Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power

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Project ID # ACE081

Overview

Timeline

- Start date – September 2012
- End date – September 2016
- Percent complete – ~4%

Budget

- Total funding: $14,488,388
  – DOE share: $8,750,000
  – Contractor share: $5,738,388
- Expenditure of DOE funds in
  – FY12: $199,691
  – FY13: $122,443 (10/12 - 2/13)

Barriers & Objectives

- Improved TE materials and modules
- Low cost and durable TEG system design
- Improve fuel economy by 5% over US06

Partners

- Interactions/collaborations

Marlow – TE module development & fabrication

Purdue – Thermal Interfaces, heat exchanger modeling and design

Dana, Inc. – Heat exchanger design & fabrication

Eberspaecher – Exhaust system design & fab.

Jet Propulsion Lab – Modeling of TEG system; TE module testing & durability studies

Delphi – TEG electronics packaging & assembly

Molycorp – TE materials synthesis

Michigan State – Protection of TE materials

Oak Ridge Nat'l Lab – TE material properties

Brookhaven Nat'l Lab – TE material synthesis

U of Washington – TE materials research

- Project lead: General Motors

Relevance

- **Improve the US06 fuel economy for light-duty vehicles by 5% using advanced low cost TE technology:**
  - Low cost materials, modules, heat exchangers, power conditioning, and vehicle integration for exhaust gas waste heat recovery
  - Leverage innovative electrical & thermal management strategies to:
    - Reduce electrical accessory load on the alternator via TEG power
    - Electrify engine-driven accessories for increased electrical power usage
    - Use TEG power in ways that complement charging the battery and supplying accessory and electrical loads (e.g., direct hybrid vehicle propulsion)
    - Implement fast engine/transmission warm-up strategies
  - Develop low cost, commercially viable manufacturing processes and plans for scaled-up TEG production (100k units/year)
- **This project is specifically focused on reducing petroleum usage for transportation by increasing fuel efficiency via waste heat recovery using advanced TEG technology**

Relevance – Objectives

TE materials and modules:

- Boost TE material performance for large-scale production to be as good as laboratory results (e.g., achieve literature values of ZTs)
- Improve and optimize p-type skutterudites
- Enhance interfaces (thermal, electrical), bonding (mechanical compliance), diffusion barriers, TE material protection (oxidation & sublimation)
- Develop better high throughput synthesis processes

Temperature profile and ΔTs:

- Create innovative heat exchanger design to optimize conversion efficiency
- Develop good thermal interfaces for high temperature to help optimize actual ΔT

Low cost and durable TEG system design:

- Focus on simple and manufacturable components
- Reduce complexity of TEG system and subsystems
- Develop low cost and durable TEG system and subsystems to accommodate a broad range of operating temperatures.

Electrical power conditioning and interconnects:

- Reduce electrical system complexity through use of IC board connections

Low cost vehicle controls & integration:

- Design TEG system to be integral to vehicle systems

Approach and Strategy

- **Task 2.0 – Overall System Development and Vehicle Integration:** Under this task, the project team will develop the overall system and integrate the TEG subsystem onto a light-duty vehicle.
  - **Subtask 2.1 – Model and Analyze System Design, Performance, and Cost**
  - **Subtask 2.2 – Develop Controls for Prototype System**
  - **Subtask 2.3 – Integrate TEG Assembly onto Demonstration Vehicle**
  - **Subtask 2.4 – Test System on Demonstration Vehicle**

- **Task 3.0 – TE Generator (TEG) Subsystem Development:** Under this task, the project team will design, build, and test two major iterations of the TEG subsystem. In addition, the team will develop manufacturing plans for producing 100,000 units per year.
  - **Subtask 3.1 – Develop Initial TEG Design**
  - **Subtask 3.2 – Design, Build, and Test Components for Initial TEG**
  - **Subtask 3.3 – Fabricate and Assemble Initial TEG**
  - **Subtask 3.4 – Bench Test Initial TEG Assembly**
  - **Subtask 3.5 – Develop Improved Final TEG Design**
  - **Subtask 3.6 – Design, Build, and Test Components for Final TEG**
  - **Subtask 3.7 – Fabricate and Assemble Final TEG**
  - **Subtask 3.8 – Bench Test Final TEG Assembly**
  - **Subtask 3.9 – Develop Volume Manufacturing Plans**

Approach and Strategy (cont.)

