Thermoelectrics: The New Green Automotive Technology

John W Fairbanks
Vehicle Technologies Program
US Department of Energy
Washington, DC

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Gasoline Prices 201X...
Use Thermoelectrics to generate electricity for powering auto components

- (lights, pumps, occupant comfort, stability control, computer systems, electronic braking, drive by wire, audio and video systems, TE HVAC.)

Reduce size of alternator (target: 1/3rd reduction in size)

Improve fuel economy (targets: 5% to 6%)

Reduce Regulated Emissions and Greenhouse Gases
Gasoline Engine Waste Heat
Typical Waste Heat from Gasoline Engine Mid Size Sedan

- **Combustion**
  - 100% Gasoline

- **Exhaust Gas**
  - 40%

- **Coolant**
  - 30%

- **Engine**
  - 30%

- **Friction & Radiated**
  - 5%

- **Mobility & Accessories**
  - 25%

Vehicle Operation
Combustion of Hydrocarbon Fuels Releases Carbon

- Gasoline $C_7H_{16}$
- Diesel $C_{18}H_{30}$
- Methanol $CH_3OH$
- Ethanol $C_2H_5OH$
- Natural Gas (Primarily Methane, $CH_4$)
- Propane $C_3H_8$

Carbon:
- PM
- HC
- Unburned
- Fuel, Lube Oil
- CO
- $CO_2$
Beltless or More Electric Engine

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

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

Electric Oil Pump
Variable speed Higher efficiency
Air Conditioner / Heater (TE HVAC)
Engine Waste Heat Generator (TEG)
Pre-start Engine Oil and Transmission Fluid warm up.
Battery Thermal Management
Beverage Cooler/Warmer
Computer and Radar (Collision Avoidance) Cooling
**Unusual Combination of Properties**

- **Seebeck coefficient or thermopower** ($\Delta V/\Delta T$)
- **Electrical conductivity** ($\sigma$)
- **Total thermal conductivity** ($\kappa$)

$$ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \cdot T$$

- $\sigma \alpha^2 = \text{Power Factor}$
- $\sigma = \frac{1}{\rho} = \text{electrical conductivity}$
- $\rho = \text{electrical resistivity}$

### TE Materials Performance: Figure of Merit (ZT) [Oregon State]

- Total thermal conductivity ($\kappa$)
- Electrical conductivity ($\sigma$)
- Seebeck coefficient ($\alpha$)

Unusual combinations of properties are sought for high $ZT$ values.
Nanoscale Effects for Thermoelectrics (courtesy Millie Dresselhaus, MIT)

Interfaces that Scatter Phonons but not Electrons

- **Electrons**
  - Mean Free Path: \( \Lambda = 10-100 \text{ nm} \)
  - Wavelength: \( \lambda = 10-50 \text{ nm} \)

- **Phonons**
  - Mean Free Path: \( \Lambda = 10-100 \text{ nm} \)
  - Wavelength: \( \lambda = 1 \text{ nm} \)
Highest ZT Achieved with Triple-filled Skutterudites (GM and U of Michigan)

- $\text{Ba}_{0.08}\text{La}_{0.05}\text{Yb}_{0.04}\text{Co}_{4}\text{Sb}_{12.05}$
- $\text{Ba}_{0.10}\text{La}_{0.05}\text{Yb}_{0.07}\text{Co}_{4}\text{Sb}_{12.16}$

Atoms can be inserted into empty sites. Atoms can "rattle" in these sites—scatter phonons and lower the lattice thermal conductivity.

2. X. Shi, et al., submitted (2009)
Current TE Materials

P-type TE material

N-type TE material

Ref:  http://www.its.caltech.edu/~jsnyder/thermoelectrics/
Segmented Thermoelectric Couple Configurations

Thermal Mismatch Stresses can Separate Material Layers

Thermal Mismatch Stresses are Significantly Reduced

conventional

BSST “Y” configuration
GM Prototype TEG Fabrication for Chevy Suburban
GM Prototype TEG Installation in a Chevy Suburban Chassis

- Exhaust gas inlet
- Cooling blocks
- TE Modules
- Hot side heat exchanger
- Exhaust gas outlet
- Coolant
- DC/DC converter
- Prototype TEG
BSST 2D to 3D TEG Design Iteration for BMW and Ford Autos
Amerigon/BSST TEG for Ford and BMW

- Final assembly TEG prior to installation in BMW X6 and Ford Fusion
- Cylindrical design TEG incorporates an internal bypass of exhaust gas for high engine load
- The TEG has 3 sections with different TE materials matched to the decreasing thermal power in the exhaust gas as passes through the TEG.
TEG Location on Ford Fusion:

