Vehicular Thermoelectrics
Applications Overview

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FCVT Program Mission
To develop more energy efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.
--EERE Strategic Plan, October 2002--
reduce regulated emissions
greenhouse gases
reduce fuel consumption
tech heating
tech cooling
silent running
This presentation includes a broad brush review of the thermoelectric technology, near term vehicular applications and potential long term applications.
Thermoelectric Modules

Refrigeration

Power generation
Figure of Merit, ZT

\[ ZT = S^2 \sigma T / \kappa = S^2 \sigma T / (\kappa_E + \kappa_L) \]

where: 
- \( S \) = Seebeck coefficient = \( (\Delta V / \Delta T) \)
- \( V \) = voltage,
- \( T \) = absolute temperature,
- \( \sigma \) = electrical conductivity
- \( \kappa \) = thermal conductivity, which consists of:
  - \( \kappa_E \) = electronic thermal conductivity, and
  - \( \kappa_L \) = lattice thermal conductivity.
To increase $Z$, we want

\[ S \uparrow, \sigma \uparrow, \kappa \downarrow \]

but

\[ S \uparrow \iff \sigma \downarrow \]
\[ \sigma \uparrow \iff \kappa \uparrow \]

With known conventional solids, a limit to $Z$ is rapidly obtained.

Best alloy: Bi$_{0.5}$Sb$_{1.5}$Te$_3$

\[ ZT \sim 1 \ @ \ 300 \ \text{K} \]
Nanoscale Effects for Thermoelectrics

Interfaces that Scatter Phonons but not Electrons

Mean Free Path
\[ \Lambda = 10-100 \text{ nm} \]
Wavelength
\[ \lambda = 10-50 \text{ nm} \]

\[ \Lambda = 10-100 \text{ nm} \]
\[ \lambda = 1 \text{ nm} \]
Filled Skutterudites: Phonon-Glass-Electron-Crystal Materials

- TE power generation materials for hot-side temperature between 700 K (427°C) and 1000 K (727°C)

- Lattice thermal conductivity significantly reduceds by “rattling” filler atoms in the interstitial voids –

\[
\begin{align*}
2\text{Co}_4\text{Sb}_{12} & \\
\text{Co} & \quad \text{Sb} & \text{Filler atoms}
\end{align*}
\]
Current TE Materials

P-type TE material

N-type TE material

Ref: http://www.its.caltech.edu/~jsnyder/thermoelectrics/
Ref: Modified from - http://www.its.caltech.edu/~jsnyder/thermoelectrics/
TE Couple Configuration Alternatives with Segmented Elements

- **Alternative “Y” configuration**

- **Traditional configuration**

- Materials used: p-CeFe$_3$RuSb$_{12}$, n-CoSb$_3$, n-PbTe, n-Bi$_2$Te$_3$, p-TAGS.
Potential Location for the Thermoelectric Generator
Why Thermoelectrics in Vehicles?

- Roughly 17 Million Cars sold in US Annually
  - US Fleet ~ 220 Million Personal Vehicles
- Improve Fuel Economy
- Reduce Greenhouse Gas Emissions
- Reduce Toxic Emissions (NOx and PM)
- Establish Large Scale Production Base
Available Energy in Engine Exhaust
Increased electrical power needs are being driven by advanced IC Engines for enhanced performance, emission controls, and creature comforts:

- Stability controls
- Telematics
- Collision avoidance systems
- Onstar Communication systems
- Navigation systems
- Steer by-wire
- Electronic braking
- Powertrain/body controllers & Sensors

These requirements are beyond the capabilities of the current generators and require supplemental electrical generation, such as from a TE waste heat recovery unit.