- **Task 4.0 – TE Module and Manufacturing Process Development:** Under this task, the project team will develop and utilize manufacturing processes for the production of modules that incorporate advanced TE materials. In addition, the team will test these prototype modules and develop plans for volume production of TE materials. This work will include four subtasks.

  Subtask 4.1 – Develop TE Module Manufacturing Processes
  Subtask 4.2 – Produce TE Materials and Evaluate Production Sources
  Subtask 4.3 – Fabricate TE Modules for Testing and TEG Prototypes
  Subtask 4.4 – Test TE Modules

- **Task 5.0 – Thermoelectric (TE) Materials Research:** Under this task, the project team will develop advanced TE materials that satisfy the TEG requirements. This work will include three subtasks.

  Subtask 5.1 – Conduct P-type TE Materials Research
  Subtask 5.2 – Optimize Advanced TE Materials
  Subtask 5.3 – Investigate Materials Aspects of Encapsulation

Approach – TEG Team

- Project lead: General Motors
  - GM Global R&D: Technical & administrative project leadership, System modeling, Power electronics design, TE materials development
  - GM Energy Center: Vehicle energy analysis & Vehicle selection support
  - GM Powertrain: Vehicle controls & Integration, Dynamometer testing

- Interactions/collaborations:
  - Marlow – TE module development & fabrication
  - Purdue University – Thermal Interfaces, heat exchanger modeling and design
  - Dana, Inc. – Heat exchanger design & fabrication
  - Eberspaecher – Exhaust system design & fabrication
  - Jet Propulsion Lab – Modeling of TEG system; TE module testing & durability studies
  - Delphi – TEG electronics packaging & assembly
  - Molycorp (formerly Magnequench) – TE materials synthesis
  - Michigan State University – Passivation/protection of TE materials
  - Oak Ridge Nat'l Lab – High temperature transport & mechanical property measurements
  - Brookhaven Nat'l Lab – TE materials synthesis
  - University of Washington – TE materials research and development

Milestones and Progress

- Q1 Select demonstration vehicle – Full size pickup truck (Dec. 2012)
- Q2 Complete vehicle and TEG system gap analysis (March 2013)
- Q3 Select TE materials for first prototype modules (June 2013)
- Q4 Establish initial design targets for TEG subsystem
- Q4 Establish initial design targets for TEG components
- Q5 Deliver TE modules for initial TEG prototype
- Q6 Complete preliminary estimate of TEG performance
- Q8 Select TE materials for final prototype modules
- Q10 Deliver TE modules for final TEG prototype
- Q16 Report final TEG performance test results
- Q16 Provide demonstration vehicle to DOE
- Q16 Complete plan for scale-up of TE module manufacturing
- Q16 Identify viable source for TE materials at automotive scale
- Q16 Complete detailed production cost analysis for 100k units/year and cost reduction plan

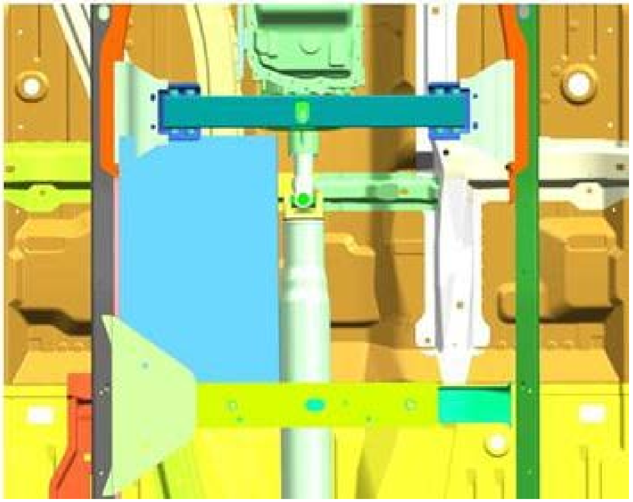
Technical Accomplishments and Progress

Selection and Characterization of Target Platform:

