Thermoelectric Conversion of Exhaust Gas Waste Heat into Usable Electricity

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Outline

- Acknowledgements
- Introduction
- Develop TE Generator (**Waste Heat 1**)
  - TEG #1 (preliminary assembly and testing)
  - TEG #2 (Bi-Te modules)
  - TEG #3 (Skutterudite and Bi-Te modules)
- Develop Cost-Effective TEG (**Waste Heat 2**)
- Summary

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Introduction

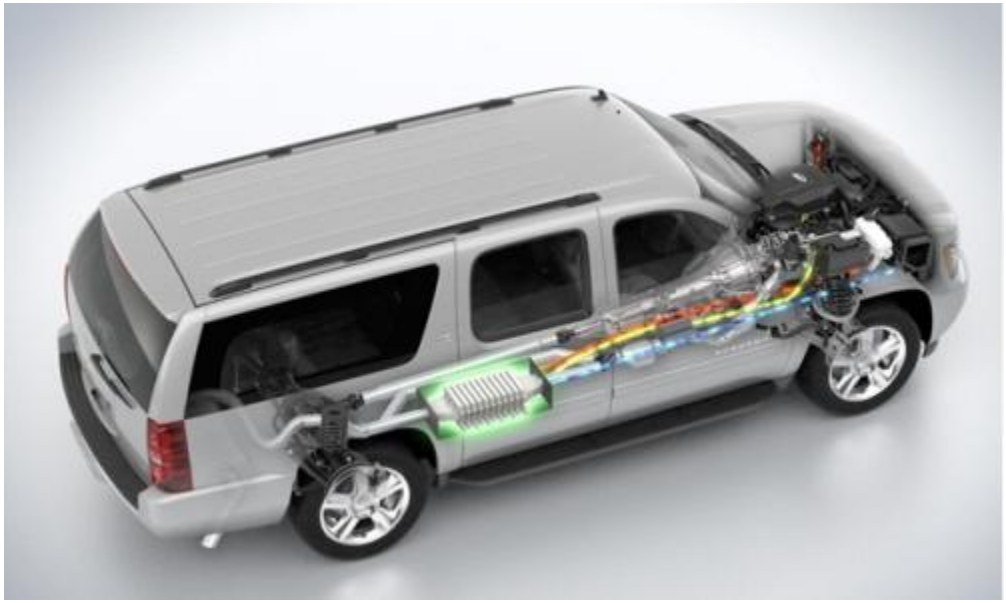
- **Achieve improvement in fuel economy (FE) without increasing emissions using thermoelectrics (TEs)**
- **Demonstrate commercial viability of advanced TE technology for automotive applications**

Waste Heat 1:

- Incorporate new advanced TE materials into operational devices & systems (model, design, fabricate, install a TE generator)
- Integrate advanced TE generator device with vehicle electrical system
- Verify device & system performance under operating conditions

Directed specifically toward reducing petroleum usage for transportation by increasing fuel efficiency via waste heat recovery using advanced thermoelectric technology. **Waste Heat 1** started in 2005, supported by United States Department of Energy Vehicle Technologies Program.

Introduction



- **Waste Heat 1:** Chevrolet Suburban demonstration vehicle:
  - Large amount of heat at high T, adequate cooling capacity of engine coolant system
  - Large space for TEG, relatively simple vehicle modification needed for installation
  - Weight impact small because of large vehicle weight
- Optimize TEG design for available space and cost of TE materials
- Construct prototype TEG for advanced TE technology R&D and to demonstrate viability of TEGs for automotive applications

Introduction

Waste Heat 1: Demonstration Vehicle

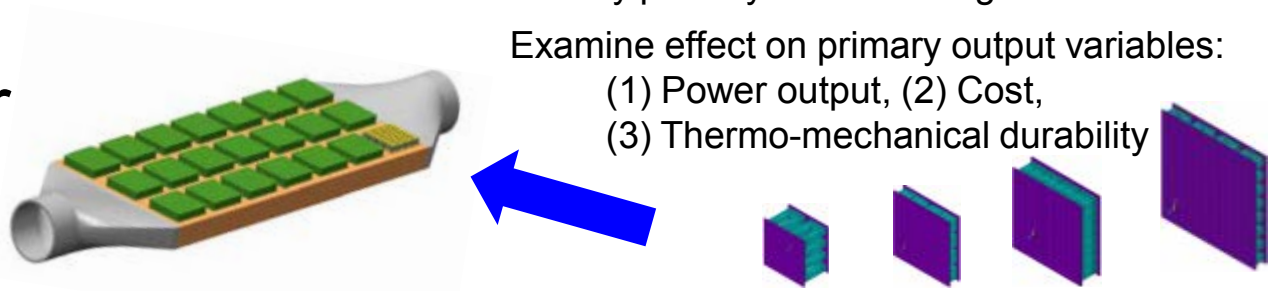
Introduction

Waste Heat 1:

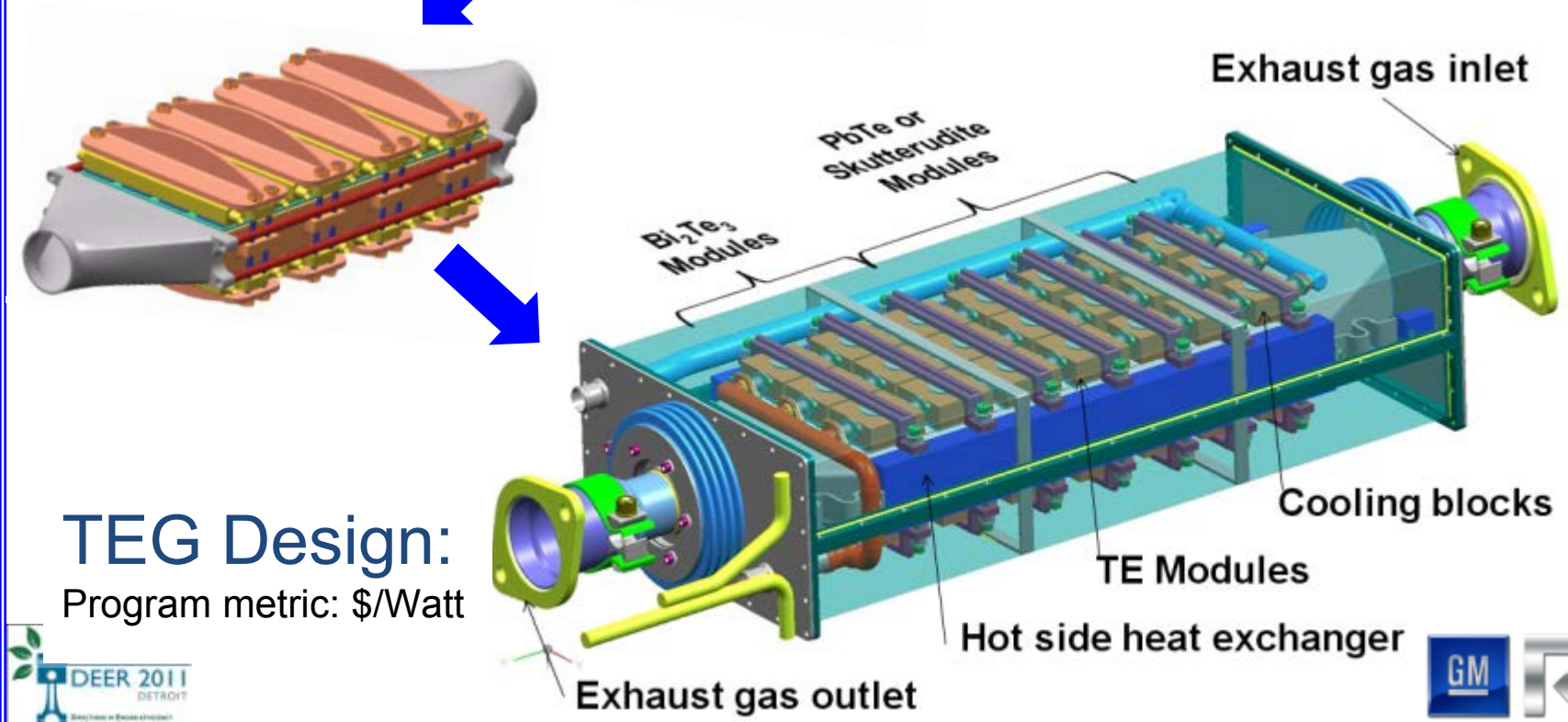
TE Module Design:

Identify primary module design variables

Examine effect on primary output variables:
(1) Power output, (2) Cost,
(3) Thermo-mechanical durability



Heat Exchanger Design:

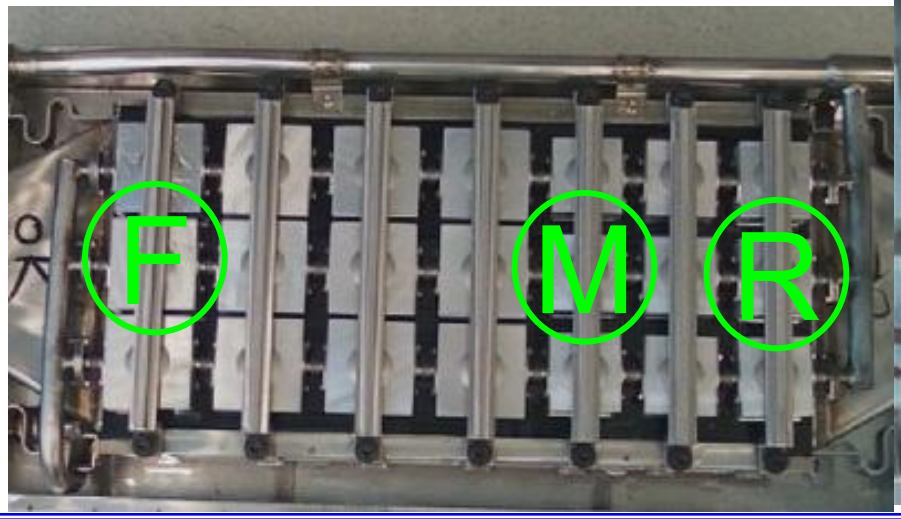


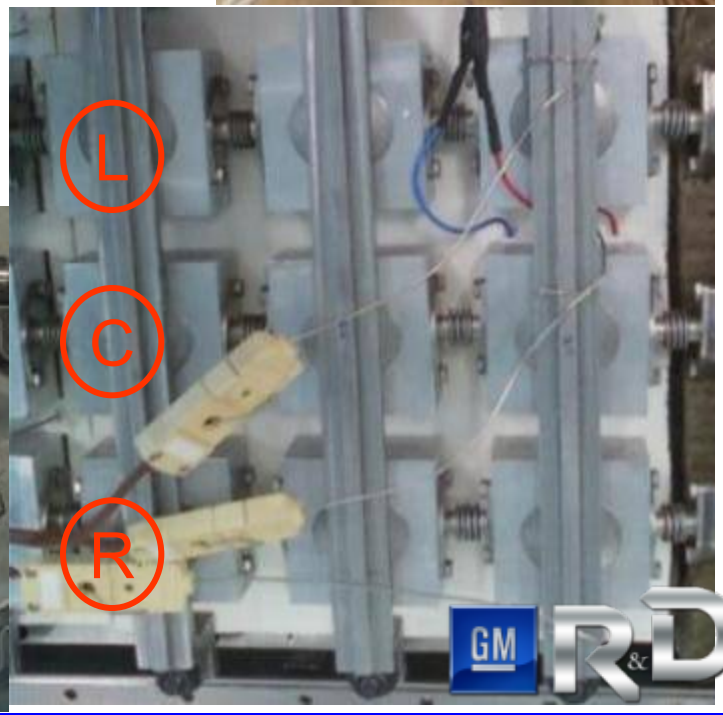
TEG Design:

Program metric: $/Watt

Waste Heat 1:

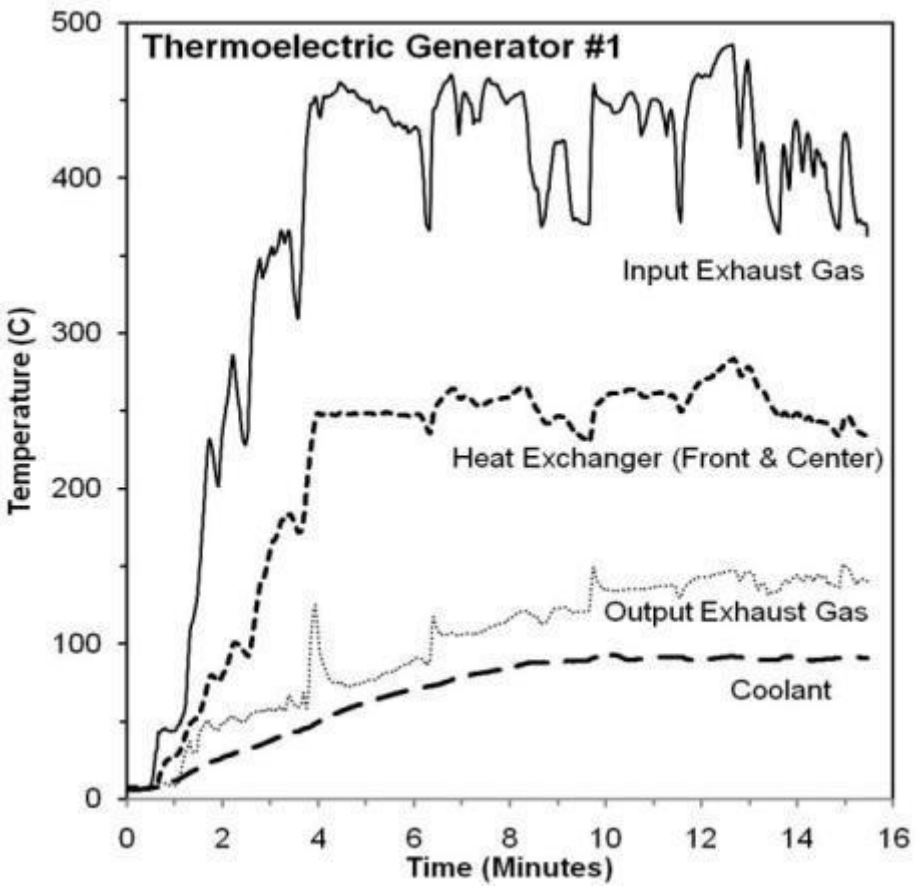
- Fabricate & assemble prototypes: TEGs #1 & #2
  - Incorporate off-the-shelf Bi-Te TE modules
- Execute vehicle modifications and integration
  - Develop control systems for T and back pressure management
  - Modify exhaust system, install bypass valve
  - Integrate TEG into vehicle electrical system (dc/dc converter)
- Test TEGs on demonstration vehicle
  - Install in exhaust system, verify functions of TEG systems and vehicle controls and integration
  - Evaluate temperature control (bypass valve) and TEG output during vehicle operation
  - Assess performance of TEG: Output voltages, temperature profile, power output





