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

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General Motors Global Research & Development

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Project ID # ACE081

Overview

Timeline

- Start date – September 2012
- End date – September 2016
- Percent complete – ~30%

Budget

- Total funding: $13,557,772
  - DOE share: $8,187,971
  - Contractor share: $5,369,801
- Expenditure of DOE funds in
  - FY12: $199,691
  - FY13: $827,422
  - FY14: $1,465,408 (thru 2/14)

Barriers

- Improved TE materials, modules, interfaces
- Optimized temperature profile and ΔTs
- Low cost and durable TEG system design

Partners

- Interactions/collaborations

  Marlow – TE module development & fabrication
  Purdue – Thermal Interfaces, heat exchanger modeling and design
  Dana Canada Corp. – Thermal System: modeling, design, DFM, fabrication
  Eberspaecher – Exhaust system design & fab.
  JPL – Modeling & design (system, heat exchangers, module); module testing & durability studies
  Delphi – TEG electronics, packaging, & assembly
  Mich. State – TE material passivation/protection
  Oak Ridge Nat'l Lab – High temperature transport & mechanical property measurements
  Molycorp – TE material fabrication
  Brookhaven Nat'l Lab – TE material synthesis
  U of Washington – TE materials development
- Project lead: General Motors

Relevance – Objectives

- **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 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 supplying accessory loads and battery charging, (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 materials synthesis and element fabrication processes

Temperature profile and ΔTs:

- Create innovative heat exchanger design for flexibility.
- 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 and mass flows

Electrical power conditioning and interconnects:

- Reduce electrical system complexity through the use IC board connections
- Avoid electrical impedance mismatch

Low cost vehicle controls & integration:

- Design TEG system to be integral to vehicle systems

Approach – Milestones

- Q1 Select demonstration vehicle (e.g., Full size truck)
- Q2 Complete vehicle and TEG system analysis
- Q3 Select TE materials for first prototype modules
- Q4 Establish initial design targets for TEG subsystem
- Q4 Establish initial design targets for TEG components
- Q6 Deliver TE modules for initial TEG prototype
- Q6 Complete preliminary estimate of TEG performance
- Q12 Select TE materials for final prototype modules
- Q14 Deliver TE modules for final TEG prototype
- Q16 Report final TEG performance test results
- 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

Approach – TEG Team

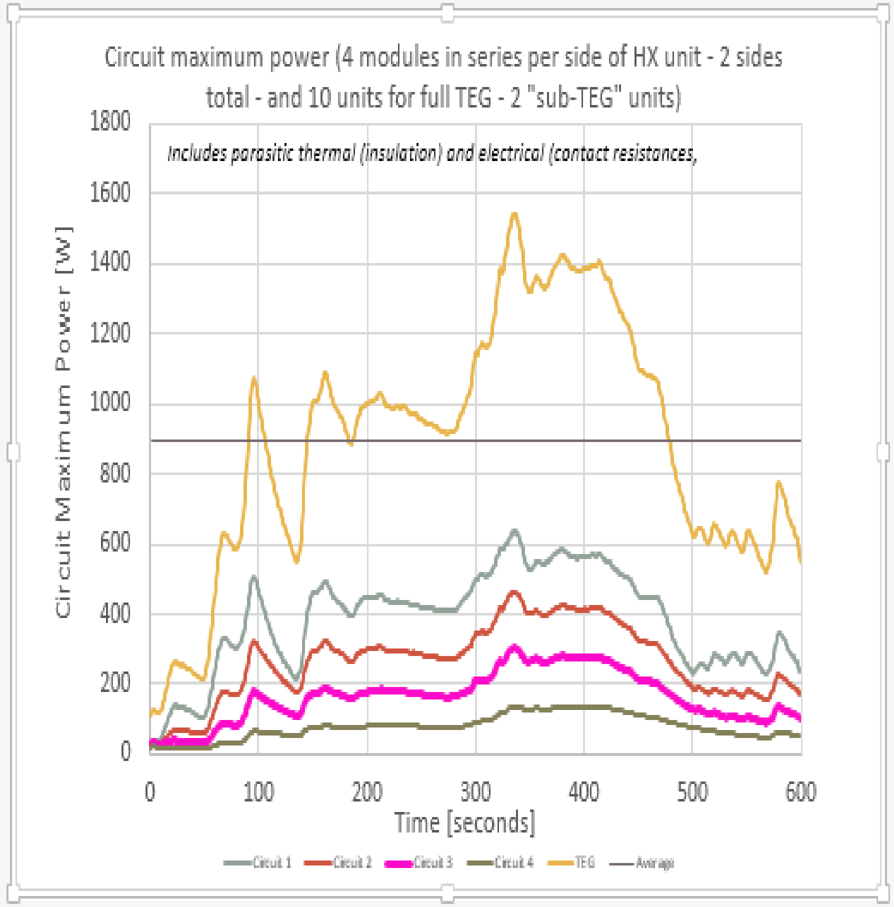
- Project lead: GM Global R&D
  - GM Global R&D: Technical & administrative project leadership, vehicle modeling, power conditioning design, TE materials research
  - GM Energy Center: Vehicle Energy Analysis & Vehicle Selection
  - GM Powertrain: Vehicle controls & Integration, dynamometer testing

