Develop Thermoelectric Technology for Automotive Waste Heat Recovery

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General Motors Research & Development

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Project ID # ACE050

Overview

Timeline

- Start date – May 2005
- End date – August 31, 2011
- Percent complete – 94%

Budget

- Total funding: $11,172,983
  - DOE share: $6,384,010 (fully funded in FY09)
  - Contractor share: $4,824,973
- Expenditure of DOE funds in
  - FY10: $607,982
  - FY11: $343,128

Barriers

- Barriers addressed
  - Integrating new advanced TE materials into operational devices & systems
  - Integrating/Load Matching advanced TE systems with vehicle electrical networks
  - Verifying device & system performance under operating conditions

Partners

- Interactions/collaborations

  Marlow – TE module development and fabrication

  ORNL – High temperature transport and mechanical property measurements

  Future Tech – TEG systems for vehicle applications

  UNLV – Computational materials development
- Project lead: GM R&D

Relevance – Objectives

- **Achieve 10 % improvement in fuel economy (FE) by 2015 without increasing emissions**
  - Demonstrate FE improvement for the Federal Test Procedure urban driving cycle (~3%)
  - Demonstrate that actual FE improvement for real world driving conditions is closer to DOE goal
- **Demonstrate commercial viability**
  - Assemble, install, and test prototype TEG on a production vehicle
  - Collect performance data, show viability
  - Identify specific design, engineering, and manufacturability improvements for path to production

This project is directed specifically toward reducing petroleum usage for transportation by increasing fuel efficiency via waste heat recovery using advanced thermoelectric technology.

Relevance – Milestones

Previous Year (FY 2009)

- Completed vehicle modification, controls, and systems integration for TEG installation and testing on demonstration vehicle
- Completed prototype TEG subsystem parts fabrication and assembly
- Installed prototype TEGs onto demonstration vehicle for system testing

Current Year (FY 2010)

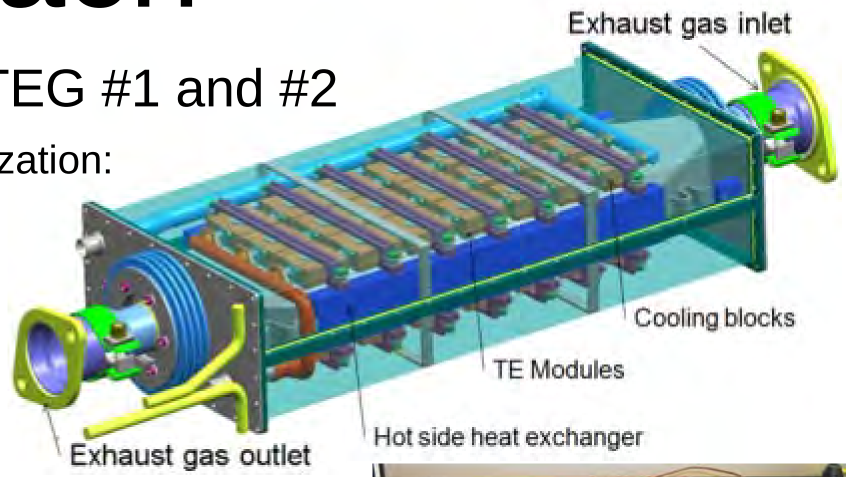
- Completed test vehicle modification and integration and preliminary testing using Bi-Te TE modules.
- Improved material ZT and thermo-mechanical properties
- Produced skutterudite TE modules for the TEG

Current Year (FY 2011)

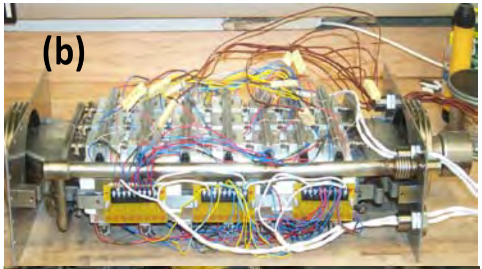
- Complete final TEG prototype construction with skutterudite modules
- Collect TEG performance data; demonstrate fuel economy improvement

Approach

- Fabricate and assemble prototype TEG #1 and #2
  - Evaluate design for roadblocks to commercialization:
    - Weight, volume, complexity
    - Thermal profile and other heat flow issues
    - Gas tight assembly (inert atmosphere for TE modules)
  - Incorporate off-the-shelf Bi-Te TE modules
    - Available in large quantity, relatively robust (<250 C)
    - Enables a rigorous testing of the assembly process and vehicle systems early in the project



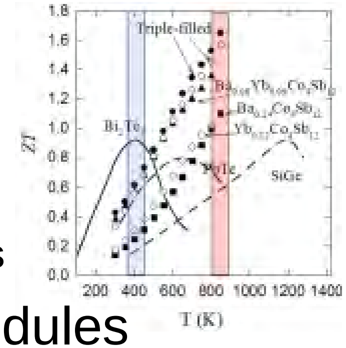
- Execute demonstration vehicle integration
  - Control systems (bypass) for temperature and back pressure
  - Exhaust system modification for TEG and bypass valve installation
  - Electrical system development and integration
    - Sensors for data input of vehicle temperatures, pressures, etc.
    - DC-to-DC converter and controls for TEG power conditioning and utilization

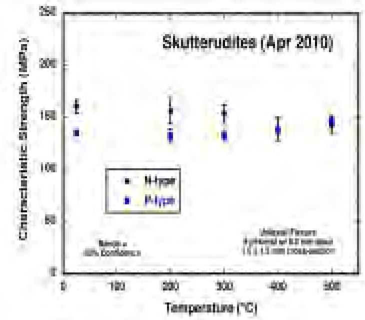


- Test initial TEGs on demonstration vehicle
  - Install in exhaust system, verify functions of TEG and vehicle controls and integration
    - Exhaust gas system function, coolant system performance, bypass valve control, DC-to-DC converter operation, data logging, robustness of design, assembly, and individual parts,
  - Evaluate performance of temperature control (bypass valve) and TEG temperature profile
  - Assess output performance of TEG with Bi-Te TE modules (TEG #1 and #2)

Approach (cont.)

