Advanced Thermoelectric Materials and Generator Technology for Automotive Waste Heat at GM

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Outline

Thermoelectric Research and Development Projects at GM Global R&D
Introduction: TE Technology for Waste Heat Recovery
Acknowledgements
Thermoelectric Materials Research
Thermoelectric Generator Development
Results
Summary: Current/Future Work
Opportunity for TE Waste Heat Recovery

Automotive Energy Flow Diagram

Gasoline

Combustion

30% Engine

30% Coolant

5% Friction & Radiated

40% Exhaust Gas

Vehicle Operation

25% Mobility & Accessories

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

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.
Develop Thermoelectric Technology for Automotive Waste Heat Recovery

Project lead: General Motors

Timeline
Start date – May 2005
End date – August 31, 2011

Budget
Total funding: $12,779,610
– DOE share: $7,026,329
– Contractor share: $5,753,281

Barriers & Targets
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 – Thermoelectric module development and fabrication
Oak Ridge National Lab – High T transport & mechanical property measurements
University of Nevada – Las Vegas:– Computational materials development
Faurecia – Exhaust subsystem fabrication and integration
NSF/DOE Thermoelectrics Partnership: Thermoelectrics for Automotive Waste Heat Recovery

Project lead: Purdue University

Timeline
Start date – Jan. 1, 2011
End date – Dec. 31, 2013

Budget
Total funding: $1,391,824

Key Research Elements

– TE materials development
– Systems-level thermal management design and modeling
– TEG prototype construction & evaluation
– Durability design & testing
– Efficient heat exchangers for transferring heat from hot gas to TE materials
– Thermal interface materials
– Measurements and characterization: TE materials, interfaces, TEG power output
Opportunity for TE Cooling/Heating

Charging challenges
The Volt would run solely on battery power. The engine’s only job would be to recharge the battery. That raises significant issues because today’s batteries can’t handle many electrical feeds.

Systems that drain car batteries:
- Stereo systems
- DVD and navigation systems
- Headlights, taillights and interior lights

Heating and cooling:
- New air conditioning and heating systems need to be built so the primary power source is electricity, not power generated from a gasoline engine.

Battery technology:
- Lithium-ion batteries are still too large and expensive for mass production.
- There have been overheating issues in electronics such as laptop computers and handheld video games.

Distributed Cooling (and Heating) for High Efficiency HVAC System
Improving Energy Efficiency by Developing Components for Distributed Cooling and Heating Based on Thermal Comfort Modeling

Project lead: General Motors

Timeline
Start date – November 2009
End date – October 31, 2012

Budget
Total funding: $5,097,592
– DOE* share: $2,548,796
– Contractor share: $2,548,796

* We thank the California Energy Commission and the DOE Vehicle Technologies Program for their support and funding of this project

Barriers & Targets
– Early stage of development for thermoelectric (TE) devices in automotive HVAC applications
– TE CoP: > 1.3 (cool), > 2.3 (heat)
– Reduce HVAC energy by > 30%
– New TEs for Waste Heat TEGs

Partners
– University of California – Berkeley:
  Thermal Comfort testing & modeling
– Delphi Thermal Systems:
  HVAC component development
– University of Nevada – Las Vegas:
  TE materials research
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:

\[ ZT = \frac{S^2 T}{\kappa_T \rho} \]

\( S \) = Seebeck Coefficient (Thermoelectric Power)

\( \kappa_T \) = Thermal Conductivity

\( \rho \) = Electrical Resistivity
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 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); Both p- and n-type TEs, Low lattice thermal conductivity $\kappa_L$, High values of $ZT > 1$; Good mechanical properties; Readily available and inexpensive raw materials. Environmentally friendly.
Introduction

US Department of Energy:

Achieve 10% improvement in fuel economy (FE) by 2015 without increasing emissions
  • Demonstrate FE improvement for a Federal Test Procedure (FTP) driving cycle (~3%)  
  • Demonstrate that actual FE improvement for real world driving 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
GOALS & OBJECTIVES:

Initial TEG Prototype Construction
- Translate conceptual design from GE into buildable unit
- Fabricate subsystem parts and complete assembly

Test Vehicle Modification and Integration
- Modify exhaust system for temperature and back pressure management
- Complete integration of electronic systems and controls for TEG output power management

TEG Installation

TEG Performance Data Collection (FTP and Real World drive testing)

TE and Thermo-Mechanical Property Improvements
- Adjust composition & processing for best performance
- Synthesize material batches for TE module production

Skutterudite TE Module Production
- Complete metallization and fabrication method studies
- Complete fabrication of Skutterudite TE modules for the TEG
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Skutterudite: a CoAs$_3$ mineral found near Skutterud, Norway, in 1845, and compounds with the same crystal structure (body-centered cubic, $Im3$, Oftedal (1928): *Zeitschrift für Kristallographie* 66: 517-546) are known as “skutterudites”.