- Interactions/collaborations:
  - Marlow – TE module development & fabrication
  - Purdue University – Thermal Interfaces, heat exchanger modeling and design
  - Dana Canada Corp. – Thermal system design for manufacturability, heat exchanger fab.
  - Eberspaecher – Exhaust system design & fabrication
  - JPL – Modeling & design (system, heat exchangers, module); module testing & durability
  - Delphi – TEG electronics, packaging, & assembly
  - Michigan State University – TE material passivation/protection
  - Oak Ridge Nat'l Lab – High temperature transport & mechanical property measurements
  - Molycorp (Magnequench) – TE materials fabrication
  - Brookhaven National Lab – TE materials synthesis
  - University of Washington – TE materials research and development

Technical Accomplishments and Progress

Development of Transient Thermal Model for TEG

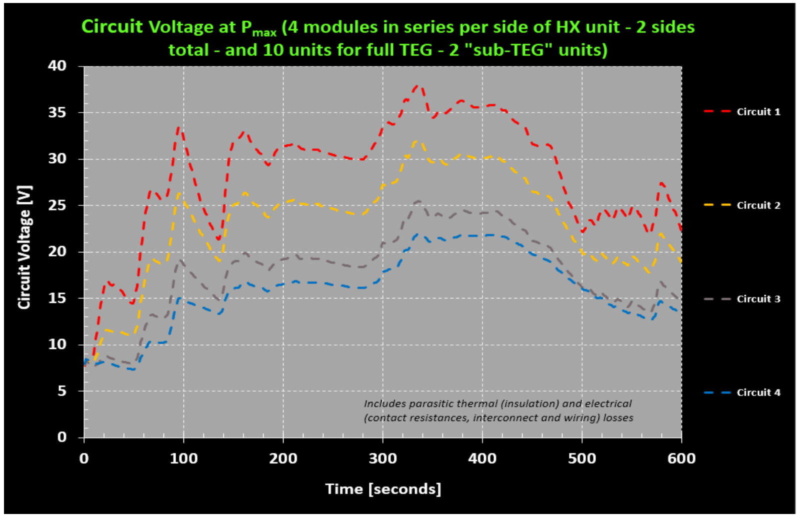
- We developed a unified thermal model for heat exchanger and TE converter system co-optimization using target platform vehicle mass flow and temperature data
- We designed heat exchangers using exhaust mass & heat flows, temperature, and packaging envelope constraints
- We analyzed heat flow from hot to cold heat exchangers that included thermal spreading resistances to determine TE leg packing factors, leg cross sectional areas, and leg height
- Manufacturability concerns and the need for isothermal TE modules led to a grouping of four rows of isothermal TE modules, with each row containing four 32-couple modules on each side of the hot heat exchanger

