Thermoelectric Generator Development for Automotive Waste Heat Recovery

Gregory P. Meisner

General Motors Global Research & Development

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Outline

- Acknowledgements
- Introduction
- Thermoelectric Materials Research
- Thermoelectric Generator Development
- Summary

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John Fairbanks (DOE), Carl Maronde (NETL)

GM R&D Thermoelectrics Team:

Researchers:
- Jim Salvador
- Jihui Yang
- Mike Reynolds

Postdocs:
- Xun Shi, Jung Cho, Zuxin Ye

Engineering Operations:
- Kevin Rober
- John Manole

Gov. Contracts:
- Ed Gundlach,
- Amanda Demitrish
- Rick Leach

Management:
- Jan Herbst
- Mark Verbrugge

GMPT Integration & Testing:
- Greg Prior (Retired)
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Collaborators/Subcontractors:

- Marlow Industries: Jeff Sharp, Jim Bierschenk, Josh Moczygemba
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- Emcon (Faurecia)
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- Michigan State University: Don Morelli
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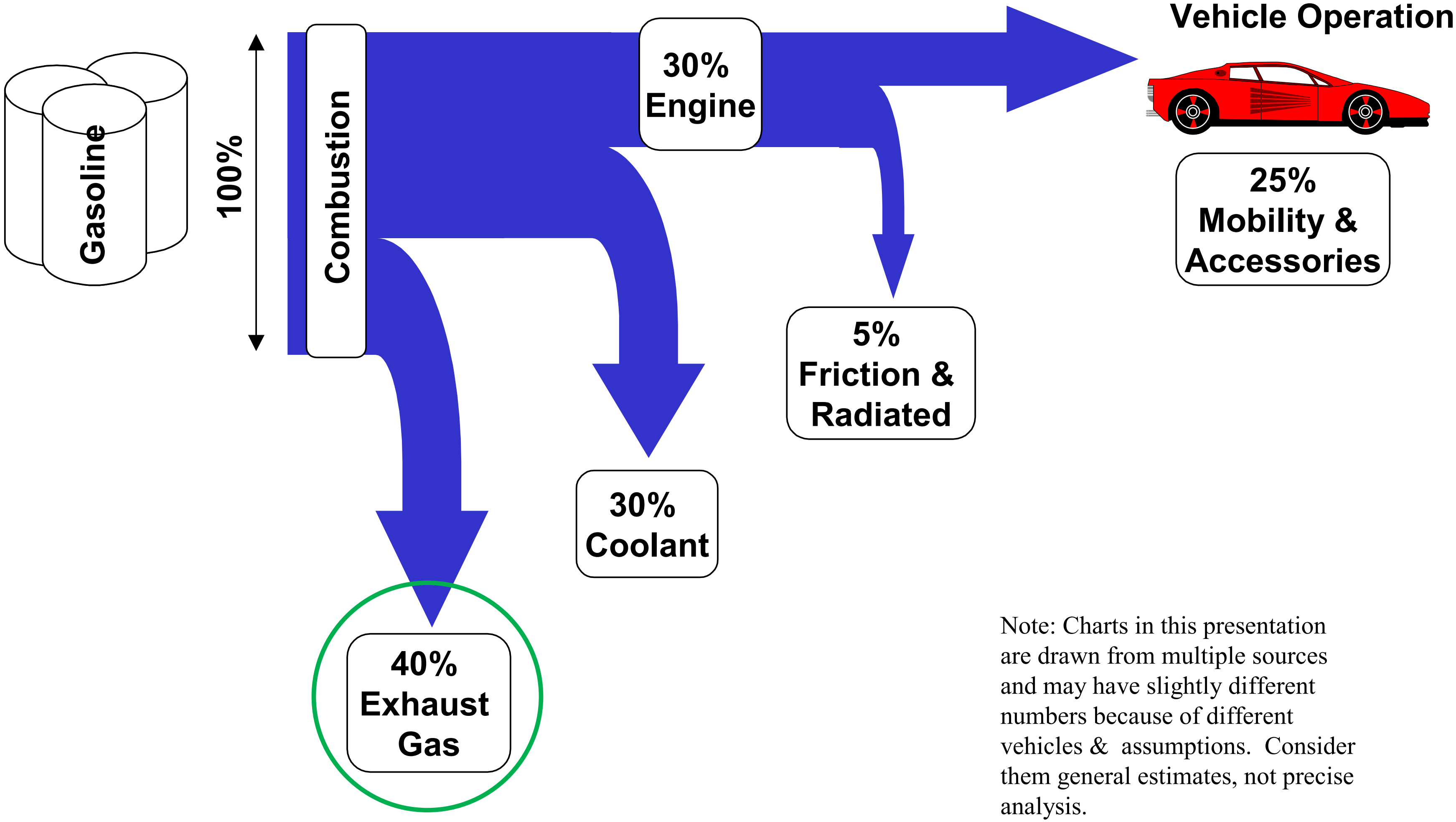
Introduction

Automotive Energy Flow Diagram

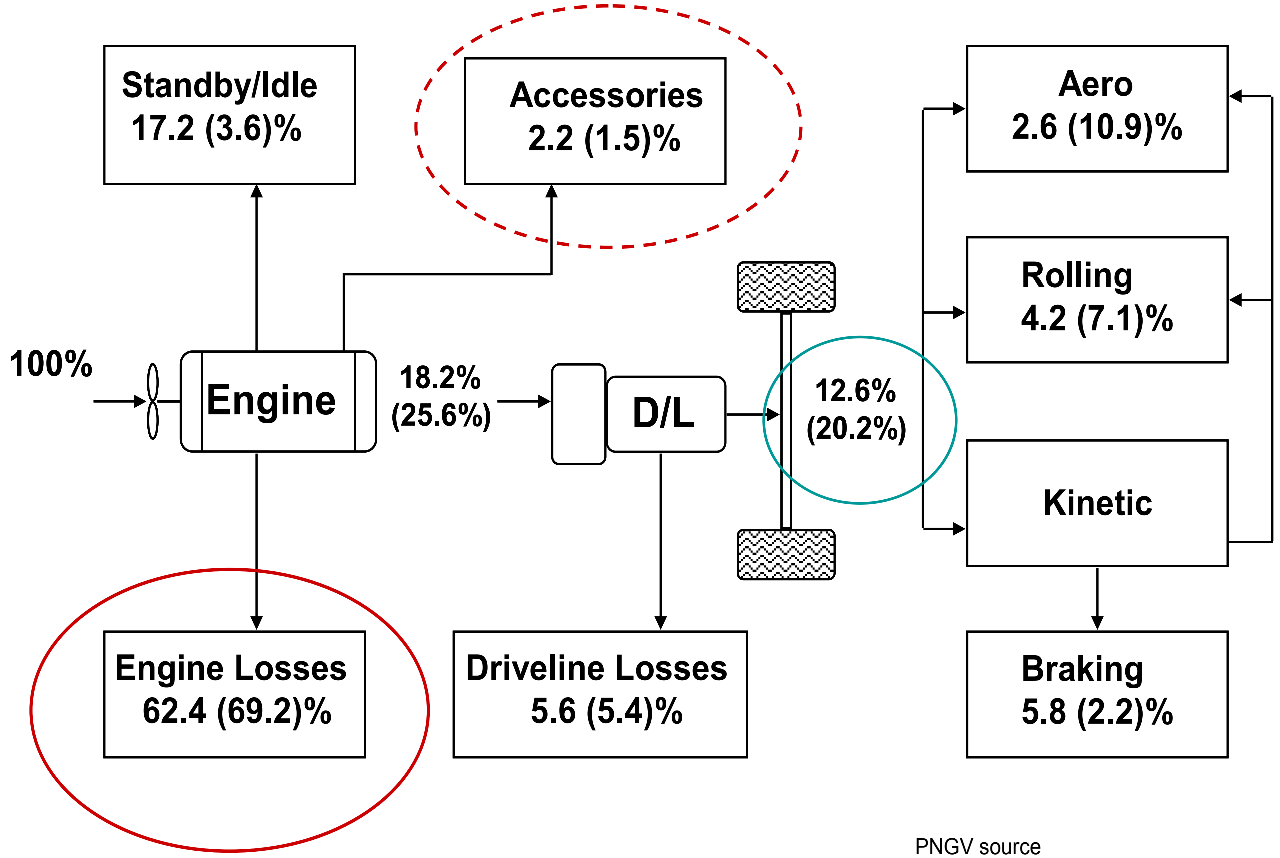


Note: Charts in this presentation are drawn from multiple sources and may have slightly different numbers because of different vehicles & assumptions. Consider them general estimates, not precise analysis.

Francis Stabler, Future Tech, (GM Powertrain , Ret.)

