Nanostructured High Temperature Bulk Thermoelectric Energy Conversion for Efficient Waste Heat Recovery

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GMZ Energy
May 18, 2012

ACE082

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Project Overview

Timeline
- October 1, 2011
- September 30, 2015
- ~15% complete

Budget
- Total project funding
  - $7,964K DOE
  - $3,386K Cost-Share
- Funding received in FY11
  - $0
- Funding for FY12
  - $1,641K obligated to date
  - $547K available

Barriers
- Barriers addressed
  - Cost-competitive TE systems
  - Scale-up to practical device size
  - TE device/system packaging
  - Component/system durability

Partners
- Robert Bosch, LLC, Boston College, Oak Ridge National Laboratory
- Project Lead - GMZ Energy
Project Objectives:

- The final objective of this program is to demonstrate a robust, thermally cyclable thermoelectric exhaust waste heat recovery system that will provide at least a 5% fuel efficiency improvement for a light-duty vehicle platform.
- A small-displacement engine of approximately 2.0 liters will act as the platform for the demonstration of the developed exhaust waste heat recovery system.
- In the first phase of the program (ending 1/31/13), the team will develop:
  - TE device technology to enable reliable power generation systems: TE materials, contact metallization, joining, characterization (electrical and mechanical)
  - System design/architecture for reliable operation and maximizing cost/performance ($/fuel efficiency increase)
## Project Milestones – Phase 1

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<td>Half-Heusler device, 4% efficiency</td>
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<td>Initial vehicle model</td>
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<td>Initial testing plan</td>
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• Proposed two-stage TEG system with half-heusler as the first stage, and Bi$_2$Te$_3$ as the low temperature stage. Thermal buses and high thermal conductivity spacers, together with thermal insulation are used to concentrate heat to low-profile generators, significantly reducing the amount of materials used for the TEGs.

• This program uses unique high-performance nanostructured TE materials based on half-heusler alloys, which have superior mechanical strength and durability compared to competing materials (e.g. skutterudites) and can still be made with low-cost, large volume processes – currently underway at GMZ.
Phase 1 will see the team focus on progress on TE device performance (electrical and mechanical) with three characterization systems:

- Scanning probe for high-resolution spatial resistance characterization (contact resistance, diffusion of contacts and joints)
- High-temperature power generation efficiency measurement system (power output, efficiency, thermal cycles)
- Electro-mechanical testing system (Instron) for tension, compression and shear testing (device/joint strength, input in system mechanical design)
Project Technical Accomplishments and Progress: Summary

• Half-Heusler Materials (Boston College, GMZ Energy):
  – Repeat legacy materials fabrication process from BC at GMZ to give high repeatable high ZT materials
  – Initial reduction of costly Hf component shows good initial success

• Half-Heusler Devices (GMZ Energy):
  – Initial contact metallization shows low contact resistance and good diffusion barrier properties
  – Power generation system designed and will be operational April 2012
  – Instron mechanical test system delivered and will be operational April 2012

• TEG System and Vehicle Model/Design (Bosch, ORNL, GMZ Energy):
  – Initial models using ANSYS at GMZ and Bosch; engineering staff developing strategy for merging models
  – Workshop on system design scheduled at GMZ for May 2012
Boston College and GMZ Energy have now made high-performance half-heusler materials (both n-type and p-type) in repeatable fashion in both locations.

- P-type performance gain is >100% improvement and drives half-heusler as a newly realistic option for use in the TEG.
In order to reduce the cost of the half-heusler materials, the reduction in Hafnium is necessary as the most costly component.

Initial work at BC and GMZ has shown that the Hf can be reduced by nearly 3x while maintaining high TE performance.
Technical Accomplishments and Progress: Half-Heusler Devices

- In order to make good devices, good contact layers are needed.
- GMZ has successfully applied thick (diffusion barrier) contacts with low contact resistivity – precursor to high-performance devices and modules.

![Graph showing voltage and position before and after annealing.]

Before annealing:

- Measured Contact Resistance: $0.827 \mu \Omega \text{cm}^2$

After annealing:

- Measured Contact Resistance: $0.763 \mu \Omega \text{cm}^2$
Technical Accomplishments and Progress: Half-Heusler Devices

- Initial brazing has confirmed HH mechanical and temperature stability
- GMZ is positioned to move quickly to make device measurements and show high power generation efficiency
Technical Accomplishments and Progress: TEG System and Vehicle Model/Design

• GMZ is building up a full performance model of power generation devices in ANSYS including TE output and thermo-mechanical stresses
• GMZ and Bosch have a plan to merge our TE model with their heat exchanger/system multi-scale model. Details will be discussed at a workshop hosted at GMZ in May, 2012.
Collaboration and Coordination with Other Institutions

GMZ Energy – Team Lead
PI – Dr. Chris Caylor
Consultant – Dr. Gang Chen

Robert Bosch, LLC
Lead – Dr. Boris Kozinsky

Oak Ridge National Lab
Lead – Dr. Jim Szybist

Boston College
Lead – Dr. Zhifeng Ren

• GMZ (Industry) – TE (materials, devices, integration and testing), heat exchangers, module integration and subsystem testing, prototype fabrication
• Robert Bosch (Industry) – automotive systems (electrical, vehicle models and testing), TE materials contacts and integration, heat exchangers
• Boston College (University) – TE materials (ZT improvement, cost-reduction, thermal-mechanical testing)
• Oak Ridge National Lab (Federal Laboratory) – dynamometer testing and vehicle model
Proposed Future Work

- **Half-Heusler Materials**
  - Build up inventory of HH materials for device making (GMZ)
  - Confirm and refine Hf reduction in HH materials (GMZ and BC)
  - Experiments to increase ZT of HH materials (BC, Bosch and GMZ)

- **Half-Heusler Devices**
  - Power generation testing of HH devices (GMZ)
  - Mechanical testing of HH devices (GMZ)
  - Diffusion and thermal cycle data on HH devices (GMZ and Bosch)

- **Bismuth Telluride Devices**
  - Power generation testing of BT devices (GMZ)
  - Mechanical testing of BT devices (GMZ)
  - Diffusion and thermal cycle data on BT devices (GMZ and Bosch)

- **Heat Exchanger Design**
  - Workshop on system design (GMZ and Bosch)
  - Mechanical and performance model of initial design (GMZ and Bosch)

- **System/Vehicle Model**
  - Workshop on system/vehicle model (GMZ and Bosch)
  - Study of fabrication and materials costs, performance and fuel efficiency gains (GMZ and Bosch)
Project Summary

• Project Relevance: this program speaks directly to the major challenges in bringing TE devices to bear on automotive efficiency
  – Nanostructured HH and BT materials offer a low-cost, high-performance, reliable and durable option for TE power generation and offers the promise of affordable scale-up and system packaging
• Project Approach: early verification of materials and device performance through power generation and mechanical testing – by December 2012
• Technical Accomplishments:
  – Repeatable HH materials with good indication of lower cost through Hafnium reduction
  – Repeatable and low resistance metal contacts and brazing to HH materials
  – Initial ANSYS model for merging with Bosch’s multi-scale system model
• Collaboration and Coordination: Interaction with BC, Bosch and ORNL going well with planned workshops to jump start collaborations on heat exchanger and system architecture and designs