- Provision of appropriately conditioned charge air for clean combustion is promoted through the incorporation of this system.
- Additional benefits through the utilization of optimized parasitics are possible.
- Utilization of other high-speed rotating electric machinery (electric-assist turbocharging) is enabled through this concept.

FY 2006 Publications/Presentations

1. 2006 DEER Conference Presentation – "Exhaust Energy Recovery", presented by Christopher R. Nelson, 24th August, 2006.

IV.6 Very High Fuel Economy, Heavy Duty, Constant Speed, Truck Engine Optimized via Unique Energy Recovery Turbines and Facilitated by a High Efficiency Continuously Variable Drivetrain

Todd Reppert
Mack Trucks Inc.
13304 Pennsylvania Ave.
Hagerstown, MD 21742

DOE Technology Development Manager:
Roland Gravel

NETL Project Manager: Sam Taylor

Subcontractors:
- Volvo Aero Corp., Malmo, Sweden
- Volvo Technology, Gothenburg, Sweden

Objectives

- Increase engine efficiency by 10% while meeting U.S. 2010 emissions standards.
- Achieve efficiency increase by implementing energy recovery devices in the form of turbocompounding and narrowing the engine operating speed range. Couple the engine to a continuously variable transmission (CVT) to enable the engine to operate in a narrow or constant speed (1,000-1,300 RPM).
- Test the engine-CVT combination over road cycles in a test cell to demonstrate system efficiency increase.

Accomplishments

- Through simulation, demonstrated an engine efficiency increase of 8.2% when operating over a road cycle and 10.5% during steady-state operation over the ESC/OICA at U.S. 2010 NOx levels (0.2 g/bhp-hr).
- Met the milestone that the added investment for the CVT and energy recovery devices will be returned in less than 1.5 years assuming fuel prices of $2.50 per gallon.
- Net fuel efficiency when coupled to a CVT was estimated to be a 5% increase.

Future Directions

- Design a compressor and two turbines (turbocharger and compound), tailored for the highly weighted operating points. Design of complete turbocharger and turbo compound units.
- Test these compressor and turbines in special rigs in order to verify the theoretical performance.
- Build prototype high efficiency turbo and turbo compound units for testing.
- Begin baseline engine development that will include high efficiency turbo and turbo compound units.
- Demonstrate the engine and CVT system in a test cell environment to determine system efficiency.

Introduction

Fuel prices have remained high for the last several years hovering at times around the $3.50 per gallon mark. The heavy-duty trucking industry is very sensitive to fuel pricing and at times passes the increased cost on to the consumer. With new and more stringent emissions standards taking effect in 2007 and than again in 2010, fuel economy will suffer as more energy is needed to drive the emissions control devices. Even as little as a 1% improvement in fuel consumption can mean huge savings for a fleet of say 100 trucks operating 100,000 miles per year.

One way to increase the engine's efficiency is to recover some of the energy that is lost through the exhaust. A mechanical turbo compound device has the ability to direct some of that energy back to the engine gear train by coupling directly to the compound turbine thus reducing a portion of the energy lost through the exhaust as can be seen in Figure 1. It is worth mentioning that a turbo compound engine reacts more positively to improved turbo efficiency than a conventional turbocharged engine. This project has taken an energy recovery approach along with operating the engine in a different speed range than today's engine. Narrowing the engine operating speed range allows the designer to select the optimum speed where engine efficiency is highest. Conventional standard transmissions operate with gear steps too wide to run the engine in a constant or narrow range but with the development of a CVT, narrow range operation is possible which will allow the engine to operate at peak efficiency over its entire operating range.

Besides the more narrow operating range, the average engine speed is also lower. This makes it possible to optimize valve timings, combustion specification etc. High efficiency turbo compressors are also important to realize increased overall efficiency.

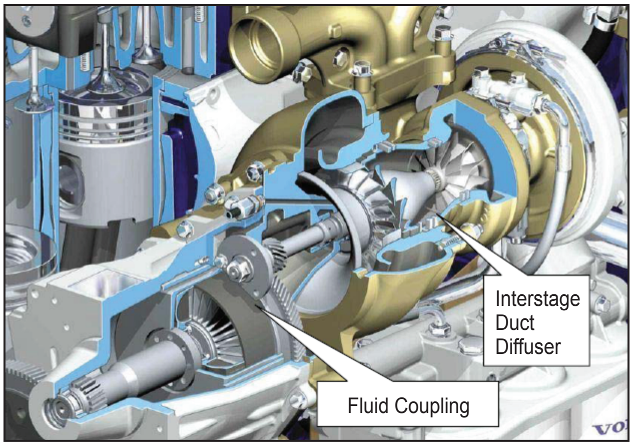

FIGURE 1. Close-up Showing the Turbocharger, Interstage Duct Diffuser and Turbocompound

The more narrow speed range allows the use of a compressor with a vaned diffuser which has higher efficiency compared to a vaneless diffuser. In order to achieve the efficiency goal, four techniques were combined: mechanical turbo compound, high efficiency turbochargers, narrow range operation and optimized combustion and valve timings.

Approach

To determine the efficiency improvement potential detailed engine simulations were done considering the Volvo MD13 (485 hp/2,600 Nm) engine to determine the benefit of reducing engine speed and impact on efficiency. The simulations guided the development of the narrow range approach and allowed the study of different operating ranges so the best one could be chosen. Simulations were also done to determine the best turbocharger and turbo compound combination that would return the highest efficiency improvement without adding significant cost to the engine. The turbo compound unit is based on a production unit for the Volvo D12 500 hp engine in Europe. Cost analyses were performed on the engine system including the CVT to determine the added cost and return on investment.