Introduction

Energy Distribution for Typical Mid-Size Vehicle using the Federal Test Procedure (FTP) Schedule: Urban (Highway) % Energy Use



PNGV source

- Today's ICE-based vehicles: < 20% of fuel energy is used for propulsion.
- > 60% of gasoline energy is not utilized and is waste heat.

Introduction

US Department of Energy:

Funding Opportunity Announcement No. DE-PS26-04NT42113, "Energy Efficiency Renewable Energy (EERE) - Waste Heat Recovery and Utilization Research and Development for Passenger Vehicle and Light/Heavy Duty Truck Applications"

Achieve 10 % improvement in fuel economy (FE) by 2015 without increasing emissions

- Demonstrate FE improvement for the Federal Test Procedure driving cycle (~3%)
- Demonstrate that actual FE improvement for real world driving conditions is closer to DOE goal

Demonstrate commercial viability

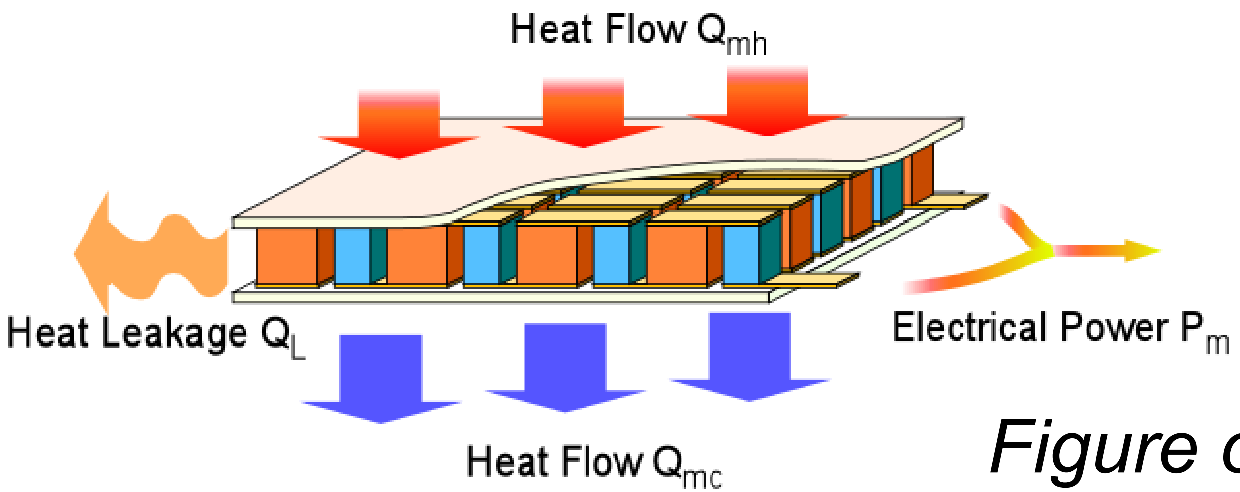
- Assemble, install, and test prototype TEG on a production vehicle
- Collect performance data, show viability
- Identify specific design, engineering, and manufacturability improvements for path to production

Approach:

- Thermoelectric Materials Research: discover, investigate, optimize advanced TEs
- Incorporate new advanced TE materials into operational devices & vehicle systems
- Integrate/Load Match advanced TE systems with vehicle electrical networks
- Verify device & system performance under operating conditions

Introduction

Thermoelectrics for Waste Heat Recovery



Efficiency:

$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}}$$

Figure of Merit:

$$ZT = S^2 T / \kappa_T \rho$$

S = *Seebeck Coefficient (Thermoelectric Power)*

κ_T = *Thermal Conductivity*

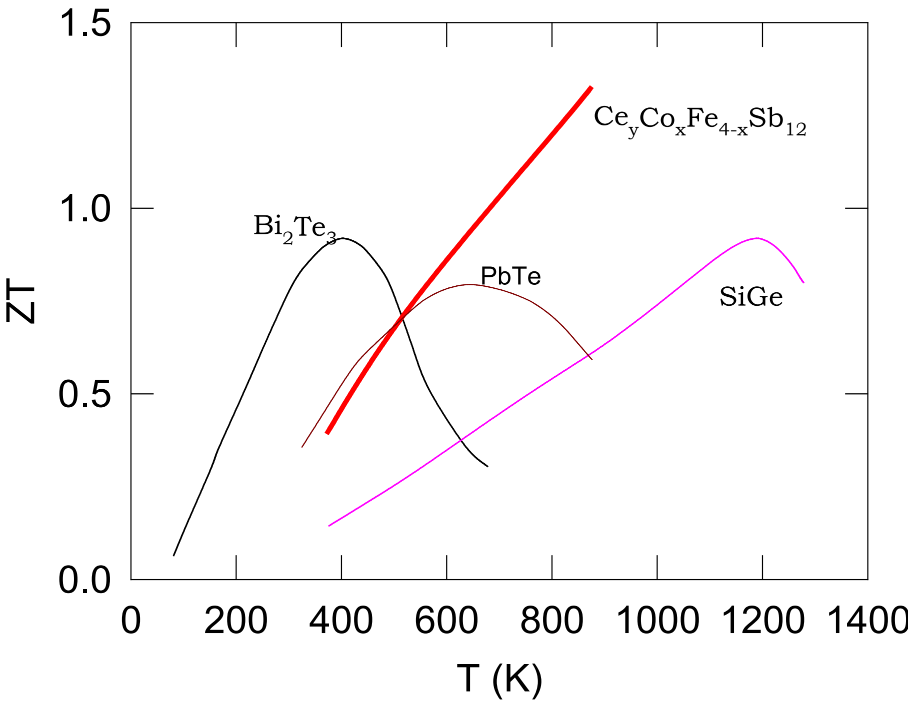
ρ = *Electrical Resistivity*

Introduction

Insulators: *S* can be very high, but electrical resistance is very high
$\Rightarrow$ *ZT* too small.

Metals: Electrical resistance very low, but *S* is very low, and thermal conductivity is too high
$\Rightarrow$ *ZT* too small

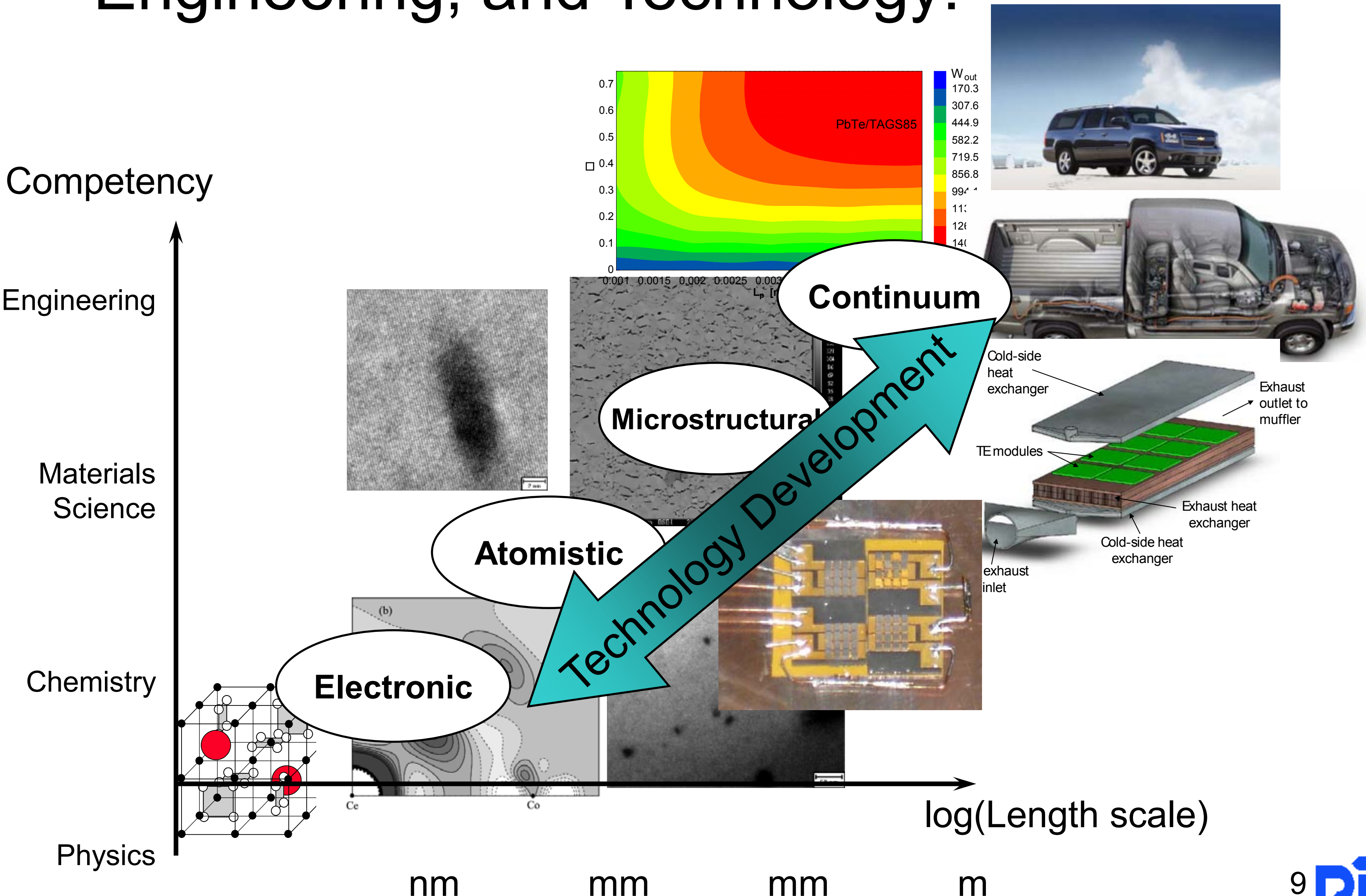
Semiconductors: Can find materials with adequate *S*, acceptable resistance range that can be tuned by doping, and low thermal conductivity. Optimized material properties can give large *ZT*.