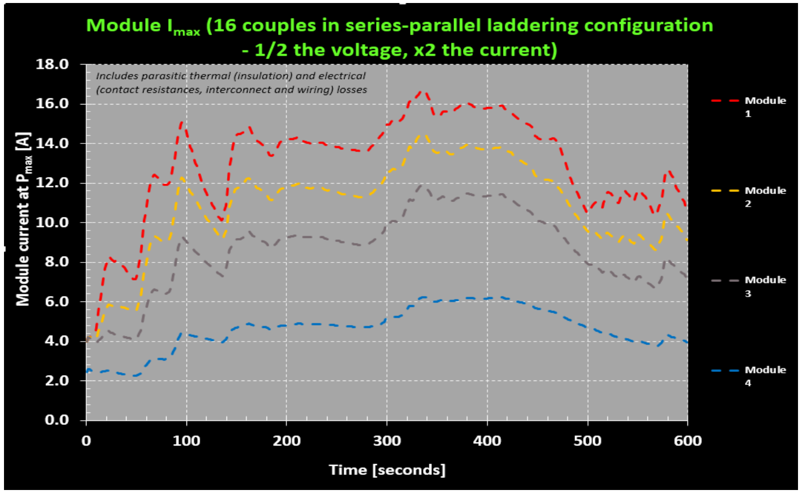


Technical Accomplishments and Progress (cont.)

Development of Transient Thermal model for TEG (cont.):

- TEG design and power output were based on the transport properties of large scale production materials made for the first prototype build
- TE module construction limited hot side heat exchanger surfaces to 525°C. This limitation reduces the overall TEG power output to an average of 0.9 kW over the US06 drive cycle
- The 0.9 kW average power output assumes coolant temperature of 100 to 110°C
- Voltage and current characteristics of the four TE module circuits are all quite different and will require specific power conditioning for use in the vehicle



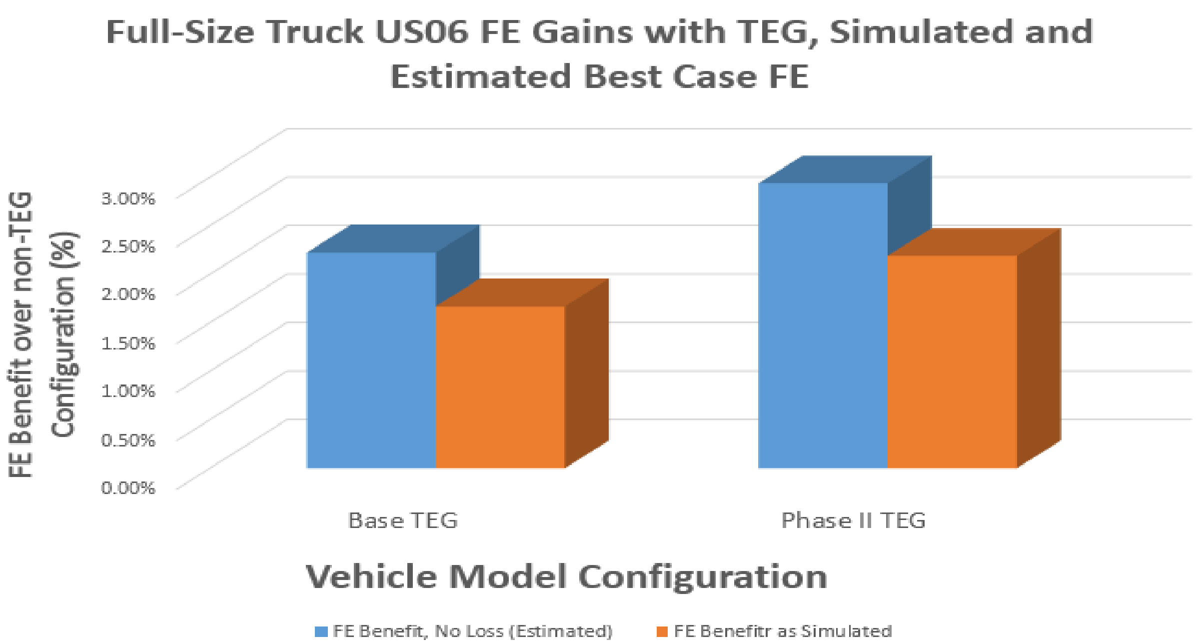


GM RESEARCH & DEVELOPMENT

Technical Accomplishments and Progress (cont.)