- Improve TE materials (skutterudites)
  - Increase ZT values (triple filled n-type material)
  - Assess and improve fracture strength and durability
  - Explore new materials for next generation TE modules
- Develop and produce skutterudite TE modules
  - Synthesize many kilograms of n-type and p-type skutterudite material
    - Identify optimum sintering process parameters for good quality material
    - Assess quality of ingots and identify production issues for scale-up of skutterudite production
  - Develop diffusion barrier, braise, and assembly processes
  - Fabricate skutterudite modules for the TEG
- Refine TEG design for final assembly (TEG #3)
  - New joining process for exhaust gas spreaders to heat exchanger
  - New heat exchanger material for lower cost, lighter weight
  - New case design for easier assembly and gas tight seal
  - Determine wiring configuration for optimum TEG performance
- Assemble and install TEG #3 with skutterudite modules
- Test TEG #3 performance on demonstration vehicle
  - Controlled driving conditions (FTP, US06, real world)



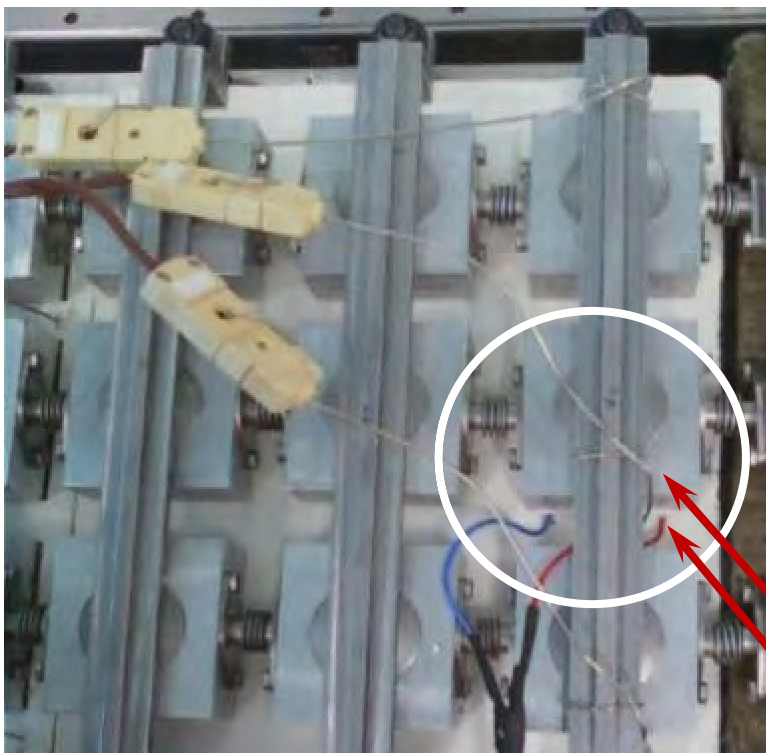


Technical Accomplishments and Progress

First prototype TEG #1 completed and tested on demonstration vehicle

Drive shaft

Bypass valve

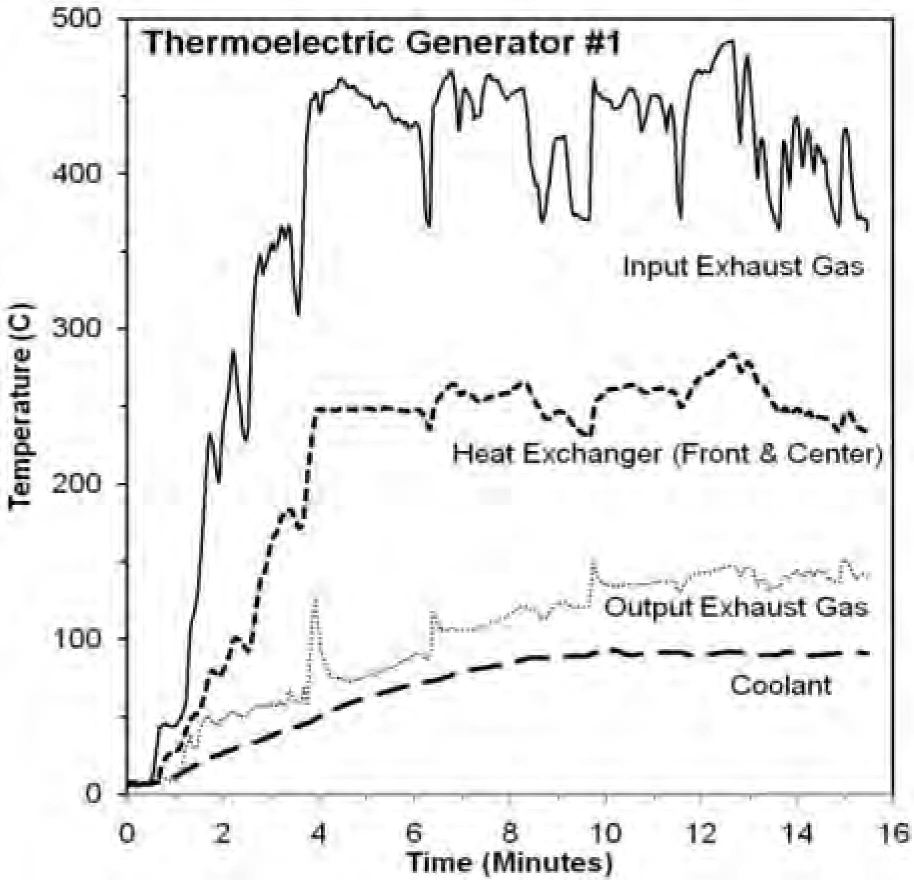


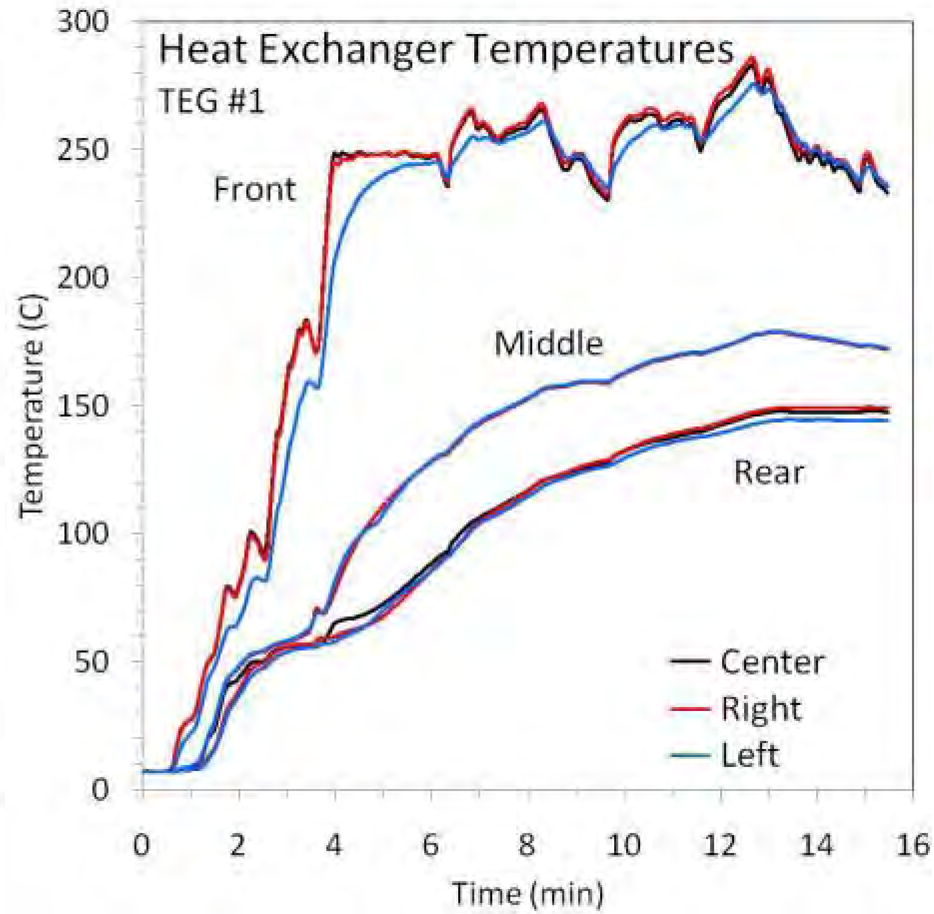
Front Center thermocouple on heat exchanger

Bi-Te TE module

Technical Accomplishments and Progress (cont.)

Results for TEG #1: Temperature control and heat exchanger temperature profile





Substantial temperature drop along the length of the TEG: 250°C (Front), 178°C (Middle), and 148°C (Rear); variation across the TEG: < 3°C.

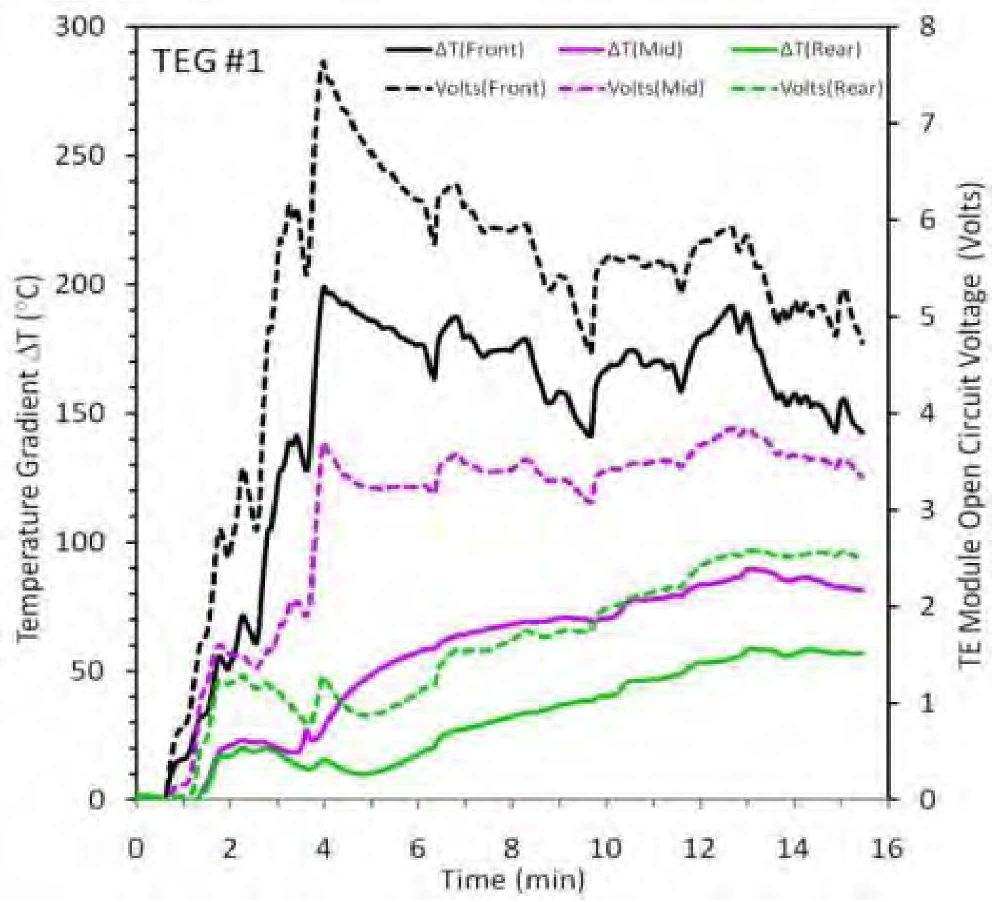
Technical Accomplishments and Progress (cont.)