Material Requirements:

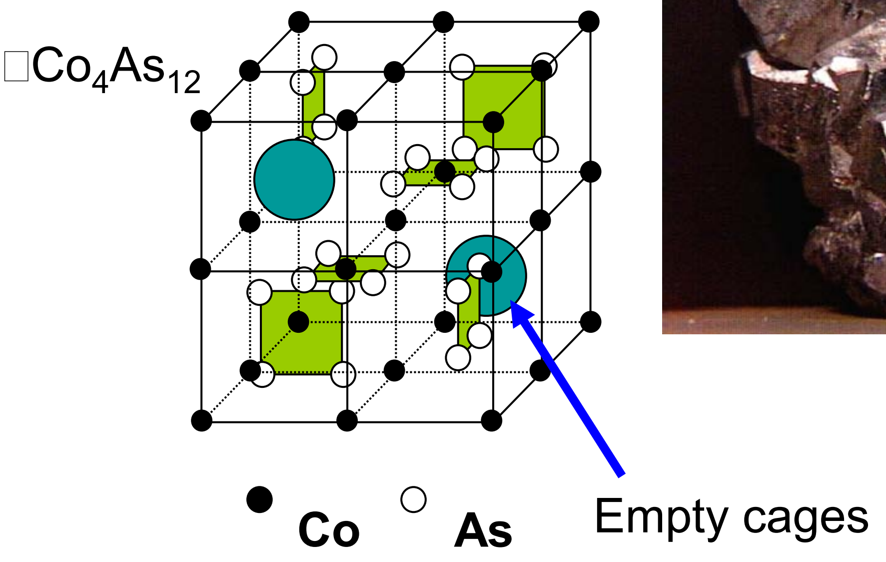
Bulk material (i.e., not thin film or nanostructured), Operating temperatures of 400-800 K (125-525°C), Need both p- and n-type thermoelectrics, Low lattice thermal conductivity κ_L, High values of ZT > 1, Good mechanical properties, Readily available and inexpensive raw materials. Environmentally friendly.

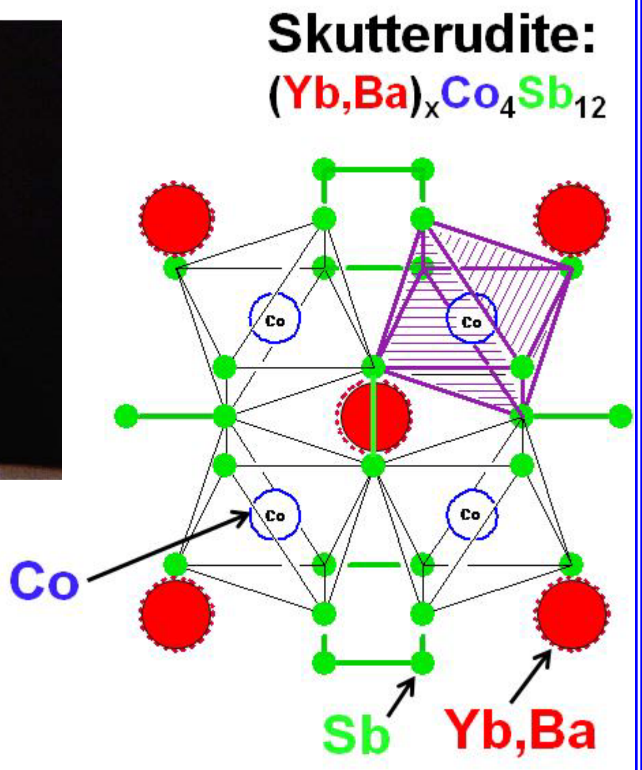
Thermoelectric Materials: Science, Engineering, and Technology:



Filled Skutterudites: Technologically Important and Scientifically Fascinating Materials

Skutterudite: a $CoAs_3$ mineral found near Skutterud, Norway, in 1845, and compounds with the same crystal structure (body-centered cubic, *Im3,* Oftedal, I. (1928): *Zeitschrift für Kristallographie* 66: 517-546) are known as "skutterudites"





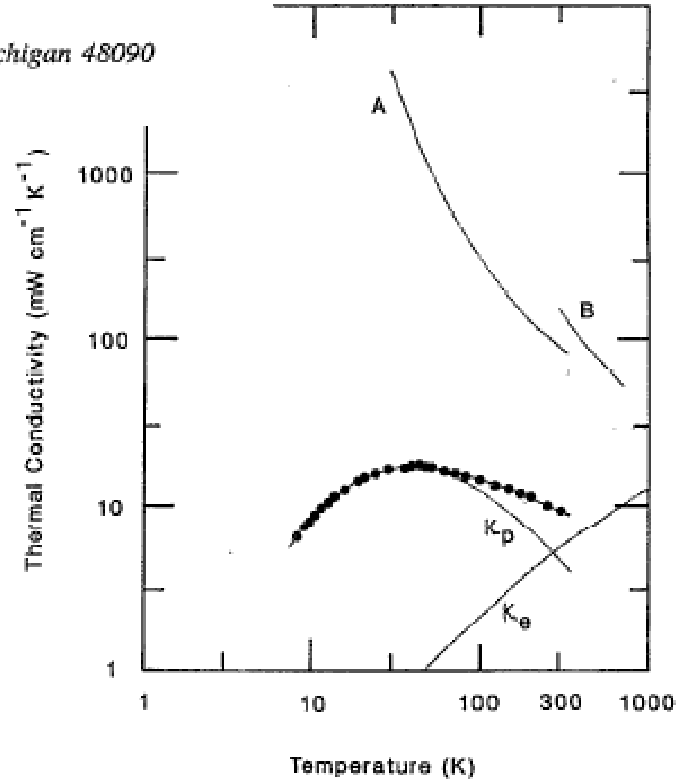
W. Jeitschko, D. J. Braun, Acta Crystallogr. 1977, B33, 3401: Filled Skutterudite Crystal Structure for $LaFe_4P_{12}$.

First experimental verification theoretical prediction of low thermal conductivity in filled Skutterudites:

Low temperature properties of the filled skutterudite $CeFe_4Sb_{12}$

Donald T. Morelli[a)] and Gregory P. Meisner
Physics Department, General Motors Research and Development Center, Warren, Michigan 48090

(Received 10 October 1994; accepted for publication 30 December 1994)
Journal of Applied Physics (1995)



High Figure of Merit in Ce-Filled Skutterudites

Jean-Pierre Fleurial, Alex Borshchevsky, Thierry Caillat
Jet Propulsion Laboratory/ California Institute of Technology, Pasadena, California, USA

Donald T. Morelli and Gregory P. Meisner
General Motors Research and Development Center, Warren, Michigan, USA

Proc. 15th Inter. Conf. Thermoelectrics

United States Patent [19] | [11] **Patent Number: 6,069,312**
Fleurial et al. | [45] **Date of Patent: May 30, 2000**

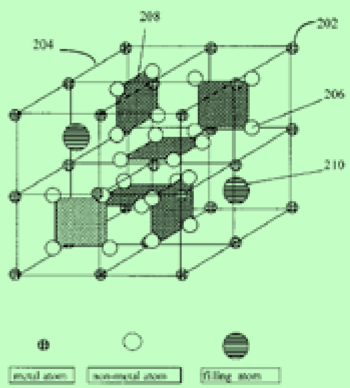
[54] **THERMOELECTRIC MATERIALS WITH FILLED SKUTTERUDITE STRUCTURE FOR THERMOELECTRIC DEVICES**

[75] Inventors: **Jean-Pierre Fleurial**, Duarte; **Alex Borshchevsky**, Santa Monica; **Thierry Caillat**, Pasadena, all of Calif.; **Donald T. Morelli**, White Lake; **Gregory P. Meisner**, Ann Arbor, both of Mich.