Selected a full-size pick-up truck for demonstration

- Fuel economy improvement achievable for vehicle platform
- Potential significant transportation sector fuel savings (trucks are a large fraction of fleet mix)
- Adequate under-floor space for TEGs facilitates design of multiple compact TEGs for adaptation to smaller vehicle platforms
- Location and available volumes for TEGs have been identified for preliminary design points:

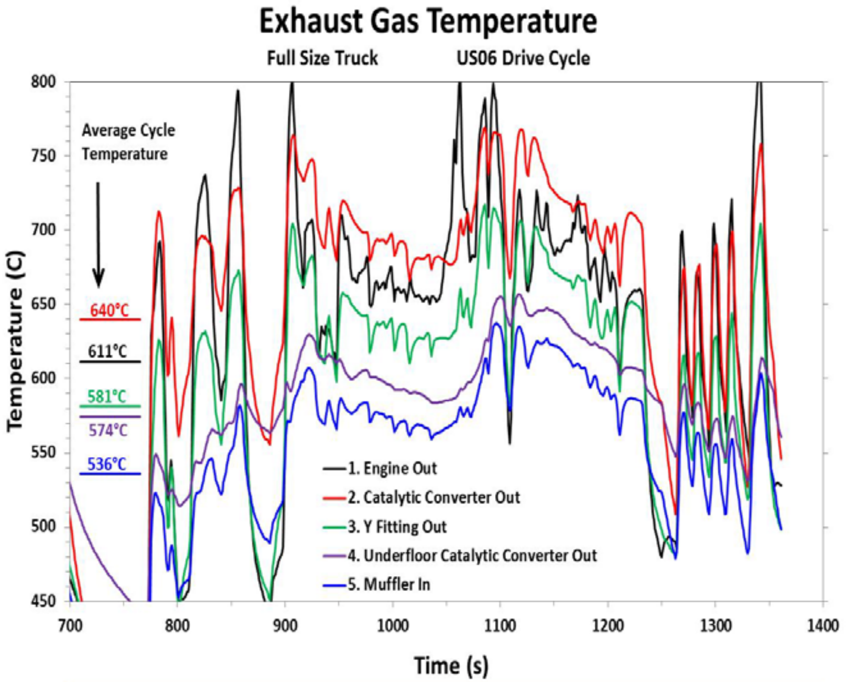
Height	227 mm (8.9 inch)
Width	394 mm (15.5 inch)
Length	594 mm (23.4 inch)

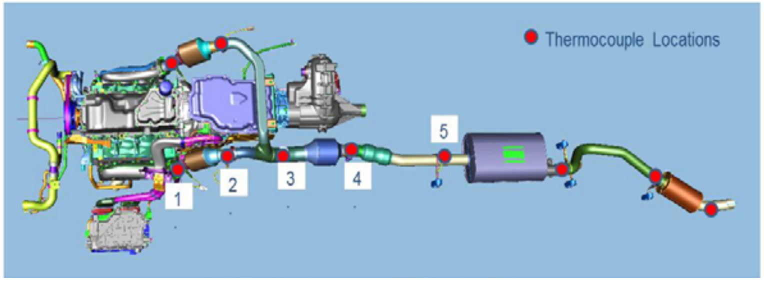


Technical Accomplishments and Progress (cont.)

Selection and Characterization of Target Platform (cont.):

- Collected temperature data at various locations in the exhaust system
- Developed a Unified Vehicle Model of the target platform; integrated our Gen 1 TEG model into it
- Obtained exhaust gas mass flow rates from the Unified Model to support our heat exchanger design efforts
- Performed Gap Analysis: electrical power output of the TEG was fed into the electrical bus of the vehicle and fuel economy (FE) benefit was calculated
- Estimated FE benefit of 2.5 to 3% at current levels of TEG power output
- Used ZT values measured on our scaled-up production materials for power output estimates, not literature values