Results for TEG #1: Temperature control and heat exchanger temperature profile

Solid Lines: Temperature gradient ΔT for
Front Center (black)
Middle Center (purple)
Rear Center (green)
measured by thermocouples inserted into small holes in the heat exchanger.

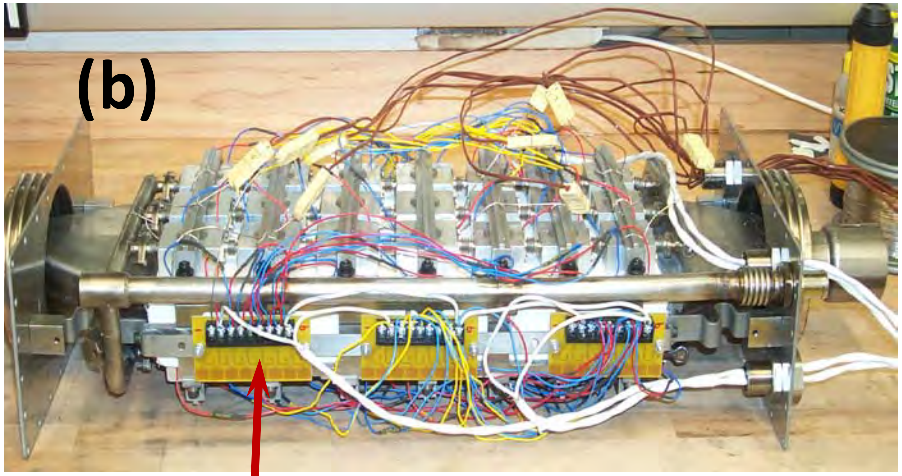
Dashed Lines: Open Circuit Voltage for Bi-Te TE modules at these same positions on the heat exchanger.

The Open Circuit Voltage is consistent with a 50°C smaller ΔT than measured between the hot side heat exchanger and the coolant

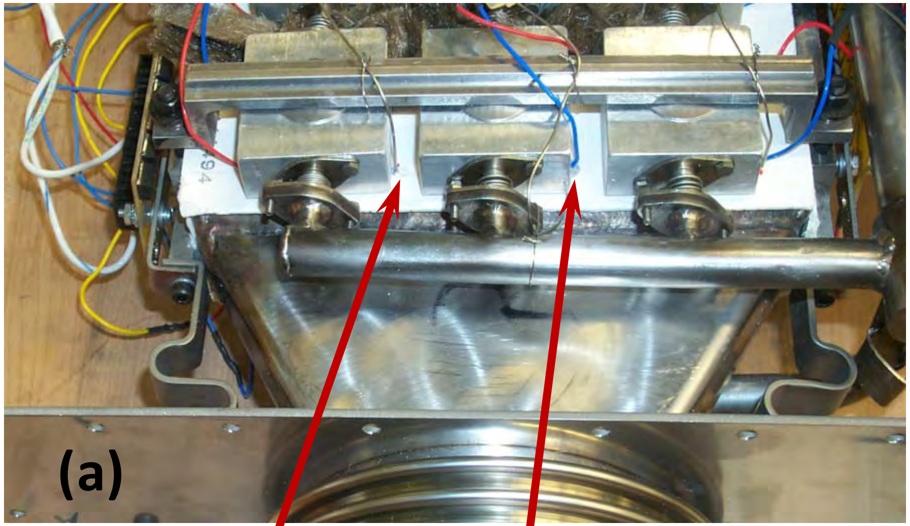


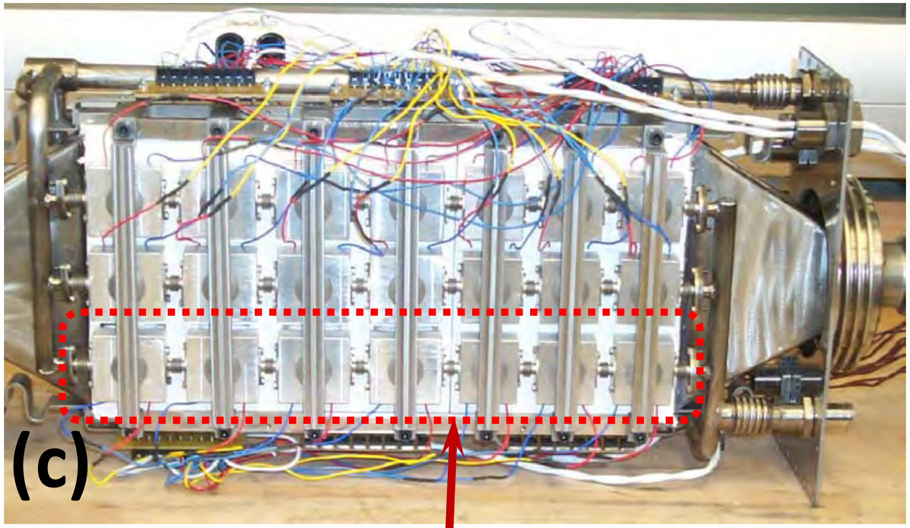
Technical Accomplishments and Progress (cont.)