[73] Assignee: **California Institute of Technology**, Pasedena, Calif.

[21] Appl. No.: **08/908,814**

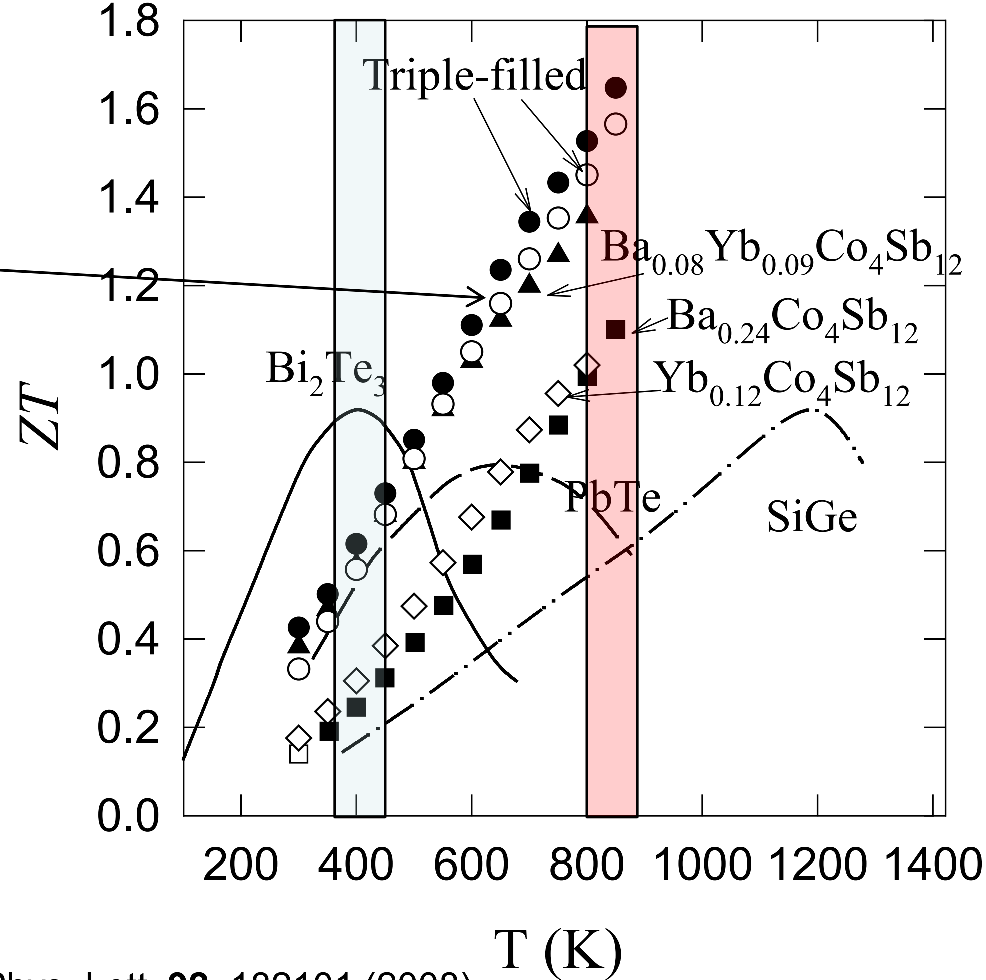
[22] Filed: **Aug. 7, 1997**



Multiple-filled Skutterudites: Much Improved ZT values

• $Ba_{0.08}La_{0.05}Yb_{0.04}Co_4Sb_{12.05}$
o $Ba_{0.10}La_{0.05}Yb_{0.07}Co_4Sb_{12.16}$

$ZT_{ave} = 1.2$



X. Shi, et al. Appl. Phys. Lett. **92**, 182101 (2008).
X. Shi, et al, Electronic Materials 38, 930 (2009).

TE Generator Development:

Incorporate New Advanced TE materials into Operational Devices & Vehicle Systems

Improve TE materials (Skutterudites) (ZT = 1.6 at 850 K, ZT_{ave}= 1.2)

Develop models and computational tools to design TE generators (TEGs) which include heat transfer physics at heat exchanger and interfaces; TE material properties; mechanical reliability, and cost

Develop thermoelectric modules for TEG

Finalize design, fabricate, and assemble prototype TEG

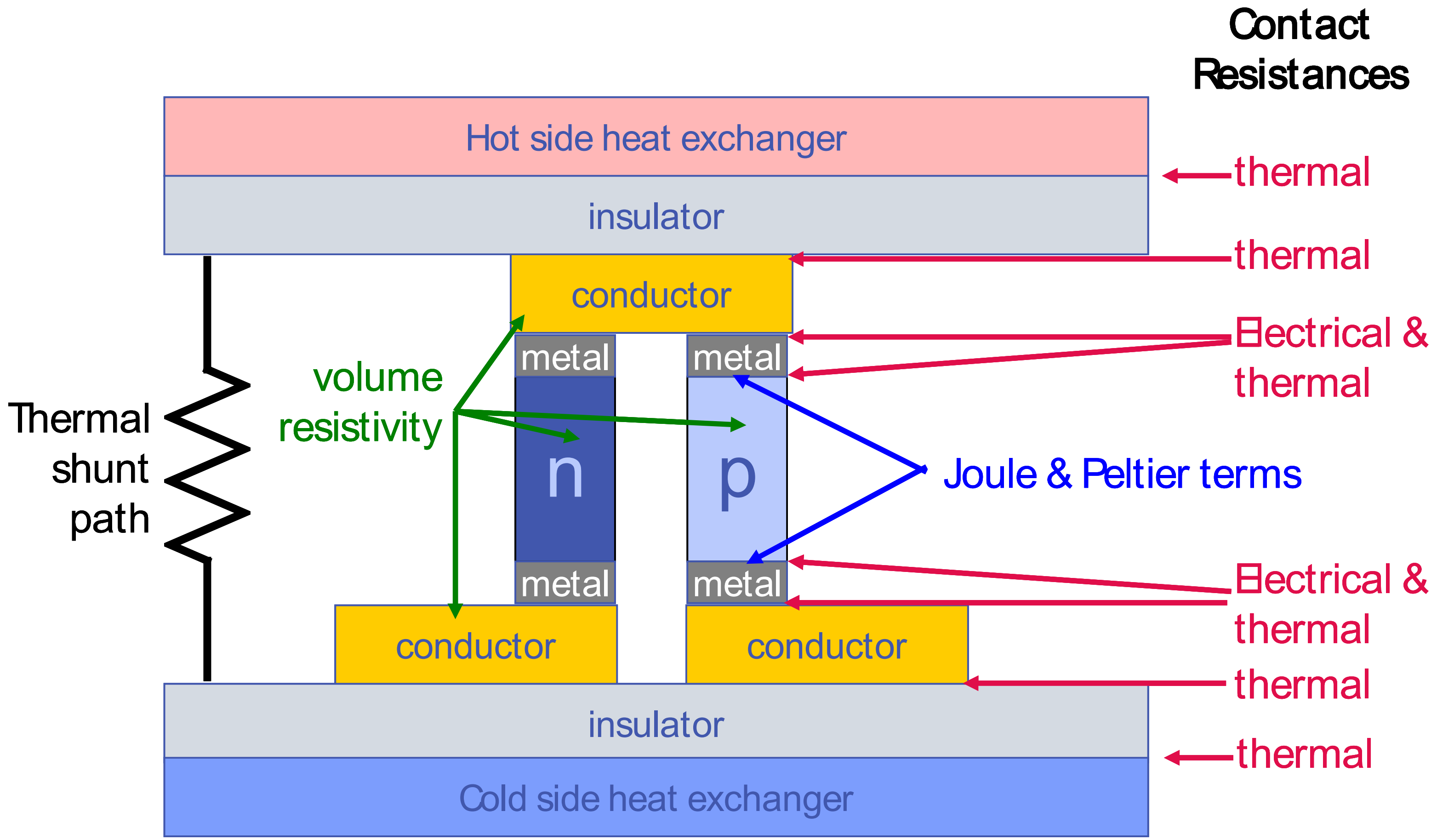
Complete vehicle modification for controls and integration of TEG