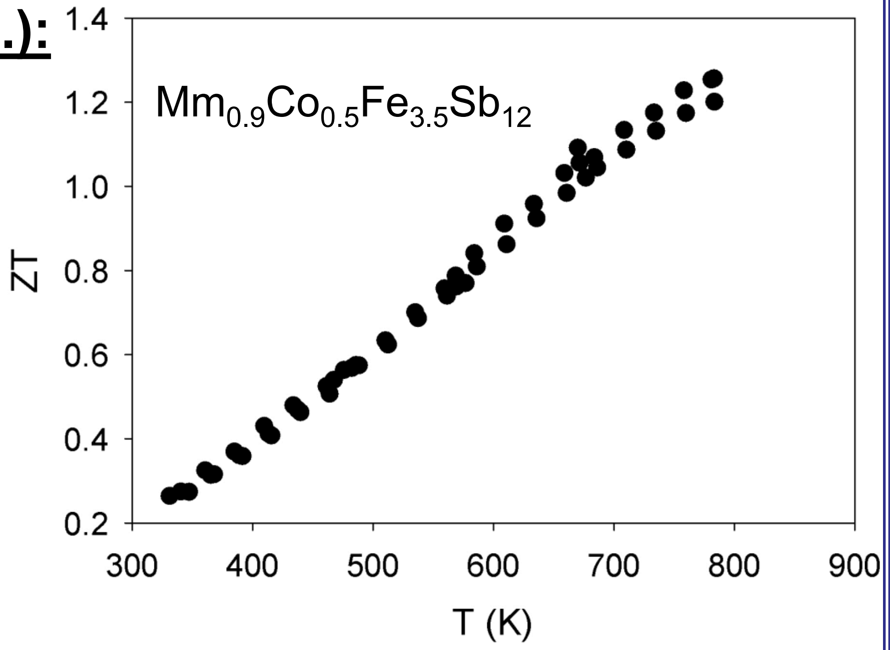
Technical Accomplishments and Progress (cont.)

Materials Development Efforts (Cont.):

Investigated early rare earth (RE) formulations using misch-metal (Mm)

- Band structure calculations indicate a wider band gap and favorable mixing of light and heavy effective mass bands in early RE filled p-type skutterudites $RE_xCo_{4-x}Fe_xSb_{12}$ (i.e., without Yb)
- Synthesized $Mm_{0.9}Co_{0.5}Fe_{3.5}Sb_{12}$ at GM by melt spinning (MS) and SPS
- Evaluated transport properties and found ZT > 1 at 700 K

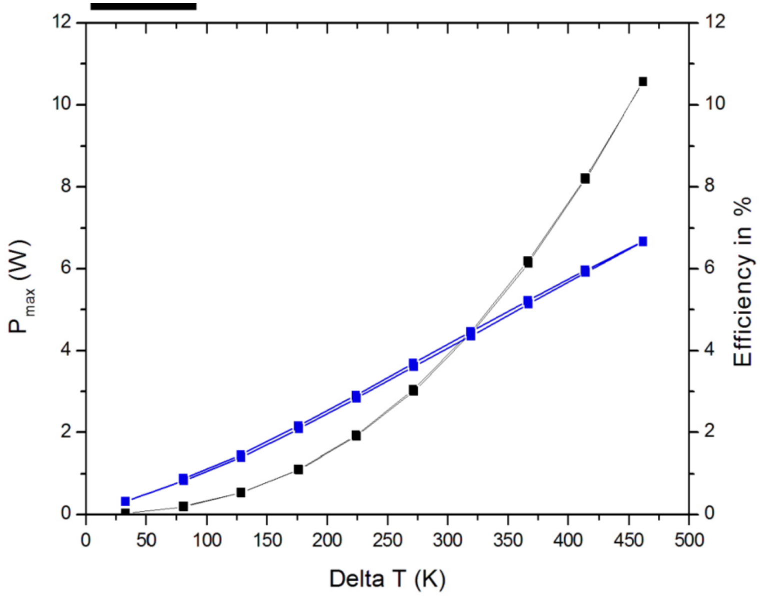
This offers an alternate p-type formulation to mitigate risk of finding appropriate and durable barriers and metallization schemes for $DdFe_xNi_{4-x}Sb_{12}$ (Dd = didymium, a alloy of Pr and Nd)