Juhui Yang GM
**Beltless or More Electric Engine**

**Truck Electrification**

- Electrify accessories
decouple them from engine
Match power demand to real time need
Enable use of alternative power sources

**Modular HVAC**
- Variable speed compressor more efficient and serviceable
- 3X more reliable compressor no belts, no valves, no hoses leak-proof refrigerant lines instant electric heat

**Shore Power and Inverter**
- Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input
- Supplies 120 Vac outlets from battery or generator power

**Down Converter**
- Supplies 12 V Battery from DC Bus

**Compressed Air Module**
- Supplies compressed air for brakes and ride control

**Electric Water Pump**
- Higher reliability variable speed
- Faster warm-up less white smoke
- Lower cold weather emissions

**Electric Oil Pump**
- Variable speed
- Higher efficiency

**Starter Generator Motor**
- Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

**Auxiliary Power Unit**
- Supplies DC Bus Voltage when engine is not running - fulfills hotel loads without idling main engine overnight
- Develop and integrate a Thermoelectric Generator into a vehicle’s electrical system to convert the engine waste heat directly to electricity

- The Goal is to improve fuel economy by a nominal 10 percent

- The Timeline is to introduce in production personal vehicles in the 2011 to 2014
- BSST with BMW, Visteon, Marlow Industries, Virginia Tech, Purdue, U of California-Santa Cruz

- GM with GE, U of Michigan, U of South Florida, ORNL, RTI

- Michigan State with Cummins Engine Company, Tellurex, NASA-JPL, Iowa State
- plenty of space for accommodating TE subsystem
- a lot of waste heat: exhaust and radiator
- current muffler: 610 x 310 x 235 (mm)
- available envelope: 840 x 360 x 255 (mm)
GM’s Thermoelectric Generators
BMW’s Electric Water Pump Improves Fuel Economy 1.5 to 2.0 %
BWM Series 5, 3 L Gasoline Engine with Electric Water pump

- BMW Valvetronic
- BMW VANOS
- Oil/coolant Heat exchanger
- One belt engine
- Electric Water Pump (200 W)

Weight: 161 kg
Power: 190 kW
Max engine speed: 7000 rpm
Rule of Thumb for Cars

10 percent Reduction in Vehicle Weight Results in a 5 to 7 Percent Improvement in Fuel economy
- Use of aluminum results in a 500 lb weight reduction, with consequent fuel saving.
- Currently, only luxury cars use Aluminum frame and body, due to high cost.
- If we can recover sufficient energy from the Aluminum manufacture process, it may become feasible to use it for mass-produced cars, due to reduced cost.

2004 Jaguar XJ
BMW’s Magnesium Engine Block
Climate Control Seat™ (CCS) System Vehicle Application

- Production CCS Assembly
- Distribution Layer
- Perforated Leather
- Waste Duct
- Back TED
- Supply Duct
- Blower Assembly
- Control Module
- Cushion TED
today...

POWER SOURCE
- Batteries

CLIMATE CONTROL
- None

...tomorrow

POWER SOURCE
- Logistic fuel based system

CLIMATE CONTROL
- Thermoelectric based cooling/heating
- On-demand

IMPACT
- >30% weight savings over existing systems

Assumptions
12 hour mission @ 110°F ambient temperature

DARPA TTO Program Manager: Ed van Reuth

Enabled by Thermoelectrics (TE)

Quantum Well TE Module

Small size (1 in³) requirement satisfied using QW TEG

Provides power for wireless sensors:

5 mW at 3 V using 41°C ∆T from ship interior thermal environment

Generator dimensions:

1 in² footprint
½ inch height
Thermoelectric Wristwatch

> Converts temperature difference between body and surrounding air into electrical energy

> No battery change needed

> When not being worn, second hand moves in 10-second increments (non power generation mode)

> Number of semiconductors in thermocouple array: 1,242 pairs

> Operating time from a full charge: Approx. 6 months (approx. 16 months in power saving mode)
Embedded Semiconductor Cooling
Removes Heat From Die to Heat Sink

Heat Sink
Thermal Interface Material 2
Substrate
Heat Spreader
Thermal Interface Material 1
Silicon Die