Second prototype TEG #2 completed and tested on demonstration vehicle



Circuit board for TE module connections





Front Left Thermocouple on heat exchanger

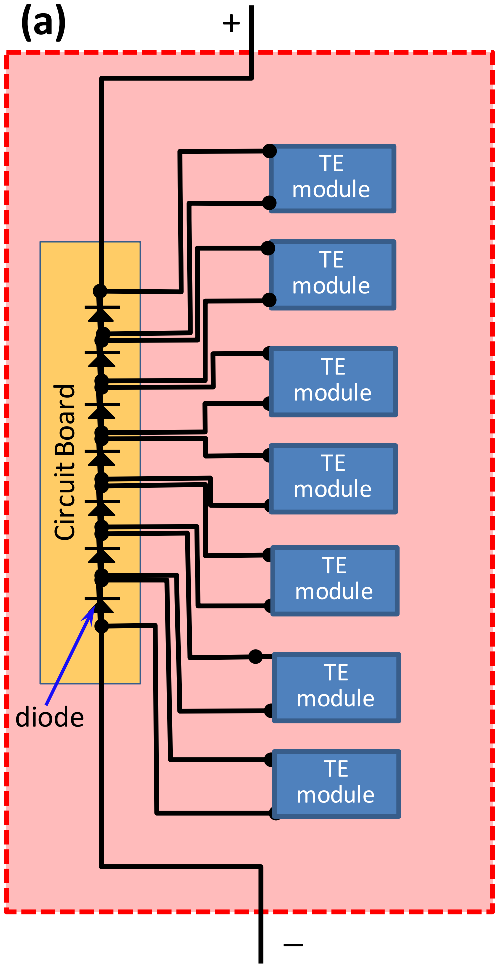
Front Center thermocouple on hot side of Bi-Te TE module

Seven TE module series

Technical Accomplishments and Progress (cont.)

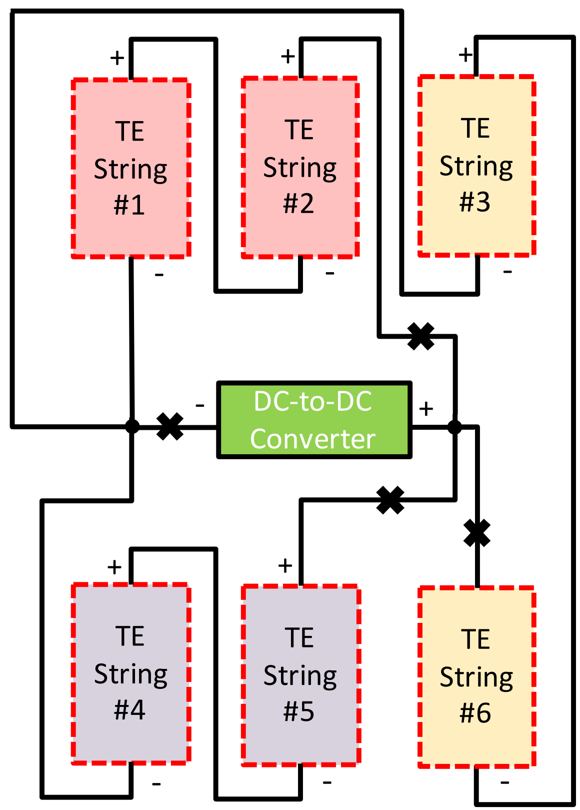
Wiring diagrams for TEG #2

(a)



Three pairs of TE Strings connected in parallel

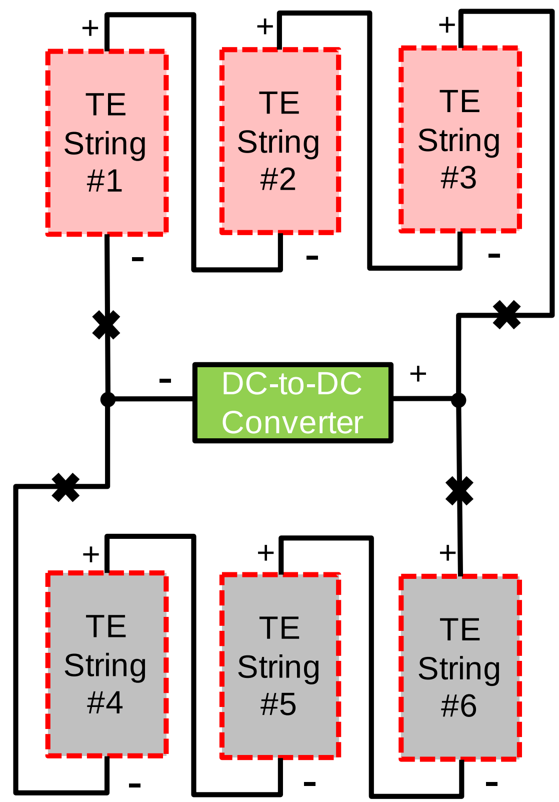
(b)