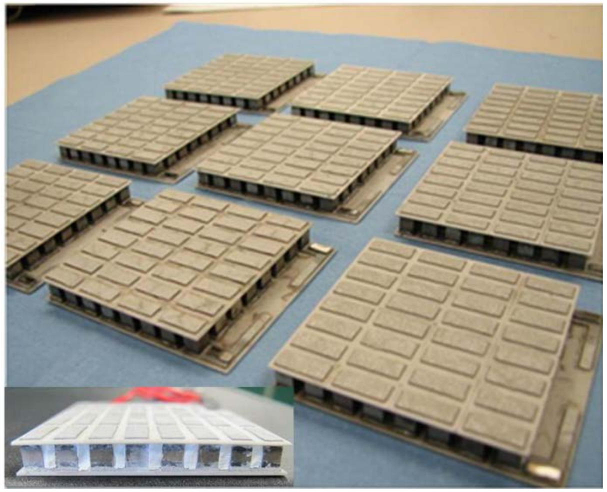


Technical Accomplishments and Progress (cont.)

Module Development Efforts:

- Re-evaluated Gen. 1 skutterudite TE modules using measurements performed at the Fraunhofer Institute
- Determined that large thermal interface contact resistances were key factors causing low power output in the previous program
- Observed significant TE module electrical resistances: up to ~20% of total module resistance was contacts and interconnects
- Re-measured TE modules; performance improved by 30% by increasing loading pressure to reduce thermal contact resistance
- Assessed conversion efficiency and found ~7% at the highest ΔT; attributable in part to reduced thermal losses due to encapsulation

