Engineering and Materials for Automotive Thermoelectric Applications

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Outline
- Potential automotive applications
  - DOE waste heat recovery program
  - System design and performance
- Thermoelectric materials by design
  - skutterudites
  - high efficiency clathrates
- Conclusions
Today’s ICE-based vehicles: < 20% of fuel energy is used for propulsion
> 60% of gasoline energy (waste heat) is not utilized
Advanced Propulsion Technology Strategy

- **Improve Vehicular Fuel Economy and Emissions**
- **Displace Petroleum**
  - Hydrogen Fuel Cell-Electric Vehicles
  - Battery-Electric Vehicles (including EREV)
  - Hybrid-Electric Vehicles (including Plug-in HEV)
  - IC Engine and Transmission Improvements

- **Energy Diversity**
  - **Petroleum** (Conventional and Alternative Sources)
  - **Alternative Fuels** (Ethanol, Biodiesel, CNG, LPG)
  - **Electricity** (Conv. and Alternative Sources)
  - **Hydrogen**

- Time
GM’s Path to Electrification

- Internal Combustion Engine
- Hybrid
- 2-Mode Hybrid
- 2-Mode Plug-in Hybrid
- Extended-Range Electric Vehicle
- Battery-Electric & Fuel Cell Vehicles

INCREASING LEVEL OF EFFICIENCY & REDUCED EMISSIONS
Opportunity for TE Cooling

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.

The Detroit News
Distributed Cooling for High Efficiency HVAC System

- Reduce onboard AC without sacrifice passenger comfort level
- Improve fuel economy and CO₂ emission
- DOE award in place to start in 2009

“If all passenger vehicles had ventilated seats, we estimate that there could be a 7.5% reduction in national air-conditioning fuel use. That translates to a savings of 522 million gallons of fuel a year,”

John Rugh, project leader for NREL’s Vehicle Ancillary Loads Reduction Project.
Target: 10% fuel economy improvement without increasing emissions

TE Power Generation from Automotive Waste Heat Recovery (Sponsored by EERE-DOE)
The Suburban was selected as a test vehicle because it simplified the modifications 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.
Exhaust Generator GEN III Design

- Located where current muffler is placed; new muffler will be located behind the axle perpendicular to vehicle axis
- Axially compliant for thermal expansion mismatch

- Maximum module compression compliance
- Quick disconnects for fluid flow
- Quick disconnect exhaust connections
- Pitched to drain condensate
- Pitch designed for boil off
- Sealed electronics

Interior View (module mounting)
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.
Small displacement $\delta$ of the filler from its equilibrium $x$ will lead to an increase of the total energy of the system.

$$E(x+\delta) = E(x) + \frac{1}{2}\ddot{E}(x)\delta^2 + \frac{1}{6}\dddot{E}(x)\delta^3 + \ldots$$

In a harmonic approximation, $\ddot{E}(x)$ is the spring constant.

$$\omega_0 = \sqrt{\frac{\ddot{E}(x)}{m}}$$

• Multiple-element filling will scatter a broad range of lattice phonons, lower thermal conductivity, and improve $ZT^{1-3}$

Calculated resonant phonon frequencies are experimentally validated.
Multiple-filled Skutterudites – Much Improved ZT values

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

2. X. Shi, et al., submitted (2009)
STEM Images of the Triple-Filled Skutterudites
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Phonon DOS Measurement – Inelastic Neutron Scattering
Evidence for Incoherent Rattler Mode – Phonon Glass
High Efficiency Clathrates \( \text{Ba}_8 \text{Ni}_{0.5} \text{Ga}_{14} \text{Ge}_{31.5} \)
No defects or no second phases have been observed so far.
Tunable ZT

![Graph showing ZT values for different compositions of Ba₈Ni₂₋ₓGaₓGe₃₋₀.₉₁ alloys.](image)

Strong charge distortion

Compositions:
- Ba₈Ni₂.₉₇Ga₃.₉₄Ge₃₈.₉₁
- Ba₈Ni₁.₉Ga₈.₀₄Ge₃₅.₉₄
- Ba₈Ni₀.₈₄Ga₁₂.₀₇Ge₃₃.₁₆
- Ba₈Ni₀.₃₂Ga₁₃.₆₃Ge₃₁.₇₁
- Ba₈Ni₀.₃₁Zn₀.₅₂Ga₁₃.₀₆Ge₃₂.₂
- Ba₈Ga₁₆Ge₃₀
Conclusions

- Thermoelectric technologies potentially offer significant energy savings through waste heat recovery and augmented cooling
- There are plenty of science and engineering to be done
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