TEG #1

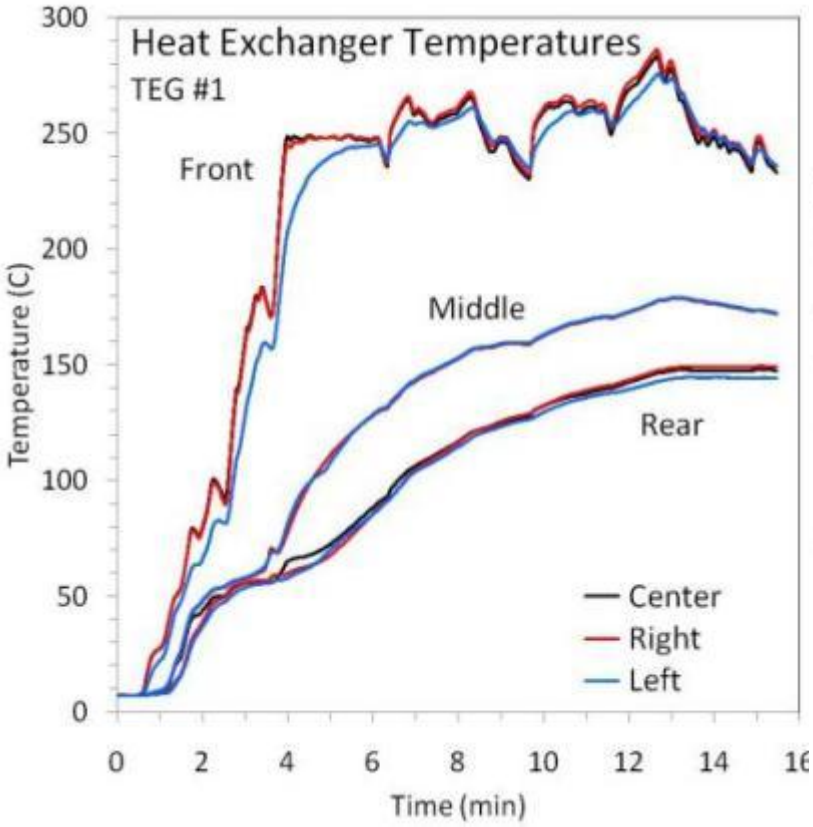
3 Bi-Te modules

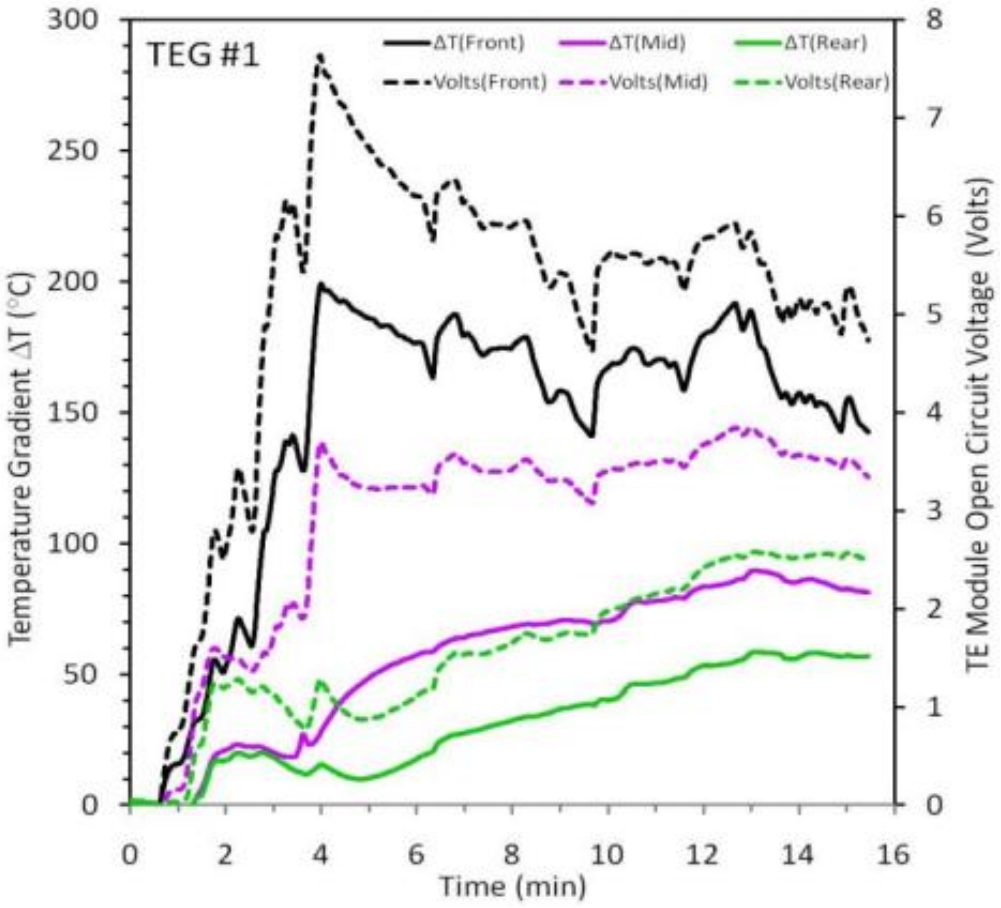


Bypass valve

Drive shaft

TEG #1





Substantial decrease in T along the length of the TEG:

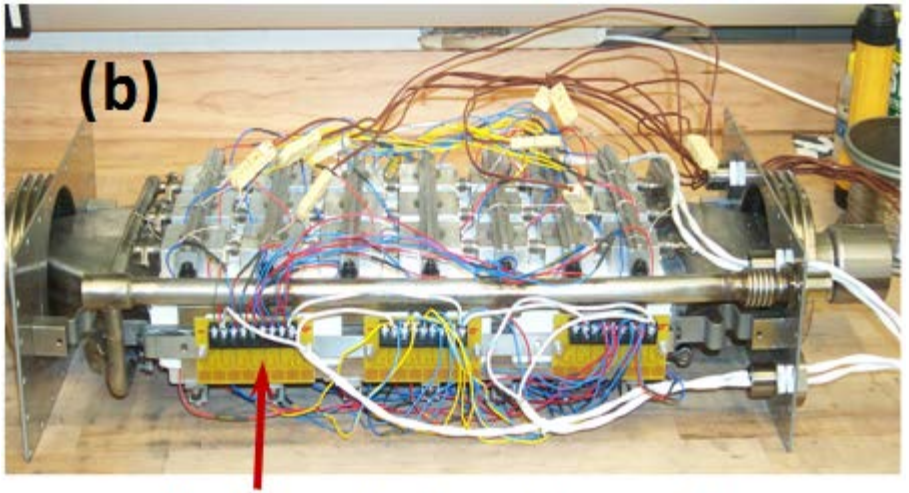
250°C (Front)
178°C (Middle)
148°C (Rear)

Lateral variation: < 3°C

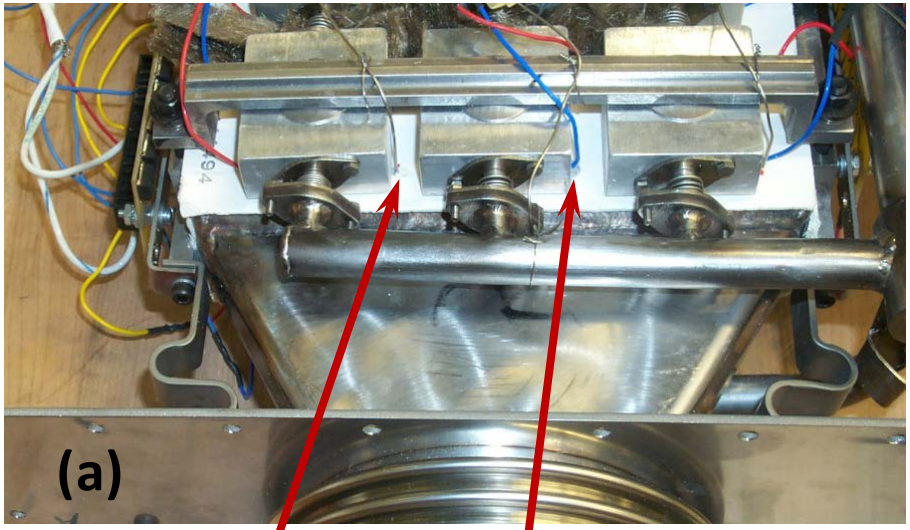
TE module open circuit voltages are consistent with 50°C smaller ΔT than measured between the heat exchanger and the coolant.