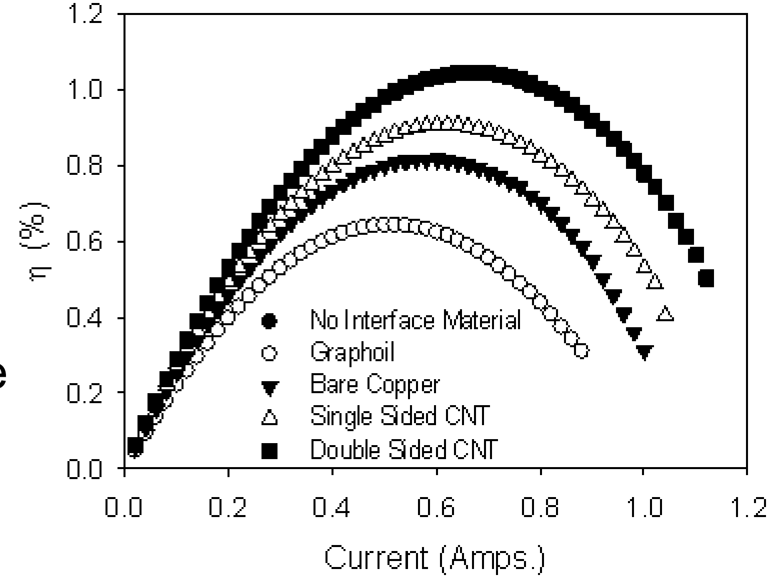


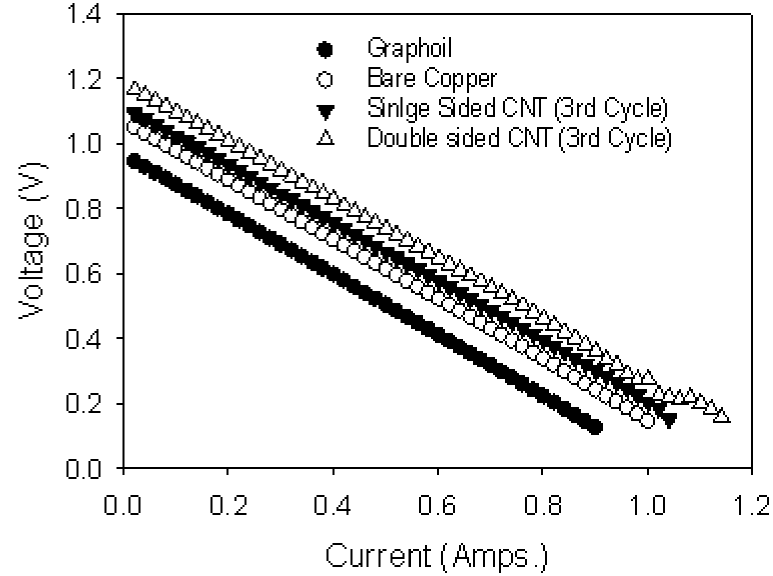


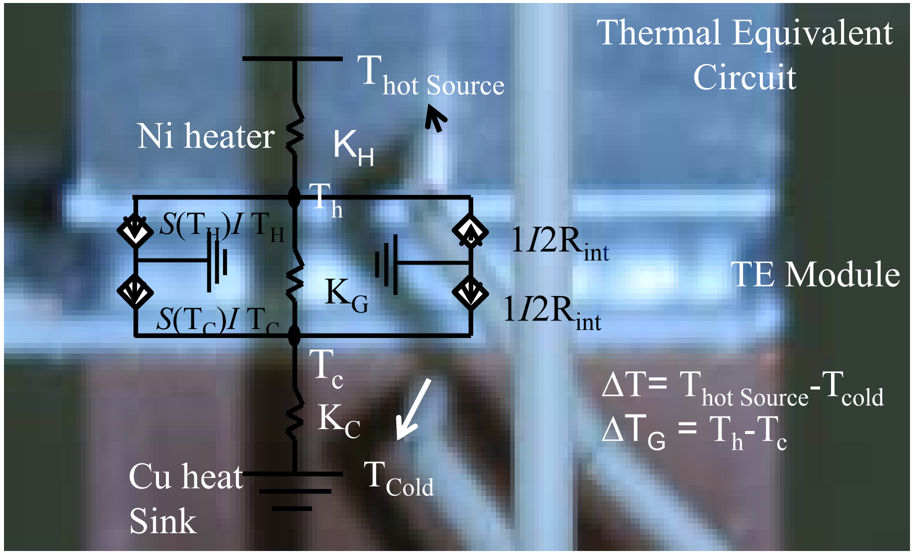
Technical Accomplishments and Progress (cont.)

Thermal Interface Contact Resistance:

- Conducted in-situ evaluation thermal interface materials
- Established efficacy of CNT arrays to reduce thermal interface contact resistance (TICR) for commercially available TE module and test stand
- Observed increase in VOC (voltage at zero current) that indicates a reduction in TICR