Larger I, Smaller V

Two sets of three TE Strings connected in parallel

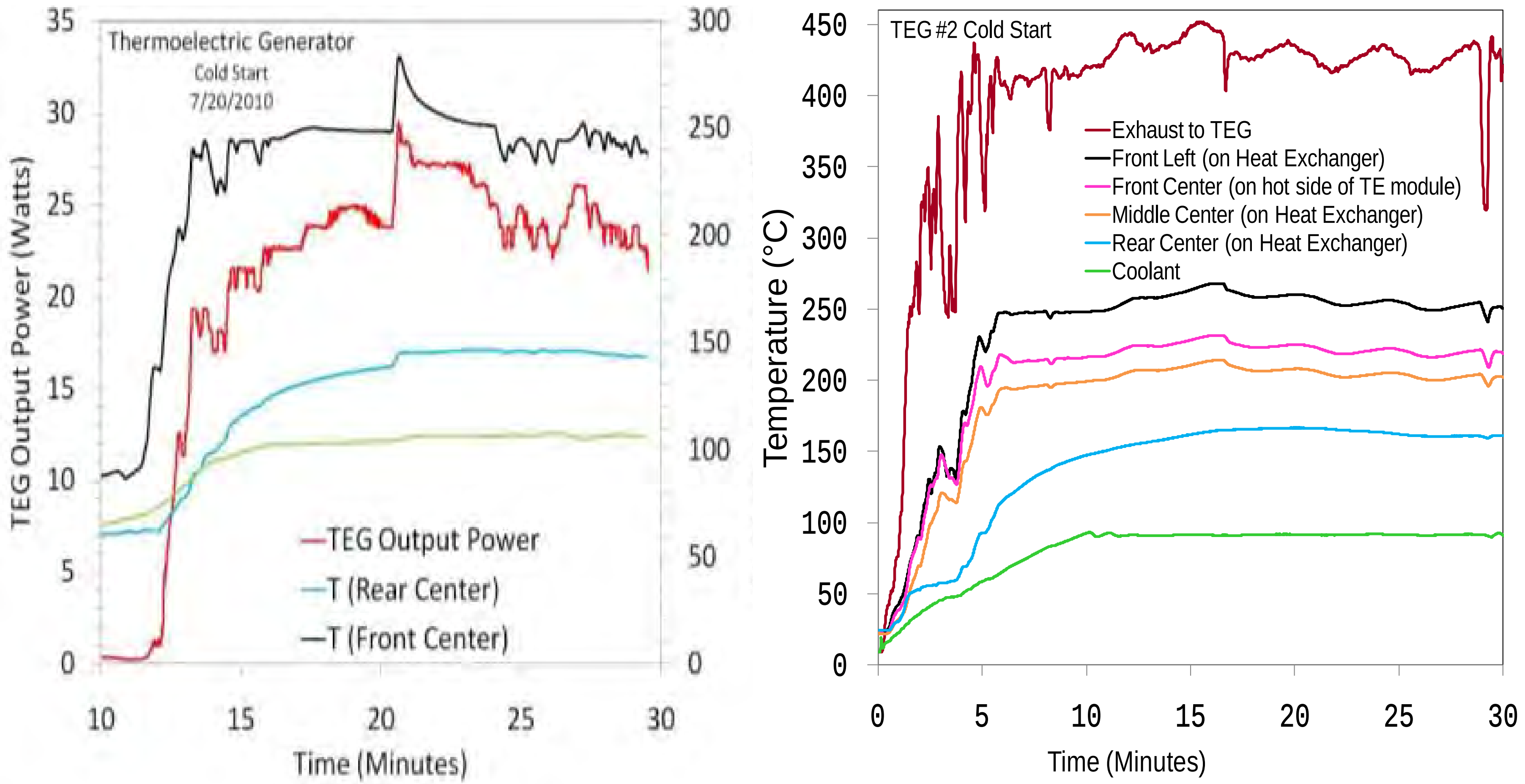
(c)



Smaller I, Larger V

Technical Accomplishments and Progress (cont.)

Results for TEG #2:

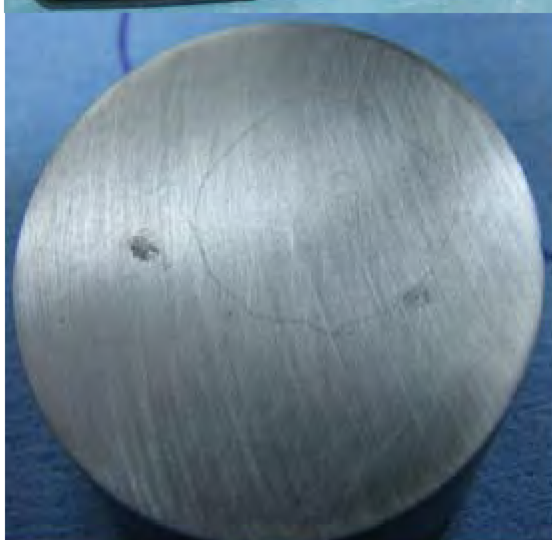


Technical Accomplishments and Progress (cont.)

Skutterudite Materials

We scaled-up our process for synthesizing a large enough quantity of both n-type and p-type for TE modules for TEG #3

Determined optimized process parameters for spark plasma sintering:



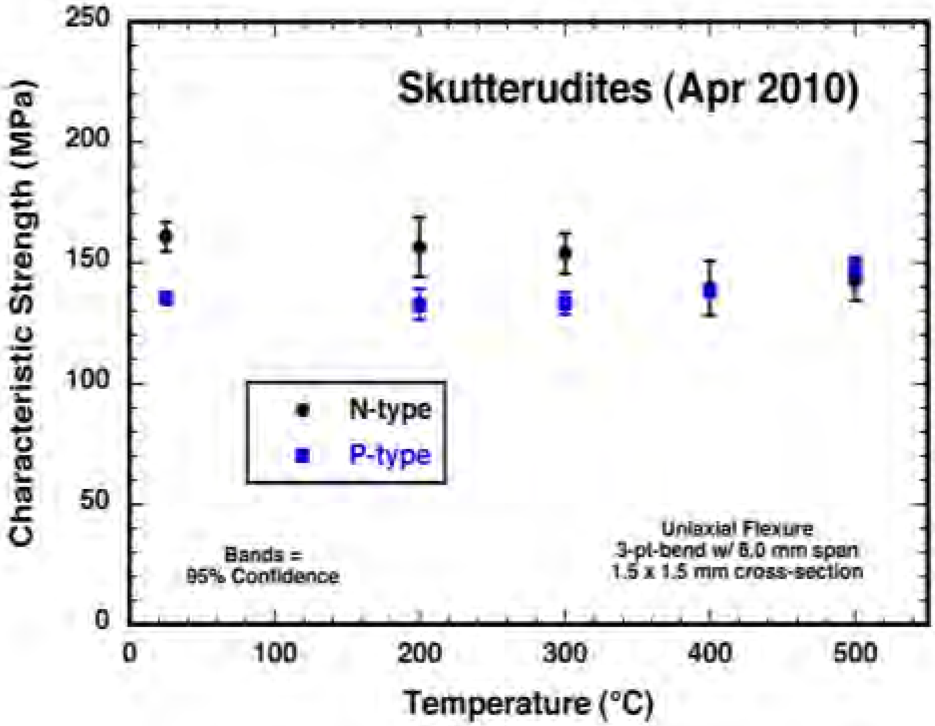
Process parameters for small lab-scale billets result in center crack and coring flaws.

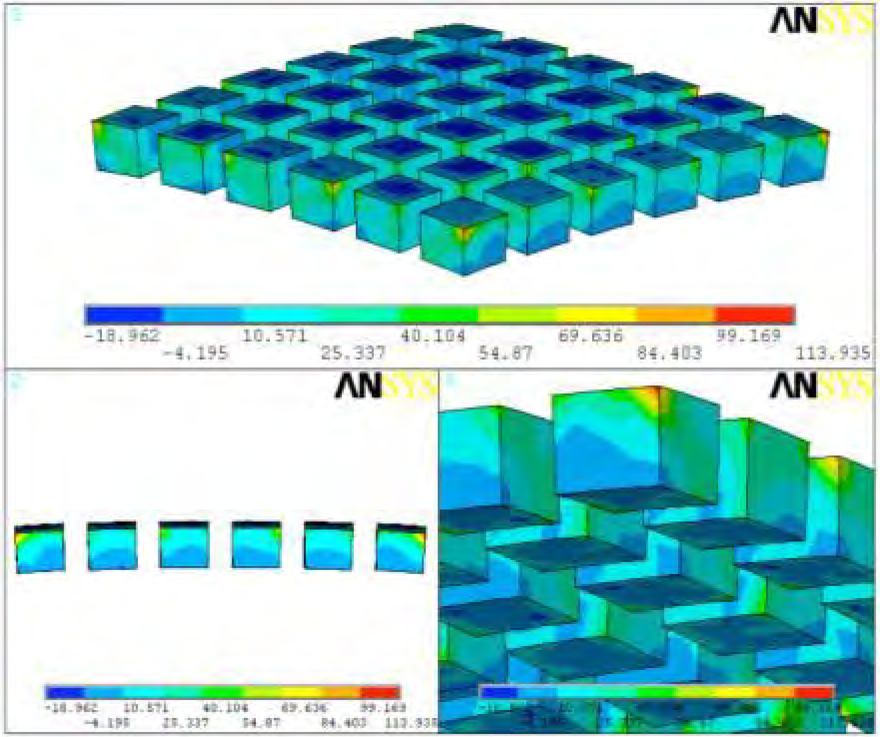
Care must be exercised to minimize flaw creation when slicing and dicing into TE legs.

Technical Accomplishments and Progress (cont.)

Skutterudite Materials

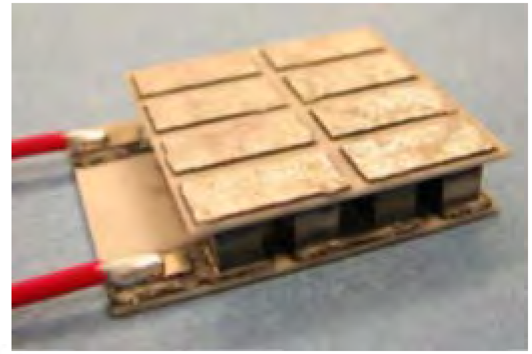
Fracture strength measurements indicate that skutterudites can withstand stresses of over 140 MPa.





Finite element analysis of skutterudite modules finds internal stresses ~ 130 MPa at ΔT = 500°C

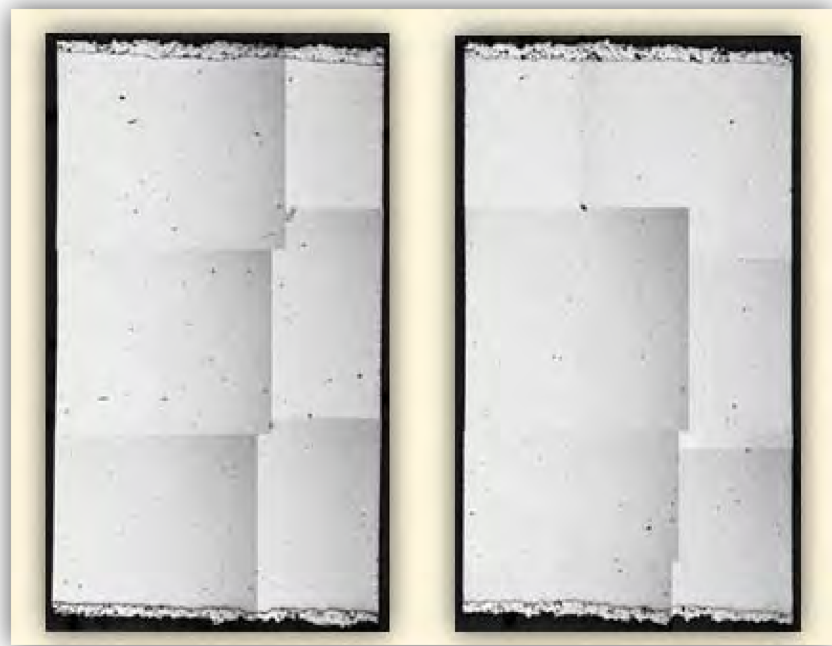
Technical Accomplishments and Progress (cont.)