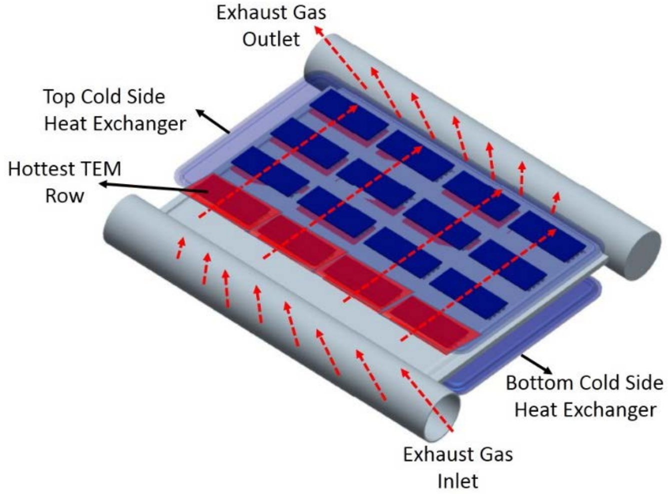
Integration of Transient TEG Model in Vehicle Model

- Modeled TEG power output was used as electrical power input for a Unified Model of the target vehicle
- Power output far exceeds low voltage (i.e., accessory) loads for the vehicle on the US06 cycle
- Full TEG electrical power will need to be utilized in an alternate fashion, and this will require hardware and software modifications to be feasible



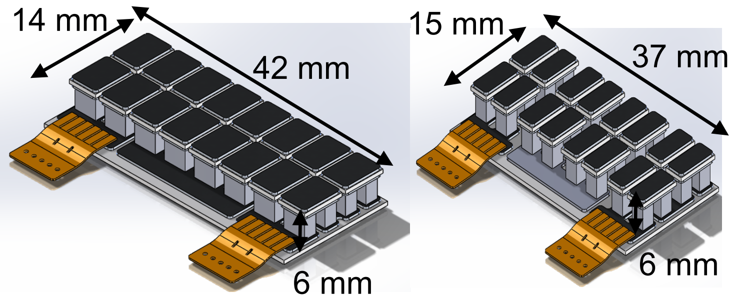
GM RESEARCH & DEVELOPMENT

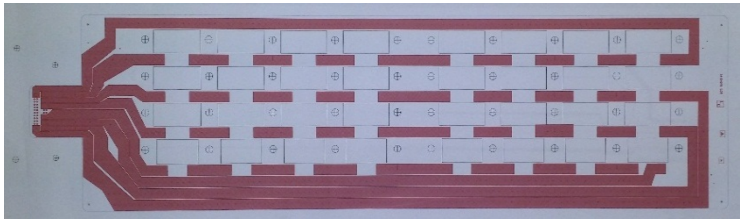
Technical Accomplishments and Progress (cont.)



TEG Design and Prototype Build

- Current TEG design is a plurality of cross flow heat exchangers, TE modules, and flex circuits
- This modular design enables performance flexibility, efficient packaging, and adaptation to a wide variety of vehicle platforms
- A small scale TEG prototype will be built and bench tested this year to functionally test all components, including heat exchangers, TE modules, circuit boards, coolant and gas routing, and power conditioning algorithms
- All skutterudite TE modules required for this initial prototype build have been manufactured
- Hot and cold side heat exchangers and flex circuit boards will be delivered in June
- Bench testing will begin in July - August 2014