Develop power electronics design for power conditioning

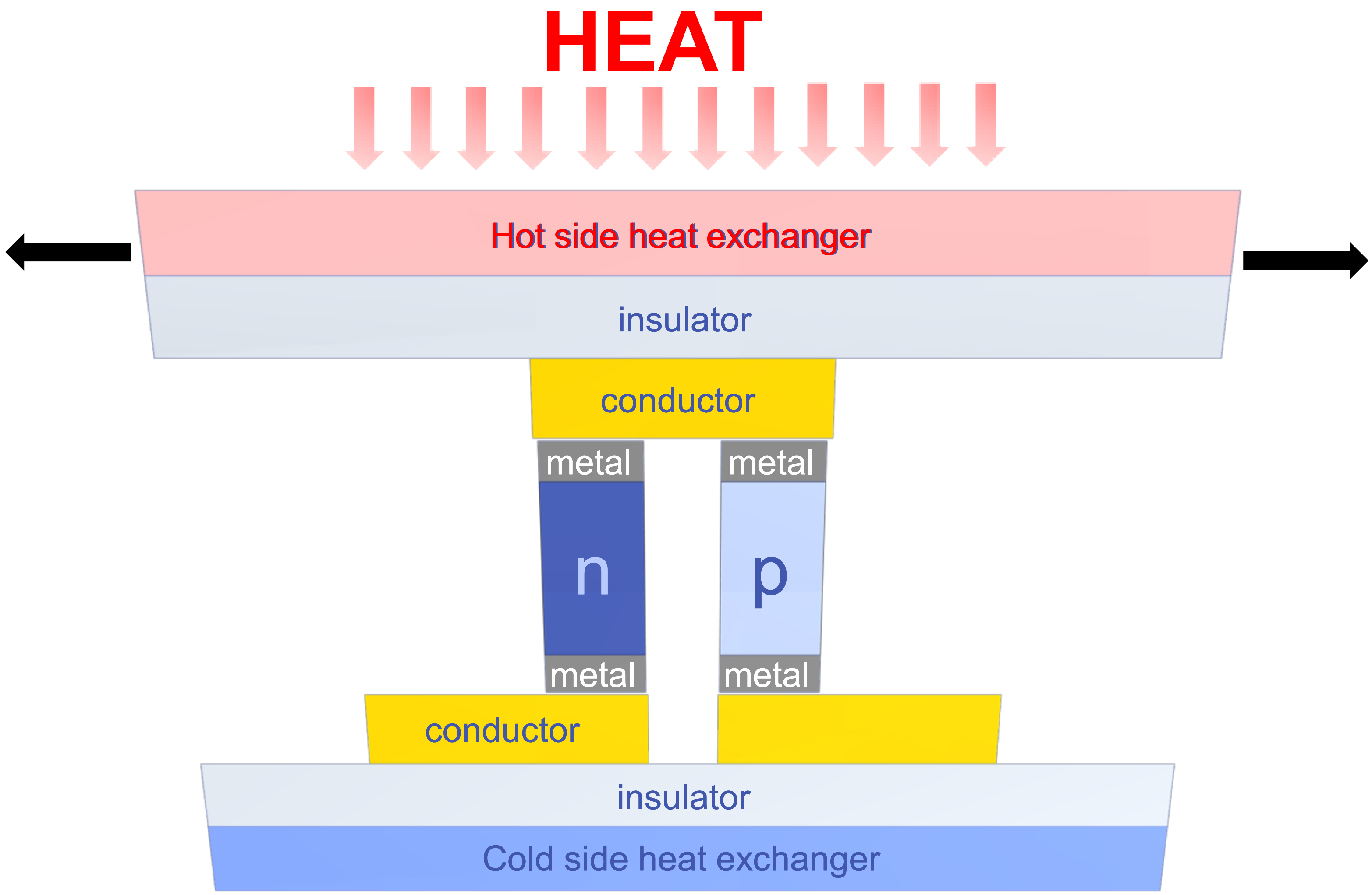
Develop system control algorithms for improved thermal-to-electrical conversion efficiency

Assess TEG performance

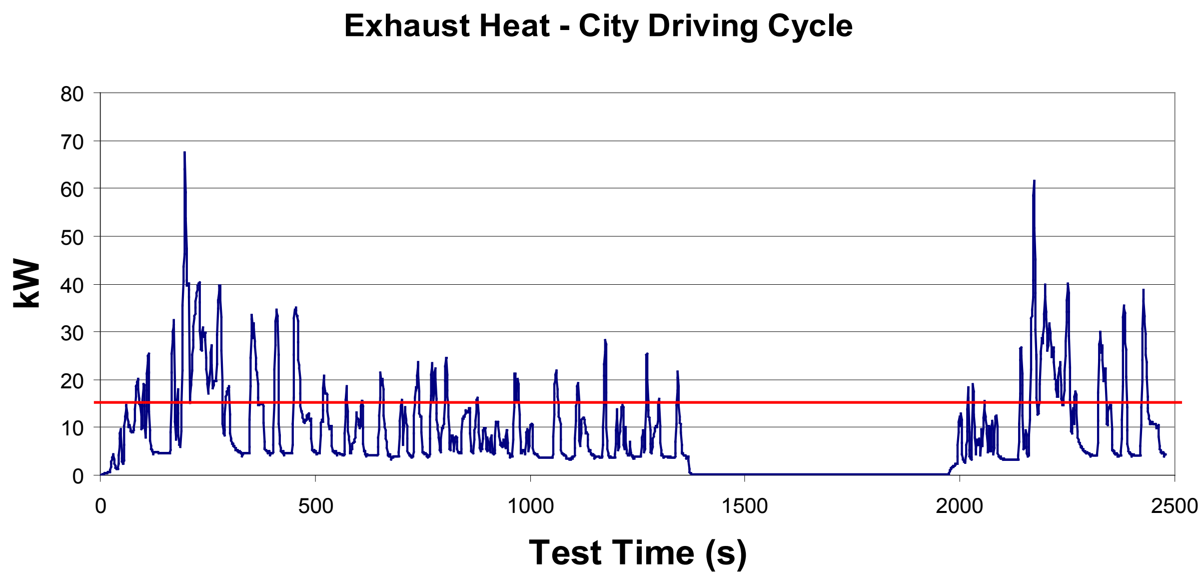
Schematic Diagram of a TE Module



Schematic Diagram of a TE Module



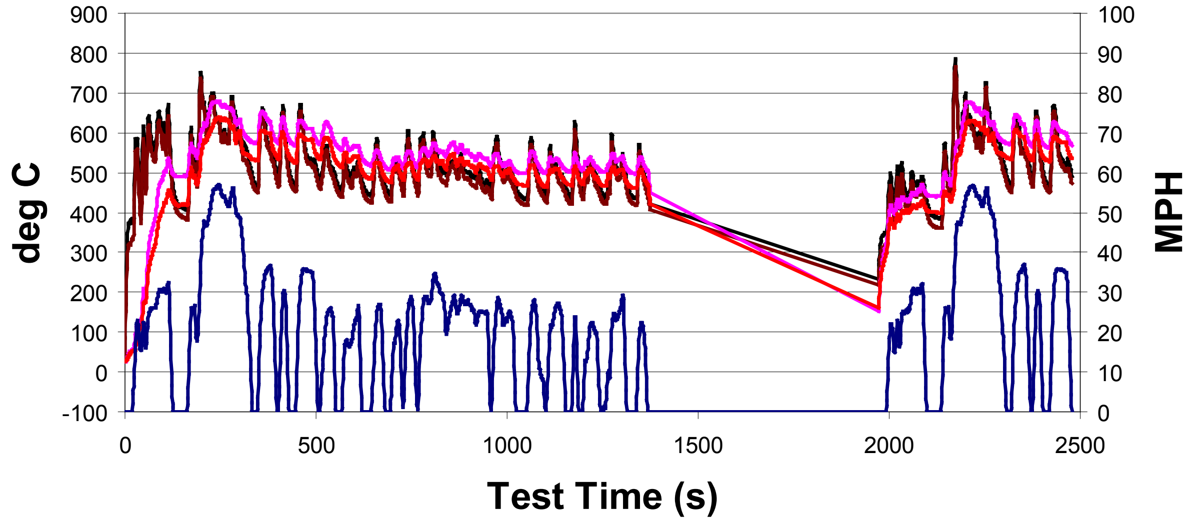
TE Automotive Waste Heat Recovery Vehicle Selection – Chevy Suburban



The Suburban was selected as a test vehicle because it simplified the vehicle modification and installation of the prototype.

Fuel efficiency improvement will be better in small, fuel efficient vehicles than in large vehicles because the electrical load in small vehicles is a larger portion of the engine output.