- Coolant Port
- Inner pipe Ø50mm
- Heat exchanger
- Main pipe Ø90mm
- Inner cone
Amerigon and Faurecia are installing production prototype TEG’s in the exhaust systems of BMW X6 and Ford Fusion.
Prototype TEG’s In Ford Fusion, BMW X6 and Chevy Suburban- DOE Programs
BMW Exhaust Gas Recirculation (EGR) 
Cooler-TEG on Diesel Engine

Source: BMW Group
DOE’s Objectives: Second Generation Automotive TEG’s

- Commercially Viable Thermoelectric Modules
  \[ ZT_{avg} = 1.6 \]
  Temperature range 350 - 900°K

- Eliminate the Alternator Entirely

- Provide a 10 Percent Reduction in On-Highway Fuel Use with Associated Reduction in Regulated Emissions and “Greenhouse Gases”
DOE/CEC’s Automotive TE HVAC Program
(Thermoelectric Heating Ventilation & Air Conditioning)

- Competitive Awards to Teams Led by Ford and GM 09/09
- Co-Funded with the California Energy Commission
- Develop TE Zonal or Distributed Cooling/Heating Concept
  Maintain Occupant Comfort without Cooling Entire Cabin
- Reduce Energy used for Automotive HVAC’s by >30%
- Eliminate all Toxic, Greenhouse and Flammable Gases
  Associated with Automotive HVAC
DOE/CEC Program Objectives: Ford & GM Vehicular TE HVAC Teams

- Maintain Occupant Comfort while Reducing Fuel Consumption
- Develop TE HVAC with:
  - COP Cooling > 1.3
  - COP Heating > 2.3
- Integrate with Compressor Downsized by ~1/3
- Develop Production Prototype
- Integrate, Test and Deliver TE HVAC in a 5 Passenger Vehicle
25-50 miles of gas- and emission-free driving plus hundreds of miles of extended-range driving
Thermoelectric HVAC and Generators Improve the Volt’s Range and Fuel Economy

- The Volt’s range is significantly reduced when providing thermal comfort to occupants under hot or cold weather conditions.
- Developing localized cooling and heating concept:
  - to directly cool and heat occupants instead of controlling temperature of entire passenger cabin
  - to downsize the A/C compressor and replace the resistive heater with efficient thermoelectrics
- Investigating thermoelectric generator application where unique On/Off operation of the Volt’s engine should accommodate a simplified system design.
Climate Control Seat™

MTM SEAT TECHNOLOGY
MICRO-THERMAL MODULE

HEAT EXCHANGER

COOLED OR HEATED AIR EXITS TO SEAT CUSHION

PELTIER CIRCUIT

WASTE AIR IS EXITS SEAT

AIR DISTRIBUTION DETAIL
PERFORATED LEATHER
DISTRIBUTION LAYER
SCRIM MATERIAL
CHANNEL MOLDED IN FOAM

ECU-ELECTRONIC CONTROL MODULE

CONTROL SWITCH
Energy Requirements (Analytical)

- Zonal Concept cools/heats each occupant independently
  - 680 Watts to cool single occupant
  - Current A/C’s 3500 to 4500 Watts cool entire cabin
Zonal TE units located in dashboard, headliner, A&B pillars and seats / seatbacks
NREL’s Support of Ford’s Team TE HVAC
Zonal Occupant Comfort Development:

- Test and Evaluate Candidate Zonal TE HVAC systems
- Analysis and Design Optimization
Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost
Maine Maritime Academy

Seawater Cooled Exhaust Stack TE Generator

Keel Coolers
Vehicular Thermoelectric Hybrid Electric Powertrain Replacing the ICE

Diagram showing the flow of energy and components:
- Air Compressor
- Fuel Pump: Solid, liquid, gas
- Multi-Fuel Combustor
- Thermoelectric
- Electric Propulsion Motor
- Exhaust
- Transmission
- Gear Box & Differential
- Radiator
- Electric Power Conditioning & Control
- Coolant Pump
- Driver Demand
- Electrical Energy Storage (Batteries or Ultracapacitors)
- Vehicle Electrical System
- 440V
- 12V
- 12V
Market Factors Involving Thermoelectrics for Automotive Applications

- Dramatic Increase in Demand for Large Quantity Thermoelectric Materials
- Historically Semiconductor Costs Decrease with Volume Thermoelectrics Should Follow this Trend
- Automotive Industry Continually Wants “New and Improved” Technology
- Ever Increasing Gasoline/Diesel Prices
- Fuel Economy Requirements and Emissions Regulations
- Should Stimulate Waste Heat Energy Harvesting Applications