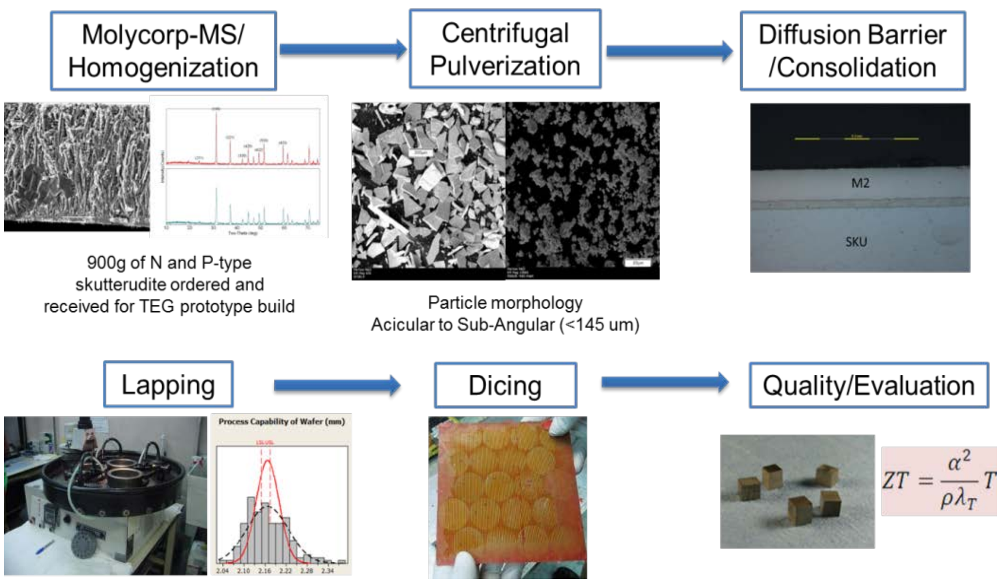




Technical Accomplishments and Progress (cont.)

Module Development (Marlow):

- We developed manufacturing methods to process melt spun ribbons into metalized pucks and fabricated skutterudite TE legs (6300 legs made to date)
- We overcame wafer height uniformity issues with post processing techniques
- We achieved low electrical contact resistance between TE materials and barriers

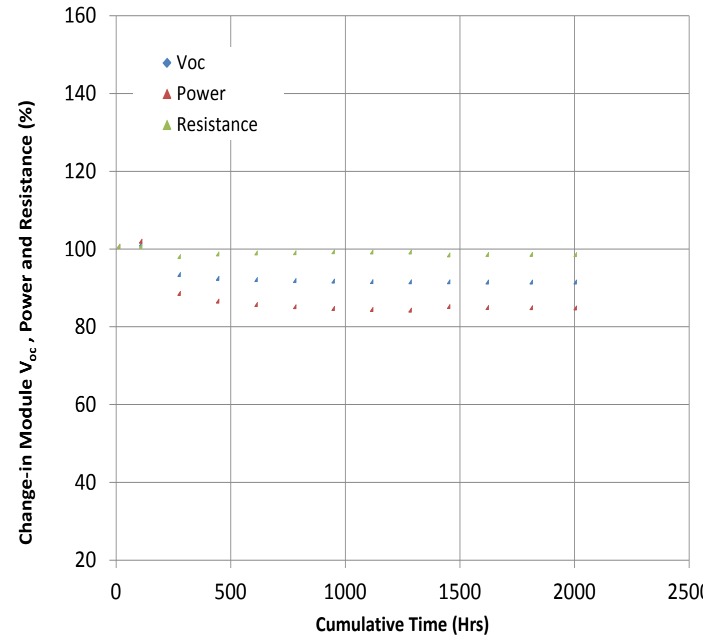


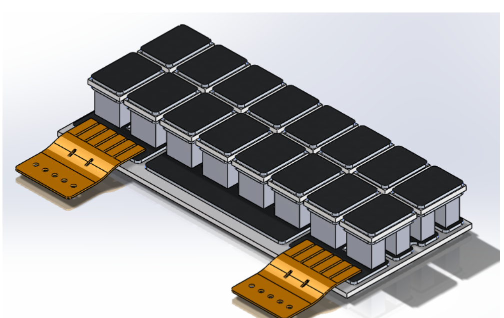
Batch ID	Sample #	ECR 1 ($\mu\Omega \cdot cm^2$)	ECR 2 ($\mu\Omega \cdot cm^2$)
FB026 p-type	1	0.24	0.28
	2	0.24	0.20
	3	0.17	0.28
FB037 p-type	1	0.73	0.53
	2	0.23	0.28
	3	0.23	0.23
FB042 n-type	1	0.30	0.34
	2	0.30	0.17
	3	Delaminated	