Change in unit cell volume

$\Delta V = V(\text{RT}_4\text{X}_{12}) - V(\text{LaT}_4\text{X}_{12})$

versus R for T = Fe, Ru, or Os, and X = P, As, or Sb.
Low temperature properties of the filled skutterudite CeFe$_4$Sb$_{12}$

Donald T. Morelli$^{b)}$ and Gregory P. Meisner

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(Received 10 October 1994; accepted for publication 30 December 1994)

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

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, Pasadena, Calif.

[21] Appl. No.: 08/908,814
Much Improved ZT values

\[ ZT_{\text{ave}} = 1.2 \]

• Validated measurements of transport and mechanical properties and performance at high temperature.

• Explored optimization of preferred materials for use in TE modules.

• Improvement in the synthesis, processing, and transport properties of Yb-filled skutterudites associated with specifically created nano-scale precipitates at grain boundaries and within grains.

• Achieved a figure of merit $ZT = 1.6$ for multiple filled skutterudites, highest value yet reached for any n-type filled skutterudite material.

• Improved TE properties of Type I clathrates by doping transition metals on the gallium sites.

• Investigated new TE materials: $\text{In}_4\text{Se}_3$, $\text{In}_4\text{Te}_3$, Cu-Ge-Se.
2010 Publications/Presentations


ROIs/Patents


TE Materials Research

Schematic Diagram of a TE Module

- Hot side heat exchanger
- Insulator
- Conductors
- Metal
- Contact resistances
  - Thermal
  - Electrical & thermal
  - Joule & Peltier terms
- Thermal shunt path
- Volume resistivity
TE Materials Research
Schematic Diagram of a TE Module

HEAT

Hot side heat exchanger
insulator
conductor
metal
metal
metal
metal
n
p
conductor
insulator
Cold side heat exchanger
• Evaluated braze methods for electrical connections to PbTe.

(a) PbTe elements with a thick nickel end cap brazed to the metallization layer, and (b) shear test results with adhesion promoting heat treatment (failure is in bulk material.)

• Designed tooling for fabricating ceramic headers for TE modules.

• Synthesized several n-type PbTe ingots and explored processing variables to reduce cracking and fragility, and to improve adhesion of electrical and thermal contacts.

Prototype PbTe module
Incorporate New Advanced TE materials into Operational Devices & Vehicle Systems

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

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

Subsystems Modeling and Design (With General Electric)

Heat Exchanger Design:

TE Module Design:
Identify primary module design variables
Examine effect on primary output variables:
(1) Power output, (2) Cost,
(3) Thermo-mechanical durability

TEG Design:
Program metric: $/Watt
TE Generator Development

TE Model System Expected Efficiency and Urban Cycle Exhaust Conditions

![Graph showing candidate material and exhaust conditions](image-url)
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, & assemble prototype TEG

- Completed thermoelectric generator design and fabrication of heat exchanger subassemblies. Prototype TEG #1 completed, TEG#2 installed.
TEG Installation
Vehicle Integration

- Power electronics designed for power conditioning and vehicle control
- Control algorithms developed for improved thermal-to-electrical conversion efficiency
TEG Testing & Validation

• Assess TEG Performance
  Start-Cart
    o First step in integration development
    o Provides a decoupled testing environment
    o Provides easy access for modification and debugging

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

Environmental Dynamometer
  o Chassis-rolls dynamometer which simulates grades, atmospheric environment

Real World Driving
Results: TEG #1

The by-pass valve set point temperature for the heat exchanger was 250°C.
• 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 is consistent with a 50°C smaller ΔT than measured between the hot side heat exchanger and the coolant
Results: TEG #2

Coolant manifold for cold side heat exchanger blocks

Bi-Te TE module

Cold side heat exchanger blocks

Circuit board with connector for TE module wires and diodes

Electrical power output wire

Graph showing TEG Output Power, Heat Exchanger Temperature, and Temperature at different locations over time.
Summary: Current Work

- Completed TEG #2 assembly (42 Bi-Te TE modules) and installation on the vehicle.
- Finalized and implemented vehicle integration with TE waste heat recovery system.
- Achieved improvements in the performance of TE materials, particularly for Skutterudites.
- Developing higher temperature Skutterudite TE modules for final prototype: TEG #3.

Synthesize n- and p-type ingots (GM):

Fabricate modules (Marlow):
Future Work

- Complete fabrication of high temperature TE modules for TEG #3.
- Conduct dynamometer tests and proving ground tests for vehicle equipped with the TEG waste heat recovery system (TEG #2 and TEG #3).
- Demonstrate fuel economy gain using TE waste heat recovery technology (TEG #3).

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

The goal of this AOI is to achieve improved efficiency and reduced emissions in advanced combustion engines for passenger and commercial vehicle applications through: 1) accelerated development of cost competitive advanced second generation thermoelectric devices for vehicle applications…

Subtopic 6A: Solid State Thermoelectric Energy Conversion Devices