TEG #2

42 Bi-Te modules

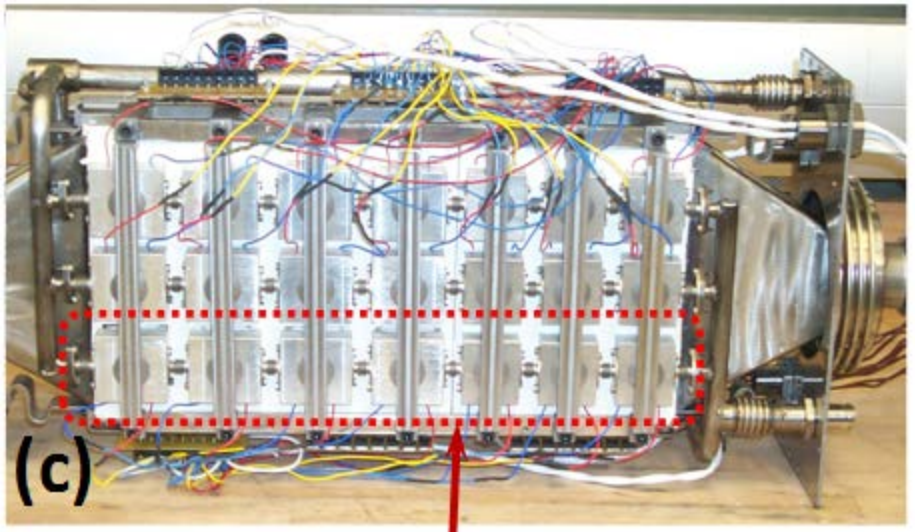


Circuit board for TE module connections



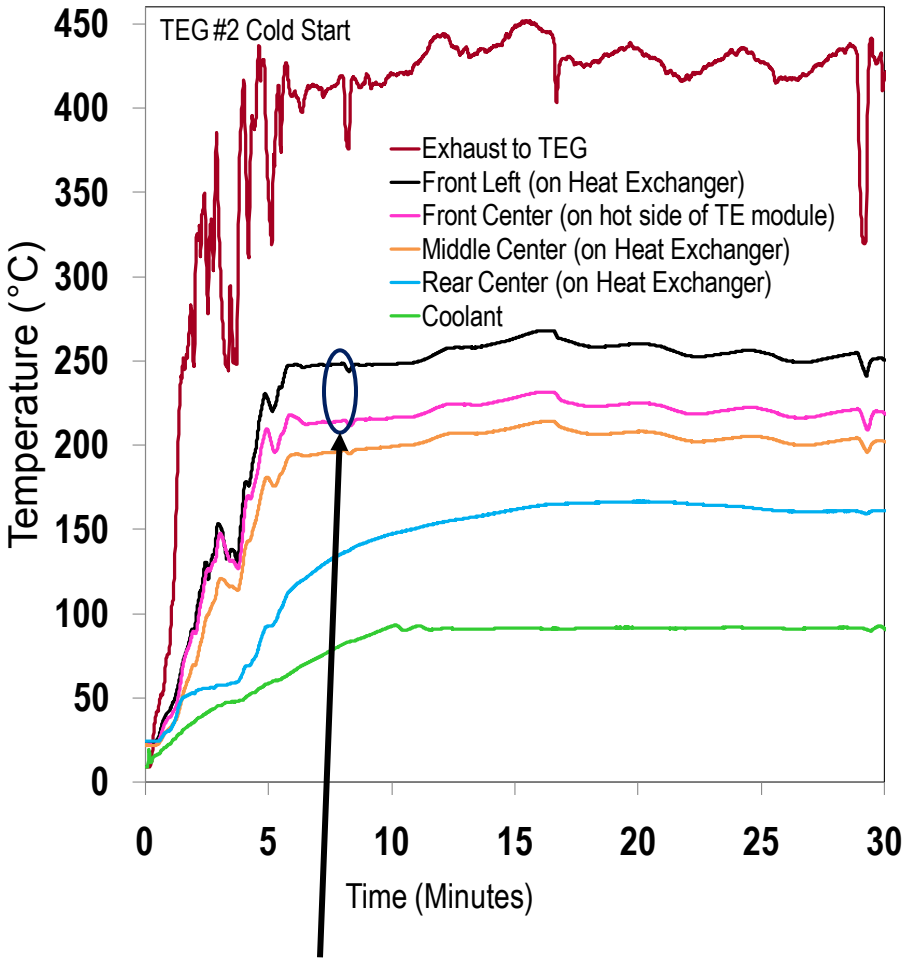
Front Left thermocouple on heat exchanger

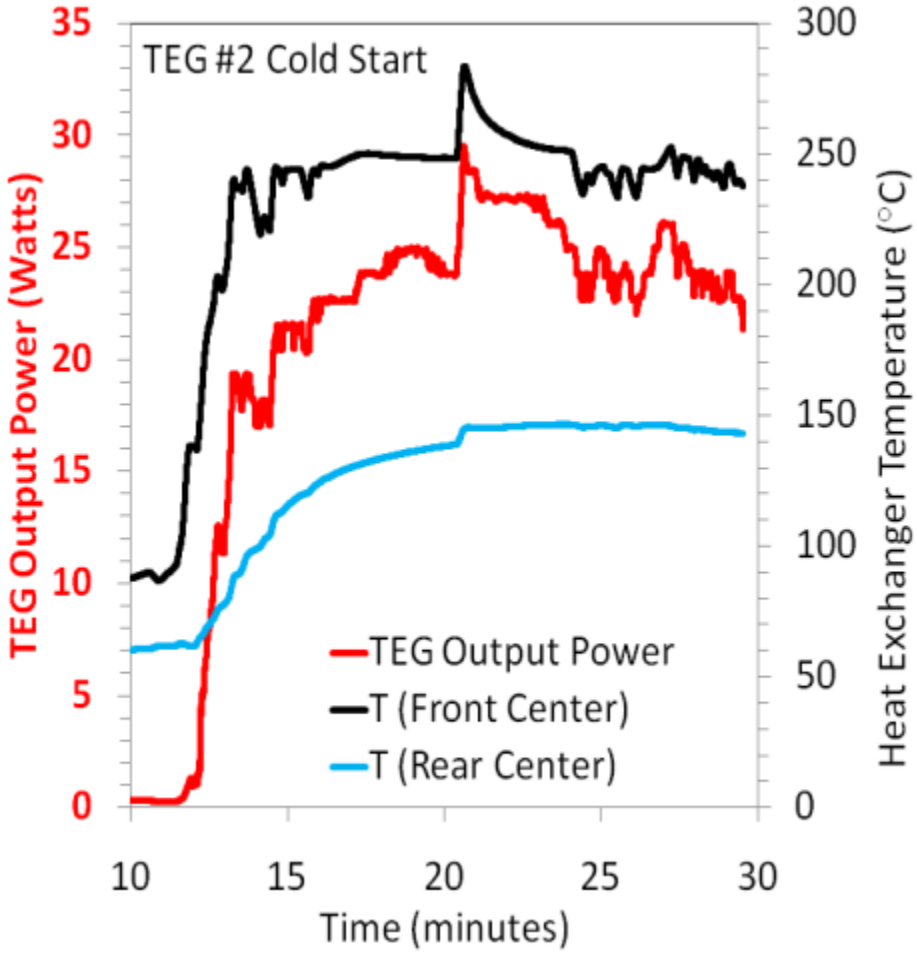
Front Center thermocouple on hot side of Bi-Te TE module