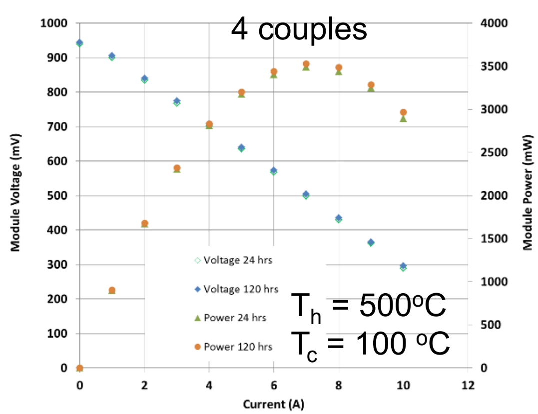
Technical Accomplishments and Progress (cont.)

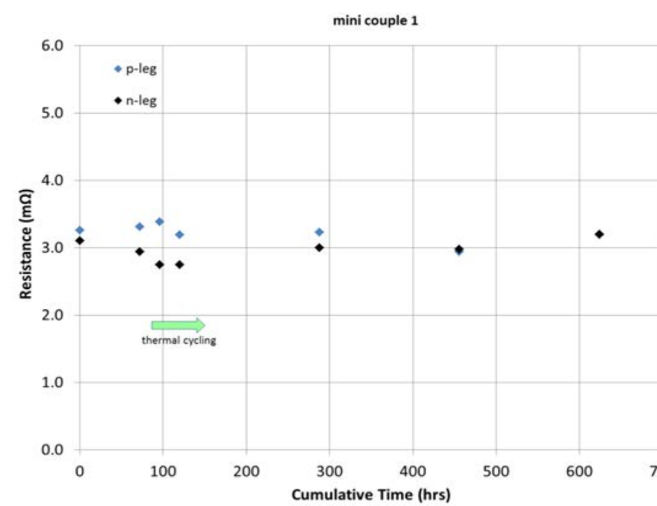
Module Construction, Performance and Durability Testing.

- We arranged TE legs in a series/parallel redundant configuration for increased reliability
- We produced over 120 skutterudite TE modules with two different TE leg aspect ratio
- We measured ACR: a majority of the TE modules are within 5% of modeled values
- We conducted initial durability trials and found good performance is retained for long term in-gradient steady state tests (2000 hrs.) and thermal cycling tests (2500 Cycles).





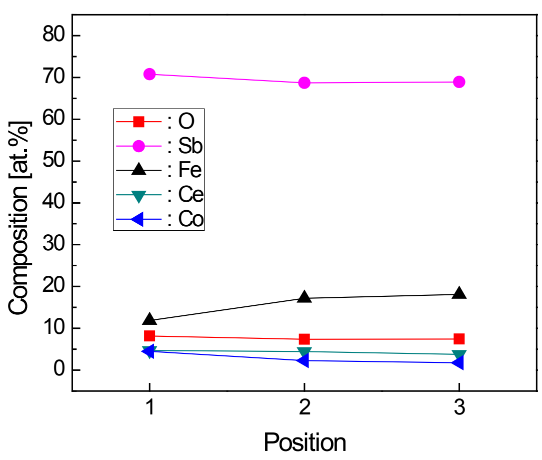




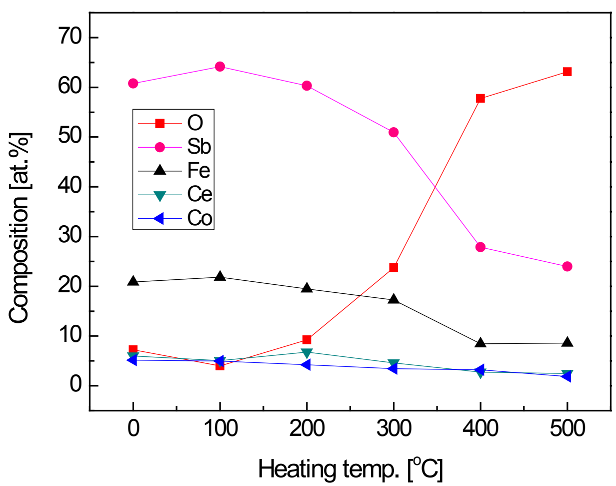
Technical Accomplishments and Progress (cont.)