Resolve Critical Path

Nextreme’s solution

Hotspots effect
- Reliability
- Performance
- Package cost

100 μm thickness

Embedded Thermoelectric in IC
- Active micro-cooling of hotspot
- Reduces total power cooled
- Simplifies package
USS DOLPHIN AGSS 555 Thermoelectric Air Conditioning Test for Silent Running
Thermoelectric Hot & Cold Mini Fridge (1.5 ft³)

Side-by-side Refrigerator/Freezer (27.5 ft³)

Thermoelectrics Replacing Gas Compression Refrigeration?
significant warranty cost savings, improved battery reliability and quality, and improved battery efficiency and performance; and enables more flexible packaging
Executive Order issued May 14, 2007 – directs DOE and DOT, and EPA to work together to protect environment with respect to GHG emissions from motor and non-road vehicles.

President’s “Twenty in Ten” initiative (DOE with primary responsibility) supports GHG initiative.

- Bringing to market technologies that will result in significant decrease in fuel consumption of motor and non-road vehicles thus reducing GHG emissions.
138 Million Metric Tons per Year of CO$_2$ equivalent Released from Personal Vehicles in the US as a Result of Using Air Conditioning

Additional significant amounts CO$_2$e released due to accidents and end of life vehicle salvage releasing R134-a
Approach: Develop a distributed, localized thermoelectric based heating and cooling system for cars and light trucks (SUV’s, Pick-ups, Mini vans) which provides:

- Reduced fuel consumption
- Reduced Greenhouse Gases
- Reduced toxic emissions (NOx & Particulates)
- Increased engine-off comfort
- Faster heating and cooling to comfort at start-up
- Reduced maintenance costs

No moving parts & no refrigerant gas recharging
Freon refrigerant gas was banned from vehicular air conditioning systems in the mid 1990’s to prevent Ozone Layer depletion

- R134-a refrigerant gas was universally adopted as the replacement
- However R134-a has 1,300 times* the global warming potential of CO₂
- The European Union is prohibiting use of R134-a in cars for
  - New models in 2011
  - All new cars in 2017

Four Dispersed Solid State Thermoelectric Coolers/Heaters

- Could comfortably cool or heat 5 occupants with 400 to 900 Watts of cooled or heated air cooled

Thermoelectric Generators being developed in the DOE/NETL Program would supply most of this DC Power

DOE/NETL initiating Competitive Procurement
Assume by 2020 that 90% of US Personal Vehicle Fleet have a TE Generator Powering a TE Cooler/Heater to replace R-134-a Refrigerant Gas Air Conditioners:

\[ (0.90) \times (281 \times 10^6 \text{ cars & Lt Trucks}) \times (62 \text{ gals A/C/car year}) \times \left(\frac{1}{365}\right) = 43 \text{ M gals/day or 1.02 M bbls/day} \]

This would save about 5% of our current average daily consumption of gasoline.

Reduce Greenhouse Gas (CO2e) Emissions by 156 Million Metric Tons Annually.

*Ref.; EIA Annual Energy Outlook, 2007*
Recent Advances in Efficiency of Thermoelectric Materials

Efficiency:
\[ \varepsilon = \frac{T_H - T_C}{T_H} \left( \sqrt{1 + ZT} - 1 \right) \frac{T_C}{T_H} \]

- Many recent thermoelectric material advances are nano-based.
Comparison of P-type B\textsubscript{4}C/B\textsubscript{9}C & N-type Si/SiGe Quantum Well materials using measured $\alpha$ & $\rho$, & published bulk $\kappa$ versus current Bi\textsubscript{2}Te\textsubscript{3}, PbTe & SiGe materials

Data: QW & Bi\textsubscript{2}Te\textsubscript{3} Hi-Z; PbTe & SiGe JPL Properties Manual
1st Generation Vehicular Thermoelectric Generators ZT ~ 1.0