TE Automotive Waste Heat Recovery Vehicle Selection – Chevy Suburban



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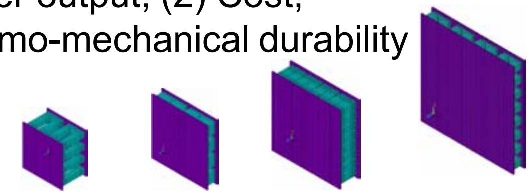
TEG Subsystems Modeling and Design

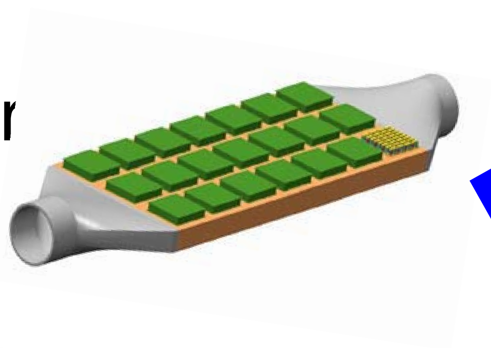
TE Module Design:

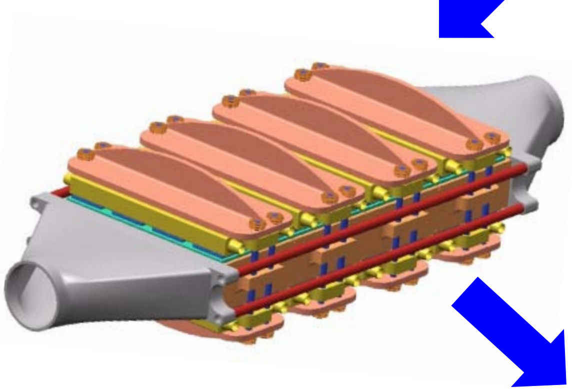
Identify primary module design variables

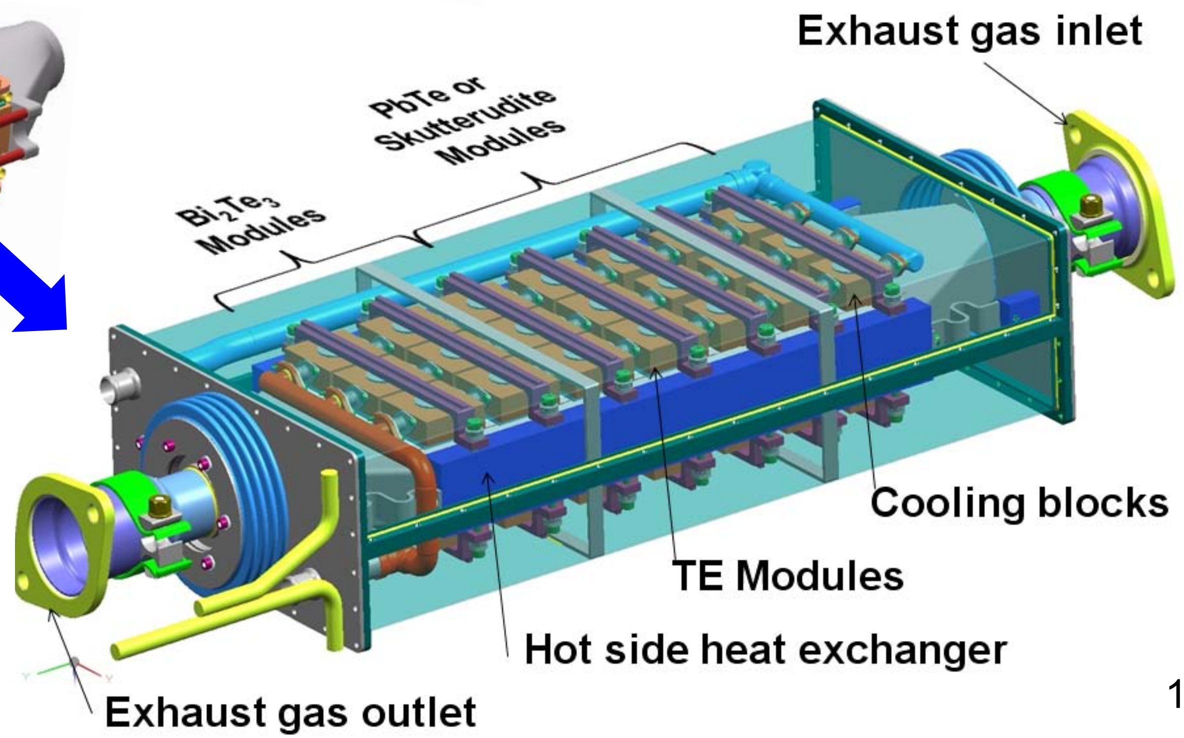
Examine effect on primary output variables:
(1) Power output, (2) Cost,
(3) Thermo-mechanical durability



Heat Exchanger Design:





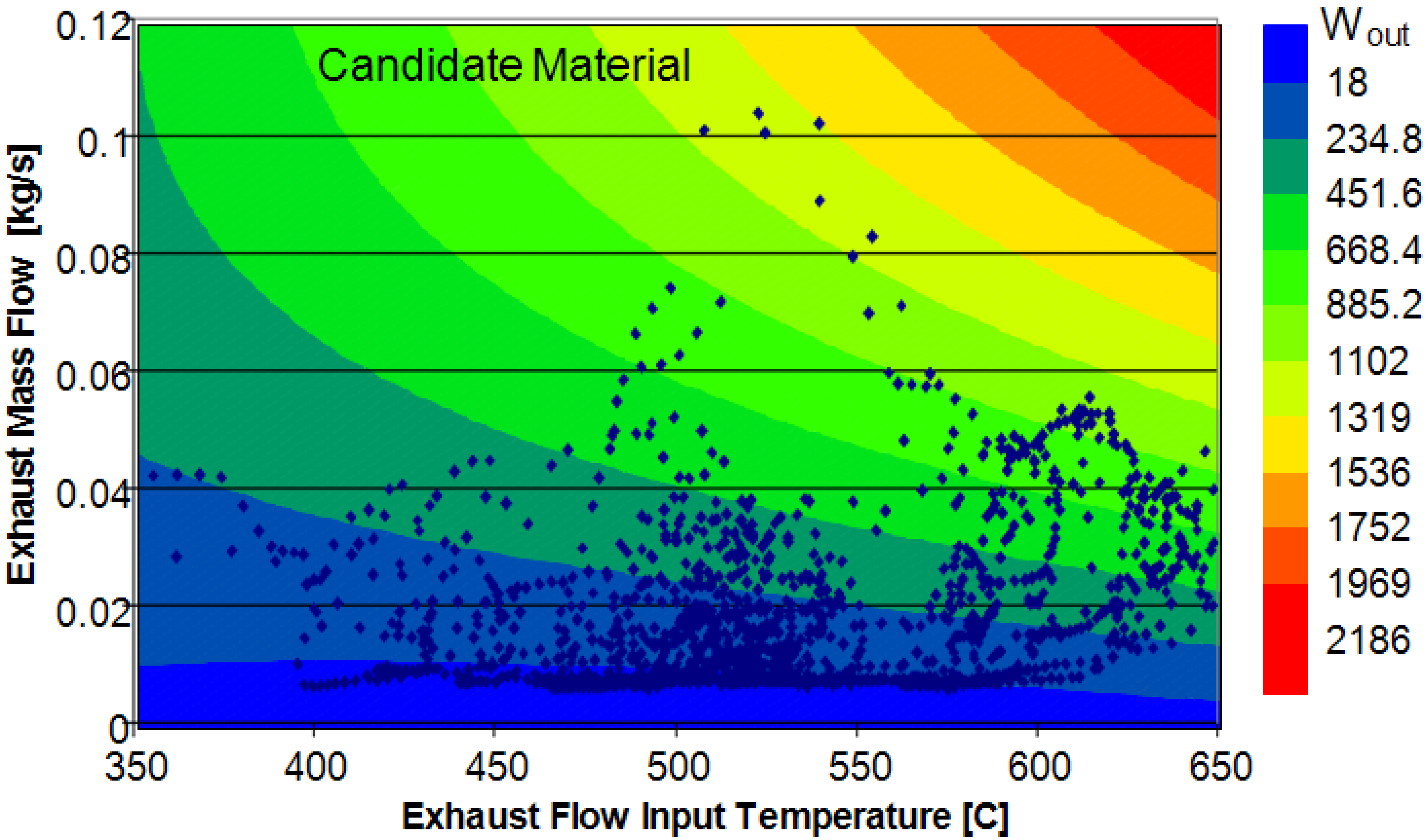


TEG Design:

Program metric: $/Watt

TEG Subsystems Modeling and Design

TE Model System Expected Efficiency and Urban Cycle Exhaust Conditions

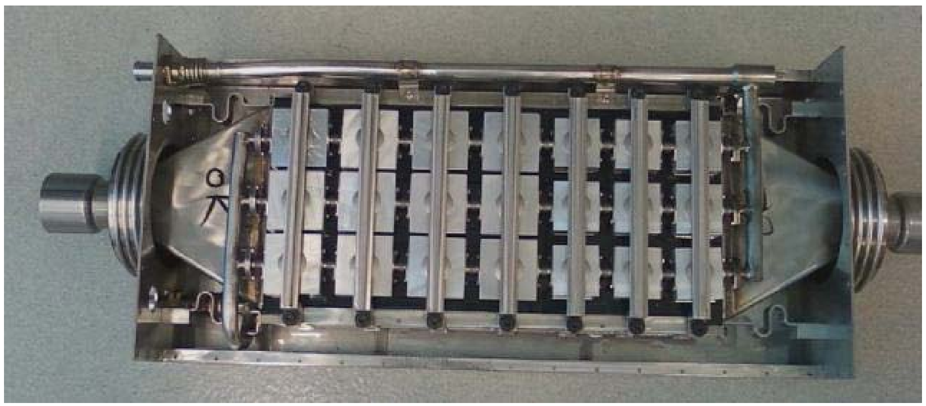


TEG Subsystems Modeling and Design

- We expect ~ 1 mpg (~ 5 %) fuel economy improvement for Suburban (average 350 W and 600 W for the FTP city and highway driving cycles, respectively.)
- This technology is well-suited to other vehicle platforms such as passenger cars and hybrids.