Seven TE module series

TEG #2





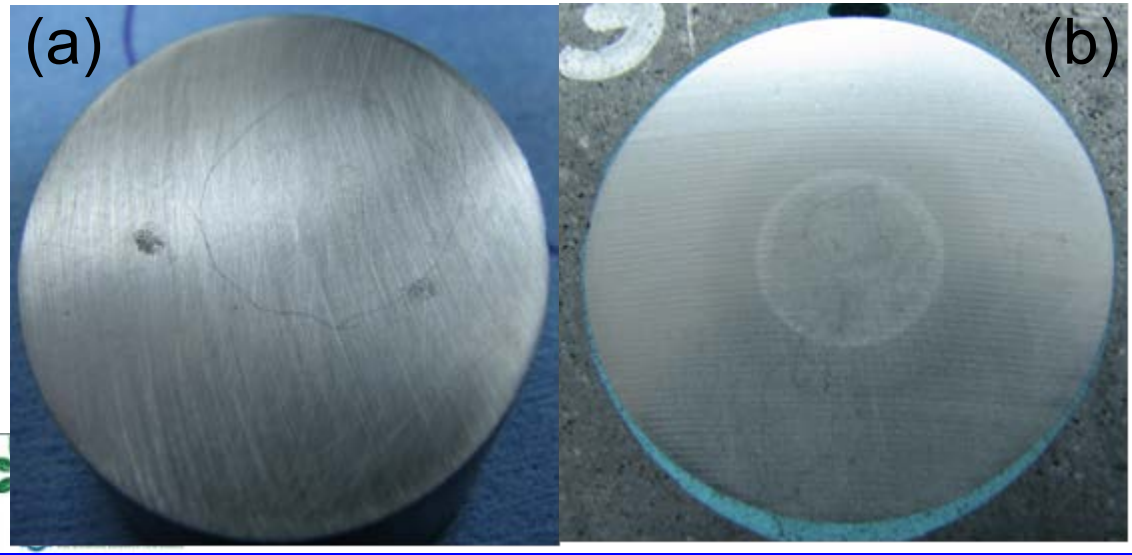
Temperature difference between hot side heat exchanger and hot side of TE module: ~ 35°C

TEG #3

Skutterudite Materials

We synthesized a large quantity of skutterudite materials for TE modules for TEG #3 at GM R&D (Jim Salvador).