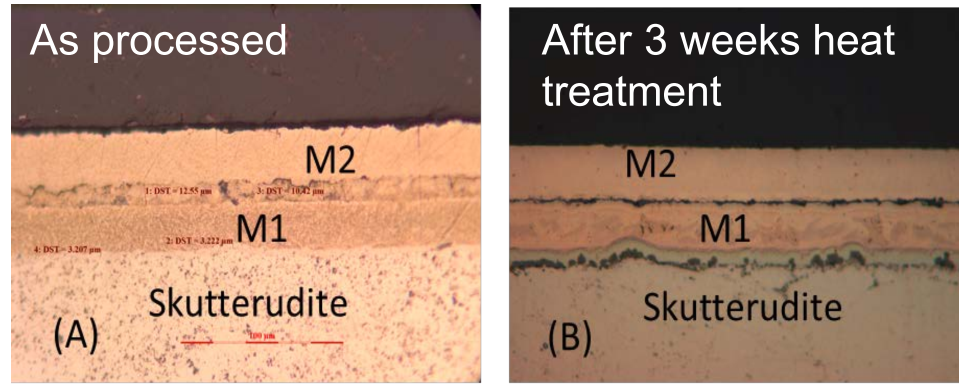


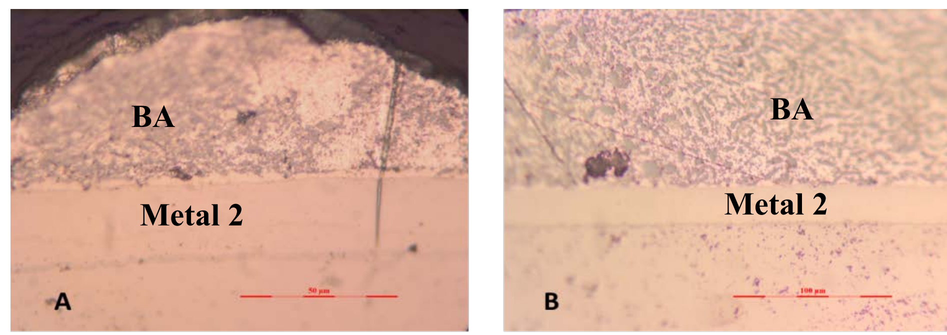


Technical Accomplishments and Progress (cont.)

Module Development (Marlow):

- Investigated new diffusion barriers and metallization schemes that are more compatible with new skutterudite formulations
- Found high electrical contact resistances for Gen 2 TE modules arising from the barriers and metallization on p-type legs
- Now fabricating Gen 3 TE modules by implementing new barrier technology with reduced contact resistance and less propensity for delamination





Collaboration and Coordination with Other Institutions

Partners:

- Marlow (Industry) – TE module development & fabrication
- Purdue University (Academic) – Thermal Interfaces, heat exchanger modeling & design. Thermal conduction mechanisms, electron-phonon interactions
- Dana, Inc. (Industry) – Heat exchanger design & fabrication
- Eberspaecher (Industry) – Exhaust system design & fabrication
- Jet Propulsion Laboratory (Federal) – Modeling of TEG system; TE module testing & durability studies
- Delphi (Industry) – TEG electronics packaging & assembly
- Molycorp (Industry) – TE materials synthesis
- Michigan State University (Academic) – Passivation/protection of TE materials
- Oak Ridge National Lab (Federal) – High temperature transport & mechanical property measurements
- Brookhaven National Lab (Federal) – TE materials synthesis
- University of Washington (Academic) – TE materials research

Proposed Future Work

Q1-Q8	Investigate TE material encapsulation techniques to prevent oxidation during operation
Q1-Q4	Investigate post-MS processing techniques, co-precipitates, grain boundary engineering, and charge compensation to obtain increased filling fractions as methods to lower thermal conductivity and thereby increase ZT in n-type materials
Q3	Establish base-line back pressure of exhaust system and define allowable back pressure limits with reduced gas temperatures
Q3	Select TE materials for first prototype modules.
Q4	Establish initial design targets for TEG subsystem
Q4	Establish initial design targets for TEG components
Q5	Deliver TE modules for initial TEG prototype
Q6	Complete preliminary estimate of TEG performance

Summary

Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power

- Overview:

Timeline: 4 years	**Barriers:** Cost, Materials (Performance & Durability), Interfaces, T (profile , ΔTs), Power Conditioning, Manufacturability, Production Scale-up Plans
Budget: $14.49M Project $8.75M DOE Funds	**Project Lead:** General Motors (GM) GM R&D, GM Powertrain, GM Energy Center **Partners:** Marlow, Purdue, Dana, Eberspaecher, JPL, Delphi, Molycorp, MSU, ORNL, BNL, UW

- Relevance:

Objectives: Improve the US06 fuel economy for light-duty vehicles by 5% using advanced low cost TE technology

(1) Low cost, (2) Innovative TEG Design, (3) TE Module Durability, (4) Manufacturability, and (5) Plan for Production Scale-up

- Approach:
  - Assemble the best team: unique skills and expertise
  - Include industrial partners who will be well-positioned for commercialization
  - Build on results from previous TEG project

Summary (cont.)

Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power

- <u>Technical Accomplishments and Progress:</u>
  - Scalable TE materials production methods developed.
  - Demonstrated improved module level conversion efficiency.
  - Selection and initial characterization of demonstration vehicle complete.
  - Gap analysis complete showing critical areas of needed improvement.
- <u>Collaboration with Other Institutions:</u>
  - Broad-based team with considerable expertise in TE technology
  - Significant involvement of industry, universities, national labs
- <u>Proposed Future Work:</u>
  - Select TE materials
  - Set design & performance targets for TEG subsystem & components