Based on the engine simulations, prototype turbocharger and turbo compound hardware will be designed and manufactured. The prototype hardware will be installed onto a 13L Volvo engine for testing to compare simulation results with actual.

The final plan is to assemble the engine with the high efficiency turbocharger and turbo compound units and CVT and place in a test cell capable of running the same road cycles that was done during the simulation phase. The results of the testing will be compared to that determined through vehicle simulations.

Results

The simulation result showed the fuel consumption reduction compared to the U.S. 2007 reference engine is 8.2% when using the U.S. 2007 weight factors (flat 70%, rolling hills 25% and hilly 5%) and 10.5% when using the European Steady State Cycle (ESC). These improvements are achieved by a number of measures compared to a conventional turbocharged engine. The main contributor is the mechanical turbo compound system which converts exhaust energy into mechanical work. This unit has a high efficiency axial turbine with a stator. The duct between the turbocharger and the compound turbine is annular with low pressure loss and high pressure recovery. The turbocharger has both a high efficiency compressor and turbine. The turbo compound system also has the advantage of positive driving pressure for the high-pressure exhaust gas recirculation (EGR) system. If a conventional turbocharged engine has too high turbine efficiency, the exhaust pressure will be too low compared to the inlet manifold pressure and the driving pressure for EGR will be negative. The other source of the improvement is the narrow range operation which allows optimized camshaft timings and combustion.

Two different engine speed control strategies were studied, constant speed and narrow range. The narrow range strategy means that the engine speed is not fixed but optimized over a certain cycle ranging from 1,000-1,300 rpm at part load. The result of this study showed that the narrow speed engine is more efficient than the constant one when the engine is not working in full power range. It can be seen from Figure 2 that, it is more economical to reduce the speed at part loads.

The engine cost estimate has been divided into four different sub-groups including turbocharger, turbocompound unit, interstage duct diffuser and modification necessary to the engine to accommodate the turbocompound unit which results in additional cost in producing the engine. This additional cost can

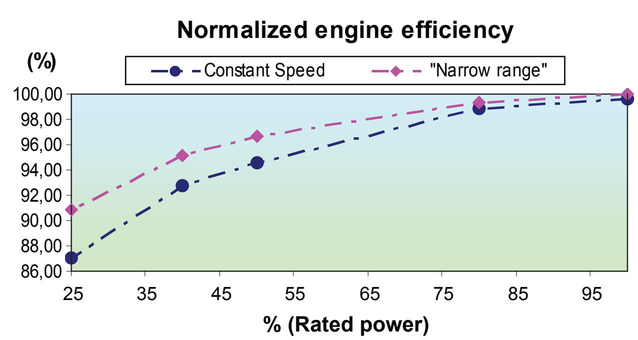

FIGURE 2. Engine Efficiency Comparison in "Constant" and "Narrow range" Speeds

be paid back by decreased fuel consumption over a period of time which depends on the fuel price and the recovered efficiency. To calculate the payback time the following premises have been used:

Truck mileage per day	600 miles (966 km)
Working days per year	240 days
Average fuel consumption	6.5 MPG (reference) (36.2 lit/100 km)
Increased fuel economy	5 – 7 – 10 % improvement
Fuel price	2.5 - 3.0 - 3.5 - 4.0 - 4.5 - 5.0 $/gallon

The added cost for the system will be returned in less than 15 months assuming fuel prices of $2.50 per gallon and the lowest recovered efficiency. Figure 3 shows the payback time for the higher fuel prices and efficiencies.

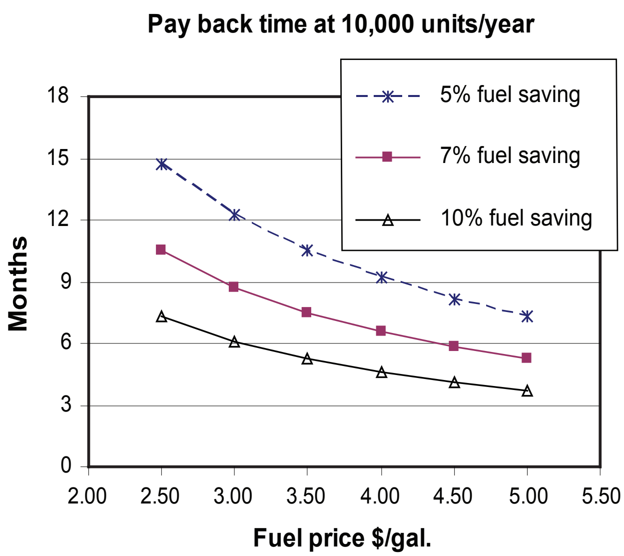

FIGURE 3. Pay Back Time in Months at Various Fuel Prices and Increased Fuel Efficiencies for 10,000 Unit Production Volume per Year

Conclusions

The target for engine efficiency increase was 10% – 13% which was met by achieving 10.5% efficiency improvement when the engine was operating over a steady-state cycle. However, the achievement in the road cycle was 8.2% increase in efficiency. When the engine was coupled to a CVT the efficiency increase was only 5%.

A comprehensive study showed that with a 5% increased efficiency and the fuel price of $2.50/gal, it takes a little less than 1.5 years to compensate the initial charges added to the engine due to the efficiency recovery units. This study has been done for a 10,000-unit production volume per year. With increase in annual production numbers and considering a learning factor of 0.87 the pay back time will reduce significantly.

At the moment, detailed design work is on going to understand the turbo flow characteristics and stress levels with the compressor, turbocharger turbine and compound turbine. This design will satisfy the highly weighted operating conditions.

References

1. Quarterly Reports DOE/NETL, Contract – DE-FC-05NT45421, 2005-2006.

FY 2006 Publications/Presentations

1. Quarterly Reports DOE/NETL, Contract – DE-FC-05NT45421, 2005-2006.