Determined optimized process parameters for spark plasma sintering

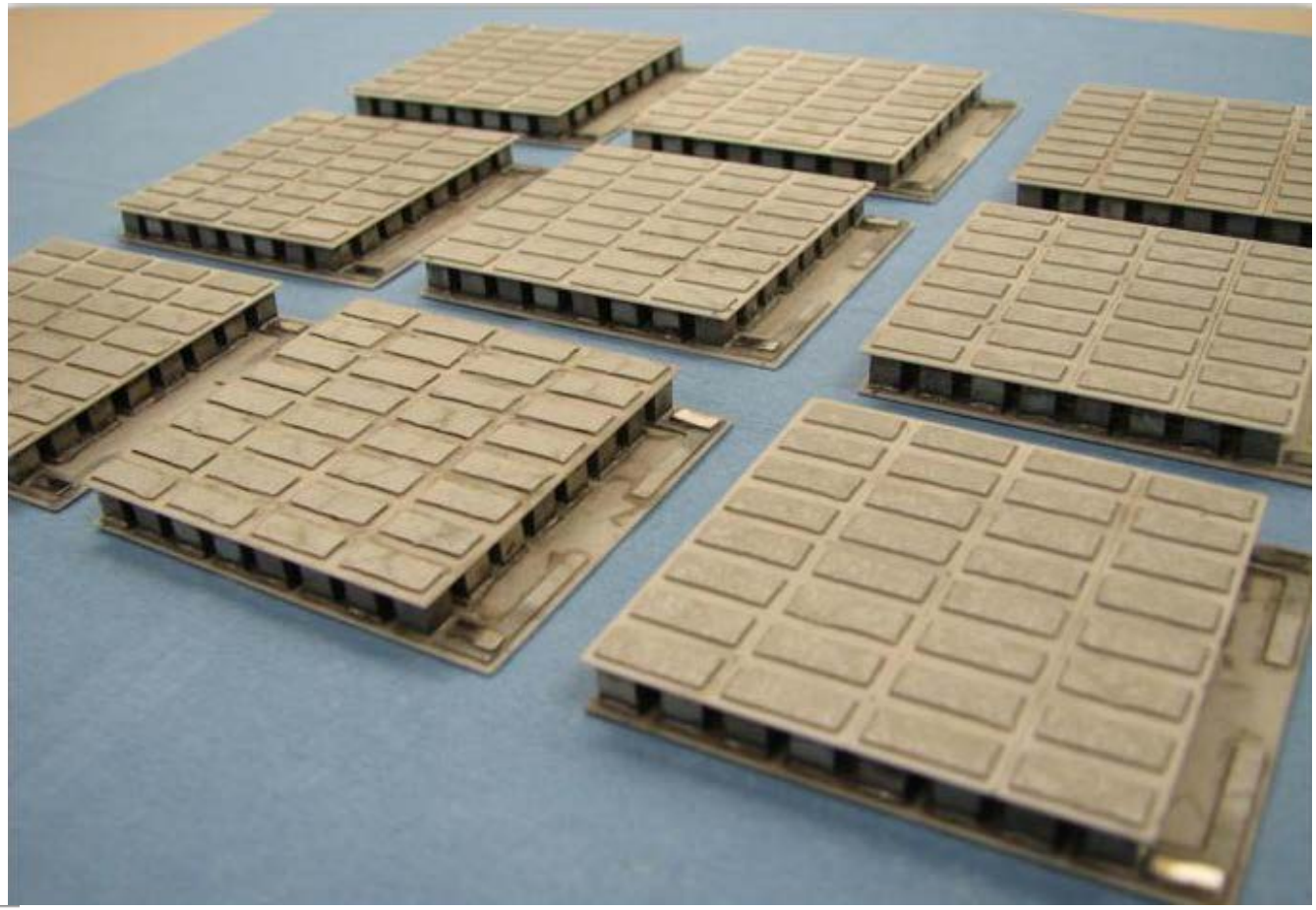


Adjusted processing to eliminate center crack (a) and coring flaws (b).

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

TEG #3

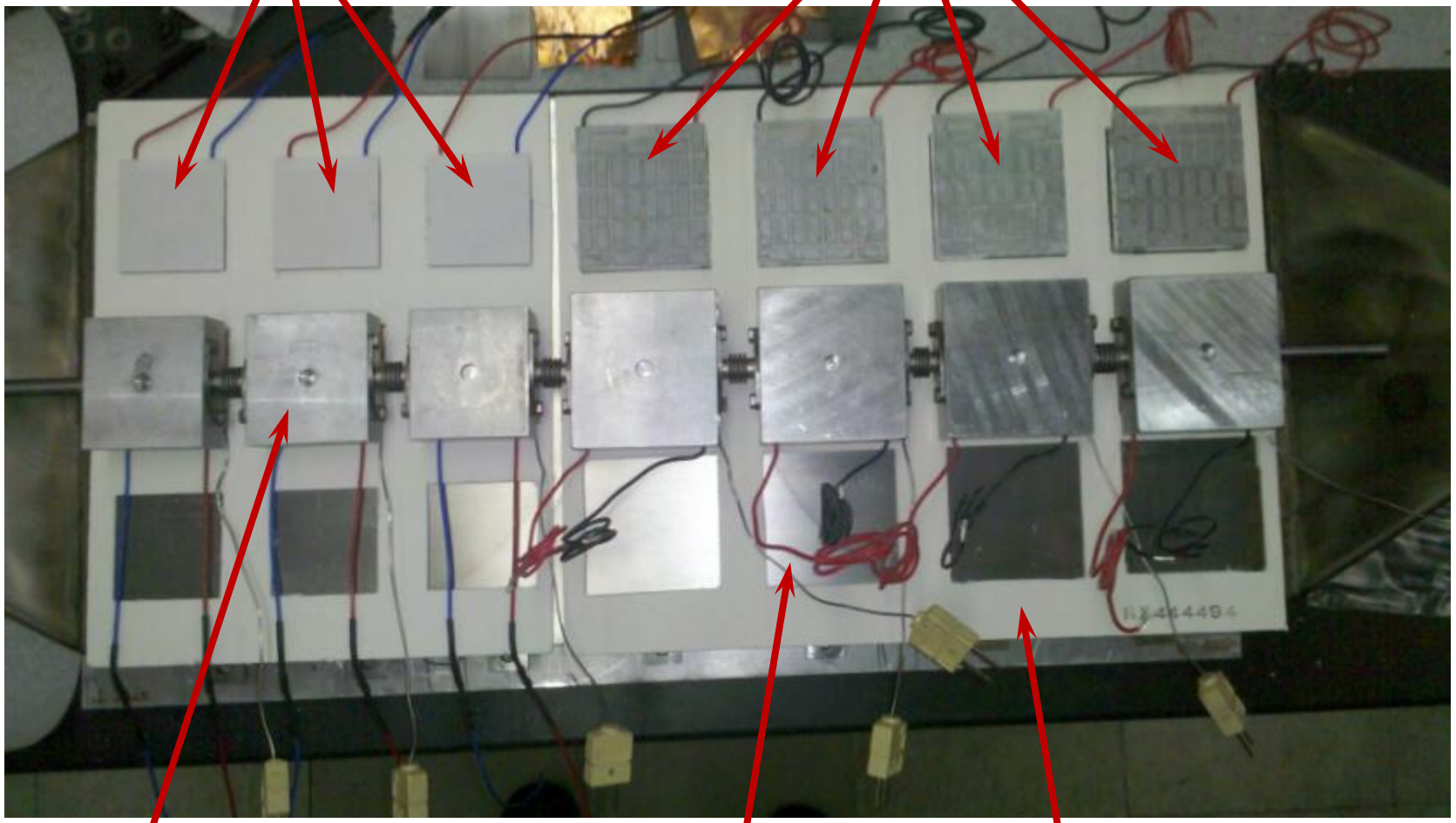
Skutterudite Modules (Marlow Industries, Inc.)