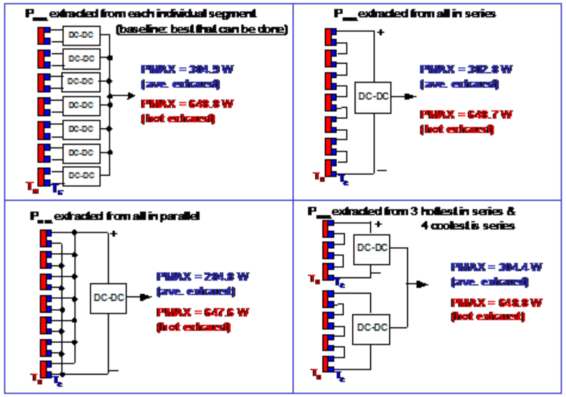
Finalize design, fabricate, and assemble prototype TEG

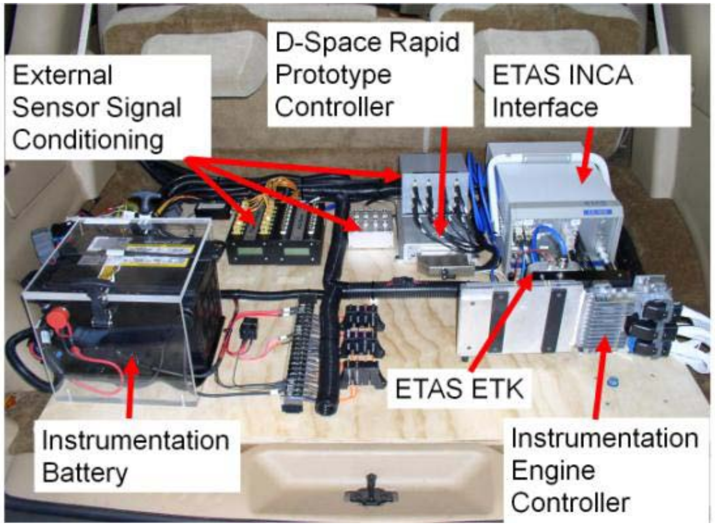
- Completed thermoelectric generator design and began fabrication of heat exchanger subassemblies. First prototype completed, second one in progress.



Vehicle Integration

- Power electronics design for power conditioning and vehicle control



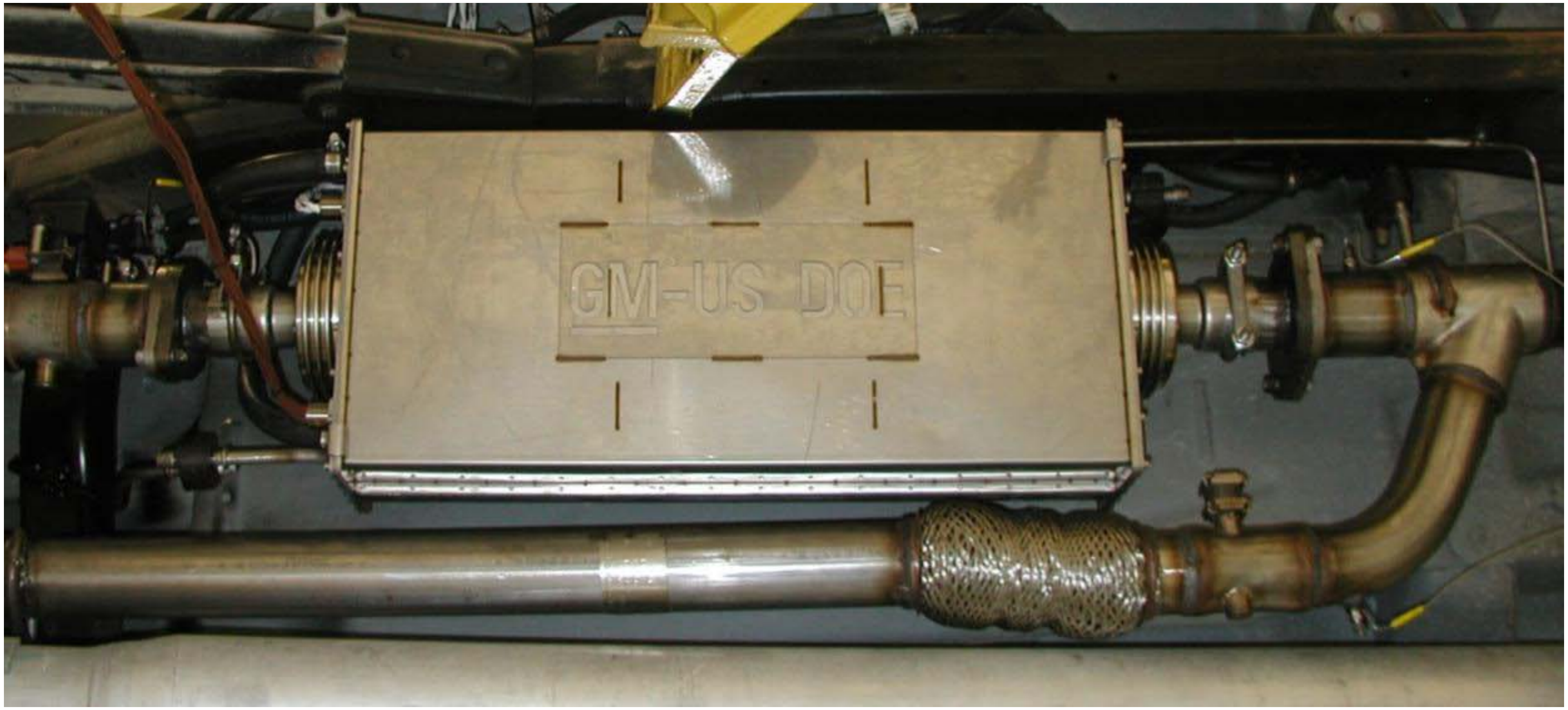


- Control algorithms for improved thermal-to-electrical conversion efficiency

  Bypass valve for exhaust gas

Vehicle Integration

- Exhaust system modified, parts fabricated and installed, TEG installed



TEG Testing & Validation

- <u>Assess TEG Performance</u>

  Start-Cart

  - First step in integration development
  - Provides a decoupled testing environment
  - Provides easy access for modification and debugging

  Chassis-Rolls Dynamometer

  - Provide a realistic loading and repeatable environment, though not a realistic environment
  - Precise data collection
  - Standard test method for fuel economy and emissions measurements