Enameling and Aerogel Encapsulation

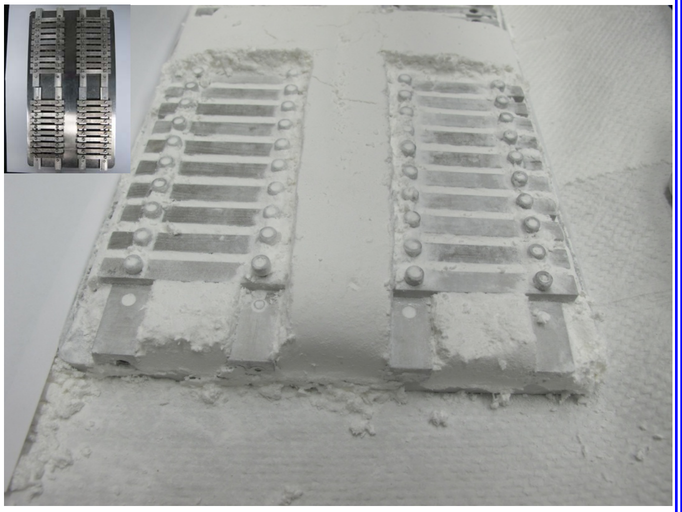
- We developed oxidation suppressing enamel coatings for skutterudite materials
- We observed that enamel shows excellent protection for both n-type and p-type skutterudites for long term exposure to 600°C.
- We developed ambiently dried aerogel for cast-in-place insulation for component protection, TE leg sublimation suppression, and increased thermal performance of the TEG.