ZT > 3.0 reported by MIT’s Lincoln Lab, RTI and Hi-Z Technologies

- Hi-Z’s Quantum Wells ZT ~ 4.5, Independent Validation using Hi-Z’s Measurement Technique
  - University of California – San Diego
  - and independent measurements scheduled at
    » NASA - JPL
    » Oak Ridge National Lab
    » NIST

This would be a > 300 % Improvement in Efficiency!
General Atomics Sputtering Capabilities

New coatings developed on R&D coater

12" Coater (LESKER)

New products developed on R&D Web Coaters

36" Web Coater (ISM)

40" Web Coater (8-Ball)

Material production on 80" Web Coater

80" Web Coater (ALOC)
Production Roll Coater can Provide Precision Polymer Coatings on up to 80-inch Wide Materials
Japanese Vehicular Thermoelectric Generator Program

Thermoelectric Power Generation for Diesel Engine Co-Generation System

Schematic of Thermo-Siphon Type Heat Recovery TE System

KOMATSU Ltd.

Diesel Engine

Cooling Water

High Efficiency Condenser

High Efficiency Plate

Cooling Plate

Tubes

High Efficiency Evaporator

Florinat

Exhaust Gas

TE Element

Courtesy of Dr. Takanobu Kajikawa, Project Leader, Japanese National Project on Development for Advanced Thermoelectrics
Current Vehicular Applications of Thermoelectrics

- Climate Control Seats
- Drink Cooler/Warmer
- Thermal Control of Electronics

Near Term Applications (2011 – 2015)
- Thermoelectric Generators Harvesting Engine Waste Heat
- Thermoelectric Coolers/Heaters replacing Air Conditioners
- Integrated Thermoelectric Generators & Coolers/Heaters
- Heavy Duty Truck Auxiliary Power Unit (APU)

Long Term (2020 +)
- Thermoelectric Generator Replacing Propulsion Engine
  - Plug-in Solid State Hybrid with Multi Fuel Capability

Very Long Term (~2060)
- Radioisotope Thermoelectric Generator/Battery Powertrain
  - Expensive but Long Life – 30 years
  - Change vehicle body every 5-8 years
U.S. Radioisotope Missions

Used safely in 28 missions since 1961

- 9 Earth orbit (Transit, Nimbus, LES)
- 7 on lunar surface (Apollo ALSEP)
- 7 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini)
- 5 on Mars surface (Viking, Pathfinder, Spirit, Opportunity)

Distances and Planets Are Not to Scale
Global Warming Contribution of Conventional Vehicle Air Conditioning

- **Direct Leakage of R134a**
  - Each personal vehicle leaks 0.3 ± 0.1 g/day
  - R134a has 1,300 x the global warming potential* of CO₂
  - \((109.5 \text{ g/year}) \times (1,300) = 142.4 \text{ kg CO}_2 \text{ equivalent per year}\)

- **Increase in CO₂ from fuel used for Vehicle A/C**
  - \((62 \text{ gals/yr}) \times (8.9 \text{ kg CO}_2/\text{gal}) = 552 \text{ kg CO}_2/\text{yr}\)
  - \((552 \text{ kg CO}_2/\text{yr}) + (142.4 \text{ kg CO}_2/\text{e/yr}) = 694 \text{ kg CO}_2/\text{vehicle}\)

- **Total CO₂ emitted from a personal vehicle’s engine/year**
  - \((696 \text{ gal/yr}) \times (8.9 \text{ kg/yr}) = 6,194 \text{ kg CO}_2/\text{yr}\)

- **Thus ~11% of total CO₂ emitted from personal vehicles comes from using Air Conditioning**
  - \((2.2 \times 10^8 \text{ vehicles}) \times (0.9) \times (6.94 \times 10^2 \text{ kg/yr CO}_2/\text{e/vehicle}) = 13.8 \times 10^{10} \text{ kg/yr CO}_2 \text{ or 138 Million Metric Tons/yr CO}_2 \text{e}}