The 60 Percent Efficient Diesel Engine; Probable, Possible, or Just A Fantasy?

John W. Fairbanks
FreedomCAR and Vehicle Technologies
Energy Efficiency and Renewable Energy
US Department of Energy
Washington, D.C.

Diesel Engine Emission Reduction Conference
Palmer House
Chicago
August 24, 2005
POSSIBLE THERMOELECTRIC TRANSPORTATION APPLICATIONS

> Current Program:
   10 Percent Gain in Diesel Fuel Economy

> Follow-On Programs:
   60 Percent Efficient Diesel
   Peltier HVAC (Air Conditioning)

> Long-Term:
   Replace Vehicular ICE Propulsion Engine
   with Thermoelectric Generator
Discovered 1831

1831 – 1940: thermocouples and scientific curiosity

1940: IAFFE in Russia produced semiconductor thermoelectric generator ~ 3 percent efficiency

1950 – 1998: Figure of Merit $ZT < 1$; 5 to 7 percent efficient

1996: analytically proposed low-dimensional thermoelectrics
  - Engineer electron and phonon transport in nanostructures
  - Quantum wells, superlattices, quantum wires, and quantum dots used to change band structures, energy levels, and density states of electrons

1997 – to date: several labs reported making thermoelectric specimens with $ZT = 2$ to 4
  - Much of this work supported by DARPA and ONR
  - 300 percent improvement in thermoelectric efficiency

2005 – 2010: DOE program to assist moving thermoelectric technology from lab to
  - commercial scale up for production
  - develop devices to improve ICE fuel efficiency by 10 %
Recent Breakthrough in Efficiency of TE Materials

Efficiency of Thermoelectric Material (ZT)

- Potential with Thin-Film Technologies
- Thin-Film Superlattice Technology
- Industry Progress – Bulk Semiconductor Technology
Recent Breakthrough in Efficiency of TE Materials

Efficiency of Thermoelectric Material (ZT)

Potential with Thin-Film Technologies

Thin-Film Superlattice Technology

Industry Progress – Bulk Semiconductor Technology

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable
Heat-to-electricity conversion efficiency depends on a figure of merit, $Z$, that is material-specific:

$$Z = \frac{S^2 \sigma}{k}$$

- $S$ = Seebeck Coeff = $dV/dT$
- $\sigma$ = Electrical Conductivity
- $k$ = Thermal Conductivity

$$\eta = \left( \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}} \right) \frac{\sqrt{1 + ZT_{\text{avg}}} - 1}{\sqrt{1 + ZT_{\text{avg}}} + \frac{T_{\text{cold}}}{T_{\text{hot}}}}$$

Carnot efficiency
Heat transfer different for nanostructures

Thermoelectric materials

Heat-to-electricity conversion efficiency depends on a figure of merit, ZT, that is material-specific:

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

where:
- \( S \) = Seebeck Coeff = \( dV/dT \)
- \( \rho \) = Electrical Conductivity
- \( k \) = Thermal Conductivity

In macrostructures: \( \uparrow \rho \Rightarrow \uparrow k \)

In microstructures: \( \uparrow \rho \) [increase electron mean free path] \( \downarrow k \) \[ k_{\text{phonons}} + k_{\text{electrons}} \]

Low dimensional thermoelectrics need substrate support
- High temperature capability, low k, strong and thin
- Kapton is a candidate

Increase \( \Delta T \) across thermoelectric generators
- Improve cooling at the cold side
Segmented TE Couple

Load

300 K

975 K

p-CeFe₃RuSb₁₂

p-TAGS

p-BiSbTe

n-CoSb₃

n-PbTe

n-Bi₂Te₃
Thermal and electrical testing - Segmented unicouple

- Experimental I-V curves fully validate projected performance
  - Translate into ~ 14% efficiency for 975K-300K ΔT
- Results independently confirmed at the University of New Mexico