TEG #3

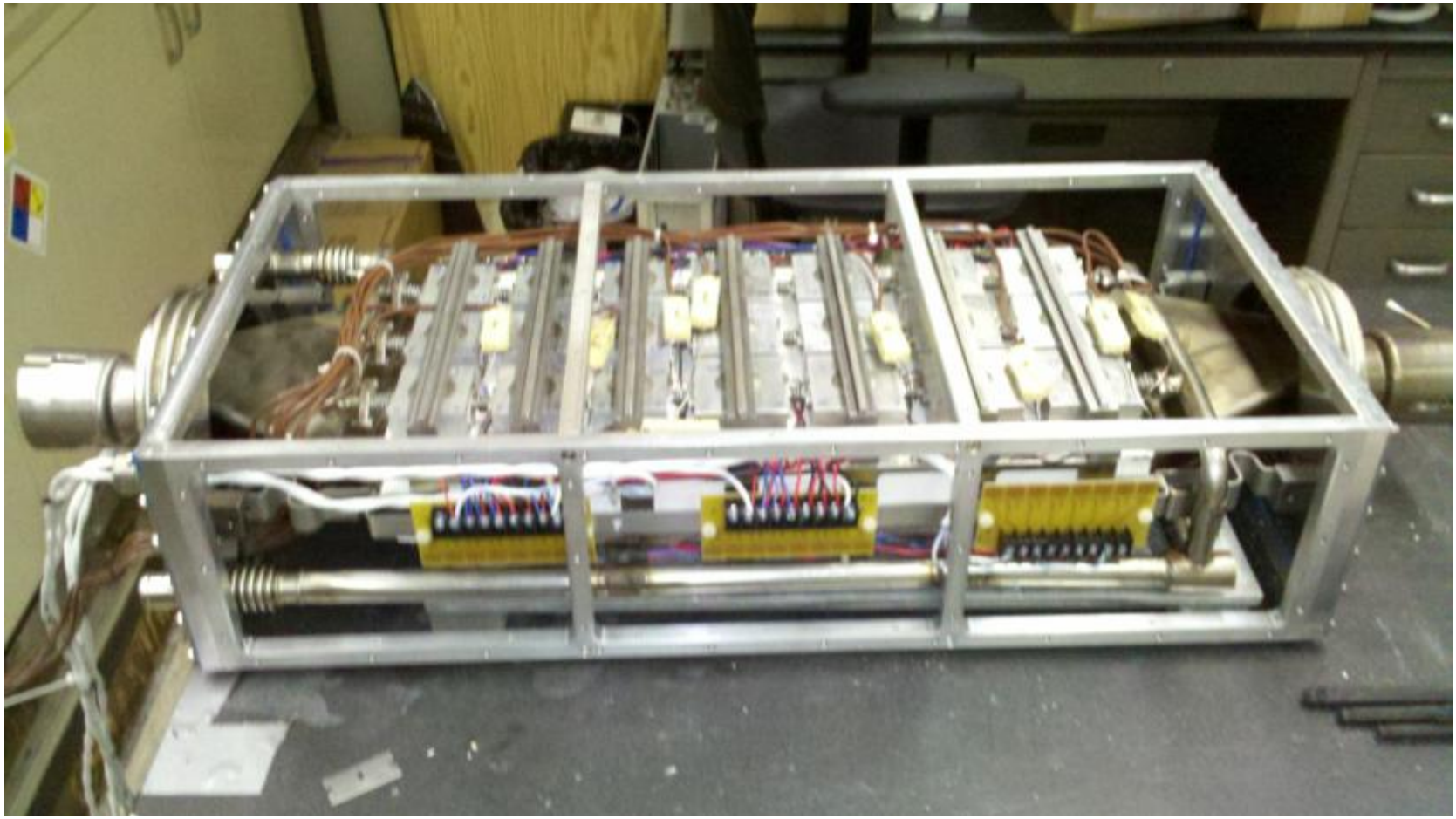
Hot side heat exchanger

TEG #3


Bi-Te modules
Skutterudite modules
Cold side heat exchanger
Thermocouple
Thermal insulation

TEG #3

TEG #3



TEG #3

Waste Heat 1: Vehicle test drive and US06 drive cycle testing is underway; control parameters and algorithms are being optimized for best performance. Final results soon!

Waste Heat 2:

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
National Energy Technology Laboratory
FY 2011 Vehicle Technologies Program Wide
Funding Opportunity Announcement
Funding Opportunity Number: DE-FOA-0000239

Area of Interest 6-- Thermoelectrics and Enabling Engine Technologies:

Subtopic 6A: Solid State Thermoelectric Energy Conversion Devices

"…achieve improved efficiency and reduced emissions in advanced combustion engines for passenger… vehicle applications through accelerated development of cost-competitive advanced second generation thermoelectric devices for vehicle applications…"

This subtopic is for research and development projects that use thermoelectric (TE) devices to offer:

a) A five (5) percent fuel economy improvement by direct conversion of engine waste heat to useful electric power for light-duty vehicle application.

Waste Heat 2:

Subtopic 6A: Solid State Thermoelectric Energy Conversion Devices:

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

Project requirements:

- Form a team involving suppliers, national labs, universities, and a vehicle OEMs
- Develop, test, and demonstrate advanced TE devices
- Document efficiency gains on an engine dynamometer and a full-scale vehicle
- Demonstrate fuel economy improvement of 5% measured over the US06 cycle
- Plan for independent confirmatory testing of hardware to verify performance
- Conduct cost assessment to identify areas of technology change and their impact on product costs
- Provide production cost analysis for 100k units/year including how costs will be reduced in manufacturing

GM has been awarded $8 M 4-year contract.

Waste Heat 2:

Project Plan:

- Select demonstration vehicle
- Optimize TE materials and subsystems for module fabrication and performance
  - TE material properties
  - Thermal and electrical Interfaces
  - Protection for long term durability
- Develop new cost-effective TEG system design for scaled-up manufacturability
  - Heat exchangers
  - Control algorithms
  - Vehicle integration
  - Electrical power conditioning
- Develop scaled-up synthesis, fabrication, and assembly processes
- Conduct TEG subsystems bench testing for component performance & reliability
- Vehicle drive cycle testing for fuel economy improvement assessment

Summary

Waste Heat 1:

- Prototype TEGs # 1 and #2 (Bi-Te modules) were assembled, installed, and tested on the demonstration vehicle
- Synthesized a large quantity of skutterudite material for TE module fabrication for TEG #3 at GM R&D
- Skutterudite modules were fabricated and assembled into TEG #3
- TEG #3 is installed in the demo vehicle. US06 testing is underway.

Waste Heat 2:

- Awarded $8 M 4-year contract from USDOE for cost-effective TEG development
- Final terms being worked out with the US DOE and R&D partners
- Work to start by 1/1/2012