  Environmental Dynamometer

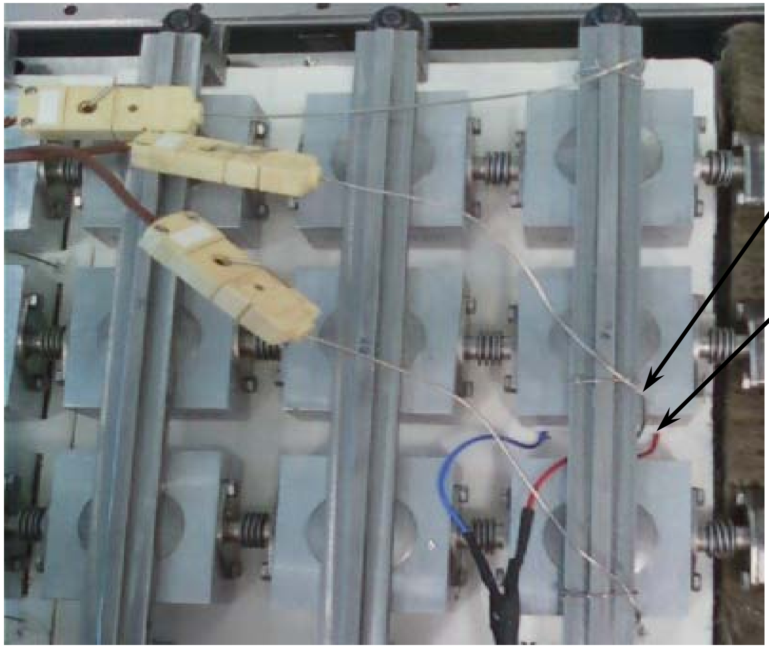
  

  - Chassis-rolls dynamometer which simulates grades, atmospheric environment

  Real World Driving

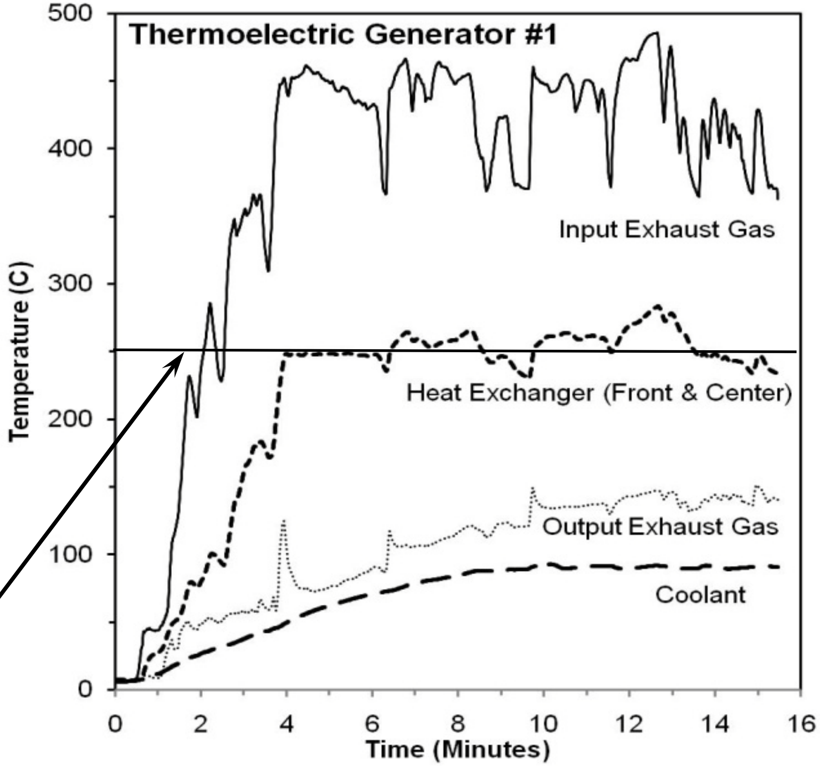
  

TEG #1: Preliminary Testing



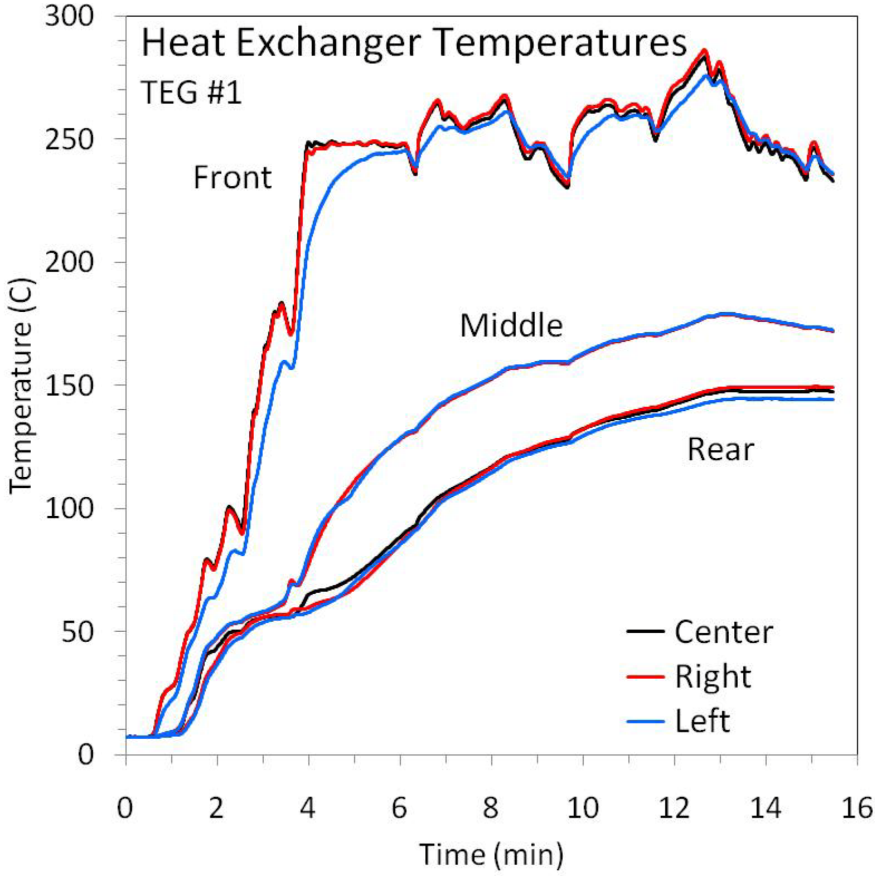
Front & Center thermocouple

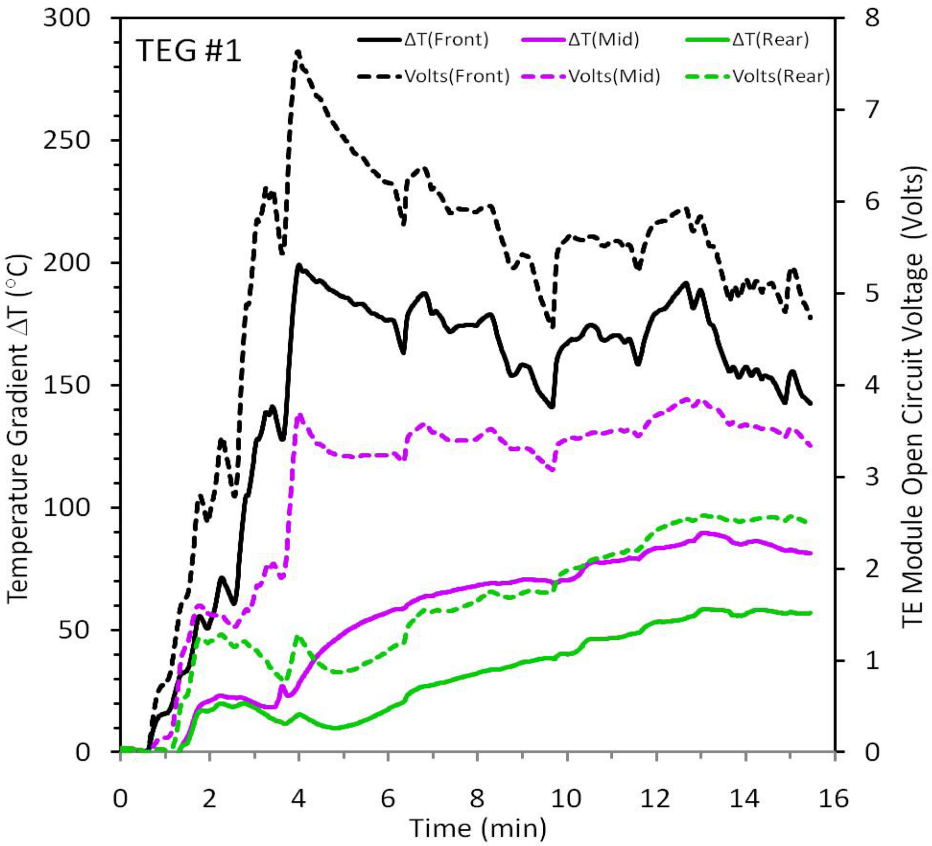
Front & Center TE module



The by-pass valve set point temperature for the heat exchanger was 250°C.

TEG #1: Preliminary Testing





- Substantial temperature drop along the length of the TEG: 250°C (Front), 178°C (Middle), and 148°C (Rear)
- Temperature variation across the TEG: < 3°C.
- TE output voltage consistent with as much as a 50°C smaller ΔT than measured between the hot side heat exchanger and the coolant

Future Work

- Complete assembly of TEG #2 with full electrical system components (42 TE modules).
- Finalize and implement vehicle integration with TE waste heat recovery system and complete the necessary vehicle modifications.
- Develop higher temperature TE modules for TEG #3.
- Carry out dynamometer tests and proving ground tests for vehicle equipped with the TE waste heat recovery system.
- Demonstrate fuel economy gain using TE waste heat recovery technology.

Summary

- Prototype TEGs are being assembled and installed on the test vehicle.
- Vehicle modifications and system integration are being completed as the TEGs are installed on the vehicle.
- Improvements in the performance of TE materials have been achieved, particularly for Skutterudites.
- Skutterudite modules are being developed for the final prototype TEGs.