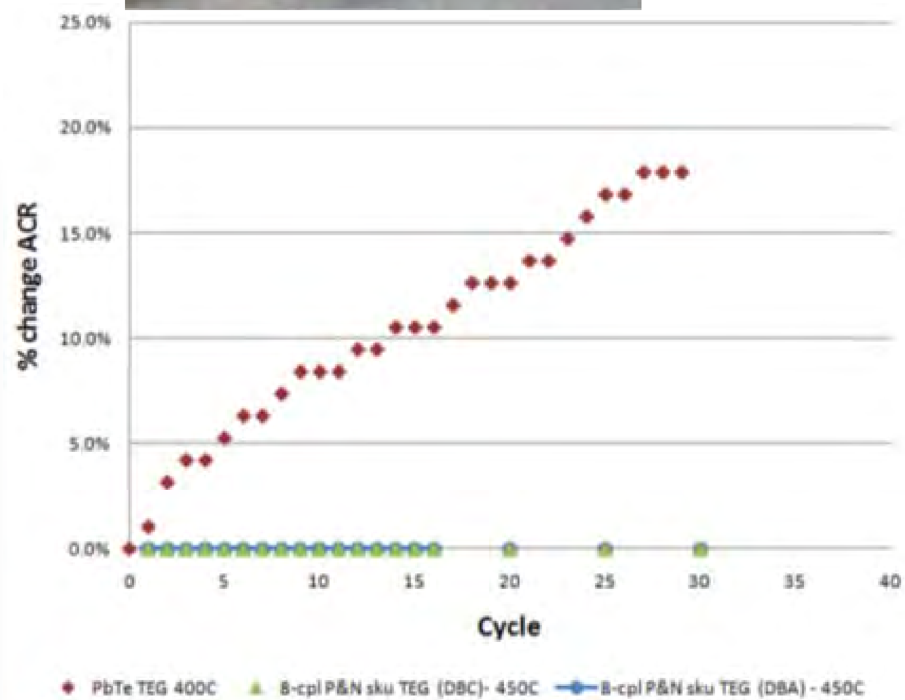
Skutterudite mini TE test module

Skutterudite Modules

Diffusion barriers were successfully applied and mini test modules fabricated and tested.



n-type p-type



Skutterudite modules perform significantly better than PbTe under thermal cycling.

Technical Accomplishments and Progress (cont.)

Skutterudite Modules

PbTe TEG

N & P-PbTe on DBC ceramic (Thermal Cycled ~400C, 29x's)

Skutterudite TEG

P&N Skutterudite on DBA ceramic (Thermal Cycled ~450C, 30x's)

Skutterudite modules withstand thermal cycling quite well, whereas PbTe modules show significant cracking which causes increase module impedance with cycling.

Technical Accomplishments and Progress (cont.)

Skutterudite Modules:

All skutterudite modules needed for TEG #3 have been fabricated!!

Collaboration and Coordination with Other Institutions

GM Global R&D: Project Management and Coordination

- ➢ TE materials research – synthesis and characterization of material properties 4 K to room temperature
  - High temperature transport property measurements (ORNL)
  - Neutron scattering for phonon DOS and phonon mode analysis (NCNR)
  - Computational research on TE properties of materials (UNLV)
- ➢ TEG fabrication and assembly (GM Global R&D)
- ➢ TEG installation, vehicle controls & integration, vehicle testing and fuel economy assessment (GM Powertrain)

Marlow Industries: TE module development & fabrication

- ➢ Large scale production of skutterudites for module synthesis (GM Global R&D)
- ➢ TE property measurements & validation (GM Global R&D, ORNL)
- ➢ Fracture strength analysis (ORNL)
- ➢ Skutterudite module testing and implementation (GM Global R&D)

Collaboration and Coordination with Other Institutions

Collaborators & Subcontractors:

- General Electric – Subsystem modeling and design
- Future Tech – Consultant
- University of Michigan, Michigan State University, Brookhaven National Lab, University of South Florida, University Nevada Las Vegas, Shanghai Institute of Ceramics, NRCR, RTI – TE materials development
- ORNL – High temperature transport & mechanical properties
- UNLV – Computational materials development

Suppliers:

- Faurecia – Exhaust subsystem fabrication and integration
- Heat Technologies, Inc. – Heat exchangers

Proposed Future Work

- Complete encapsulation of skutterudite modules for sublimation and oxidation prevention
- Complete assembly of TEG #3, including new case design for inert atmosphere operation of skutterudite modules
- Complete vehicle controls systems and integration refinements for TEG #3 implementation
- Install TEG #3 on demonstration vehicle
- Conduct dynamometer and proving ground tests and analysis on the demonstration vehicle
- Assess fuel economy improvement using the TEG waste heat recovery system

Summary

- Prototype TEGs # 1 and #2 (Bi-Te modules) were assembled, installed, and tested on the demonstration vehicle. Results provided very valuable data and validation for implementation of TEG #3
- Large quantity of skutterudite material was synthesized for TE module fabrication for TEG #3
- Skutterudite modules have been fabricated and ready for assembly into TEG #3
- TEG #3 assembly is now in progress, vehicle and fuel economy testing to follow