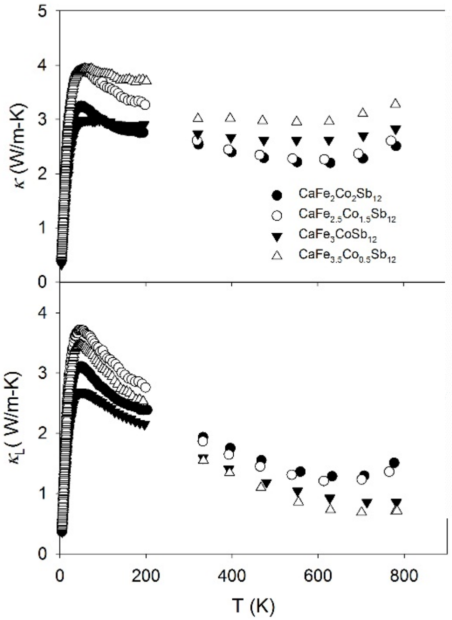
SEM-EDAX with depth after 8days/600°C

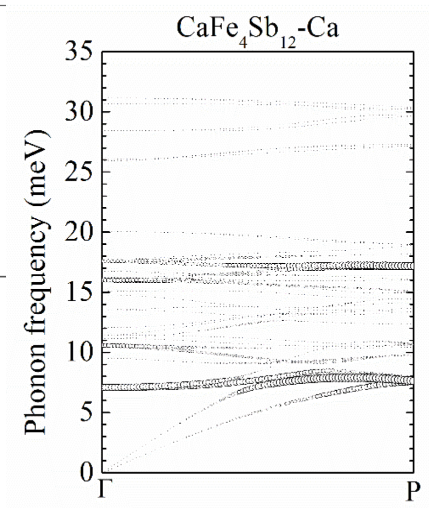


SEM-EDAX with 1hr heat



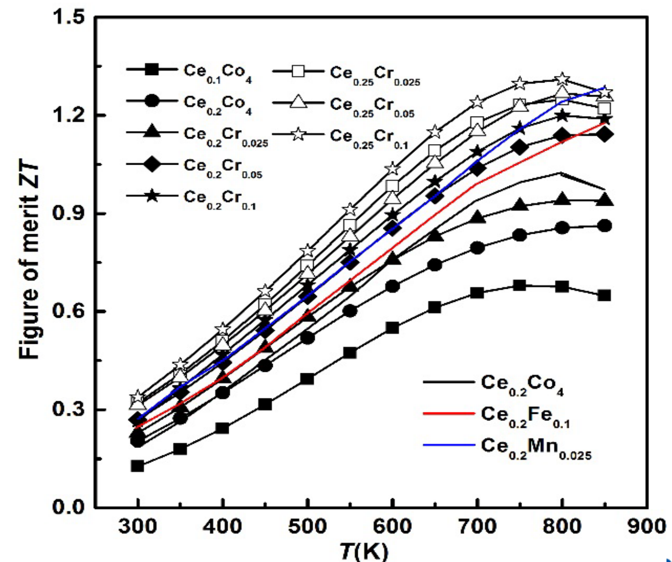
Technical Accomplishments and Progress (cont.)





Materials Development Efforts:

- We investigated low cost filler (Ca) for p-type skutterudite formulations and found a lower than expected thermal conductivity
- We conducted DFT calculations that indicate an additional low frequency phonon mode associated with loosely bound Ca ions lead to a further reduction in thermal conductivity
- We investigated the substitution of a small amounts of electron deficient TM on the Co site, and we found an increase in solubility of light rare-earth fillers and an increase in ZT
- We studied the cause of bi-polar thermal conduction and the impact of effective mass in p-type skutterudites:
  - Bi-polar effects in p-type are more significant than in n-type due to comparable mobilities of majority and minority carriers in the p-type
  - Charge carrier effective mass increases as the Fe content increases.



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 Canada Corp.(Industry) – Thermal System: modeling, design, DFM and fabrication
- Eberspaecher (Industry) – Exhaust system design & fabrication
- Jet Propulsion Laboratory (Federal) – Modeling & design (system, heat exchangers, module); module testing & durability
- Delphi (Industry) – TEG electronics, packaging, & assembly
- Michigan State University (Academic) – Passivation/protection of TE materials
- Oak Ridge National Lab (Federal) – High temperature transport & mechanical property measurements
- Molycorp (Industry) – TE materials fabrication
- Brookhaven National Lab (Federal) – TE materials synthesis
- University of Washington (Academic) – TE materials research

Proposed Continuing / Future Work

Q1-Q8	Investigate TE material encapsulation techniques to prevent oxidation during operation.
Q6-Q7	Upgrade Purdue test bench to accommodate Initial Prototype TEG testing. This will include upgrades to heater for higher thermal power on flow bench, and development of power point tracking algorithms.
Q7-Q9	Assemble Initial prototype for bench testing at Purdue University.
Q8-Q10	Assessment of Initial TEG prototype performance.
Q11-Q13	Redesign of TEG based on performance of Initial Prototype. Conduct component level testing of new designs
Q14-Q15	Manufacture parts and assemble Final TEG Prototype and conduct preliminary bench test for functionality of all components

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: $13.56M Total Funds $8.188M DOE Funds	**Project Lead:** General Motors R&D With: GM Powertrain, GM Energy Center **Partners:** Marlow, Purdue, Dana, Eberspaecher, JPL, Delphi, MSU, ORNL, Molycorp, 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 our previous TEG project and our recent advances

Summary (cont.)

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

- Technical Accomplishments and Progress:
  - Developed scalable TE materials and element production methods
  - Demonstrated improved module level conversion efficiency
  - Determined projected FE benefit based on current TEG power rating.
  - Completed Gap Analysis showing critical areas of needed improvement
- Collaboration with Other Institutions:
  - Broad-based team with considerable expertise in TE technology
  - Significant involvement of industry, universities, national labs
- Proposed Future Work:
  - Assemble and bench test Initial TEG prototypes
  - Develop hardware and software strategies for full utilization of TEG electrical power
  - Implement power conditioning hardware & software for TEG integration into target vehicle