Skutterudite unicouples fabricated by diffusion bonding
HETE Applications

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Superlattice

Quantum Dots

Applications in:
- Defense
- Transportation
- Construction
- Agricultural Equipment
Thermoelectric Watch

- Converts temperature difference between body and surrounding air into electrical energy
- No battery charge needed
- When not being worn, second hand moves in 10-second increments (non power generation mode)
- Number of thermocouples in semiconductor array: 1,242 pairs
- Operating time from a full charge: Approx. 6 months (approx. 16 months in power-saving mode)
Figure 1. Today’s soldier highlighting the lack of climate control and heavy battery weight compared to tomorrow’s soldier which will provide a lightweight system of cooling, heating, flexible armor and portable power.
Stryker Vehicle Has Space for Under armor Quantum Well Thermoelectric Generators

15% Efficiency Predicted with two 5 kW$_e$ QW TE Generators Driven by Vehicle Exhaust

When Parked APU Burner to Provide Power Using Same Thermoelectric Generator
- Contains 64 QW modules in octagonal arrangement
- Integrated coolant and QW module arrangement
  - Each QW module in compression
- QW generator provides 5X power of current Bi2Te3 module in same space
  - Fits in 27-in length and 10-in diameter with cover plate
Thermoelectric Modules and Assembly with Coolant Heat Exchangers
Auto Air-Conditioning Refrigerant: R-134a, CO₂, or Thermoelectrics

- U.S. probably will stay with R-134a
- Europe apparently going to CO₂
  - R-134a has 1,300 greenhouse gas effect as CO₂
  - Autos leak 10 to 70 g/yr of R-134a
- Japan and Asia still undecided
  - Toyota’s decision will be the key

- Thermoelectrics
  - 1 million climate control seats ordered this year by GM, Ford, and Toyota
  - Auto air conditioning will depend on cost of high efficiency of thermoelectrics being developed for direct energy conversion
  - Requires COP of 2 to 3
    - Achieved in the laboratory
R-134a has 1,300 times greater greenhouse gas impact than CO2.

Use of thermoelectrics as Peltier Devices could reduce R-134a refrigerant usage, the most common working fluid in heating/cooling systems.

- Car air conditioning leaks 10 to 70 g/year
- > 90% personal vehicles in North America & Asia and 87% European cars have A/C
Thermoelectrics Replacing Gas Compressor Refrigeration?

TODAY

Thermoelectric Hot & Cold Mini Fridge (1.5 ft³)

FUTURE?

Side-by-side Refrigerator/Freezer (27.5 ft³)
Temperature affects battery operation

- Round trip efficiency and charge acceptance
- Power and energy
- Safety and reliability
- Life and life cycle cost

Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost
Beltless 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

Truck Electrification
Electrically powered
Decouple them from engine
Match power demand to real-time need
Enable use of alternative power sources

Starter Generator Motor
Beltless engine
Product differentiation improves 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 Water Pump
Higher reliability variable speed faster warm-up less white smoke lower cold weather emissions

Electric Oil Pump
Variable speed
Higher efficiency
Integrated Motor/Alternator Starter
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 manufacturing process, it may become feasible to use it for mass-produced cars, due to reduced cost.
- Aluminum Content of Automobiles
- Rule of Thumb
  - 10% weight reduction provides 6% to 7% improvement in fuel economy
- Aluminum Association Inc. Projects
  - Aluminum in North American cars
    - 2005 – 280 lbs.
    - 2008 – 300 lbs.
- European Cars: Jaguar, Aston Martin, and Audi A-8s
  - Aluminum frame and body
  - Saves 500 to 600 lbs.
  - BMW 5 series ~ 50/50 weight balance with steel
- DOE has initiated program to recover energy from Aluminum manufacturing process
  - Possible increase in aluminum use in mass produced cars
# High Efficiency Thermoelectric Teams

| General Motor Corporation and General Electric | MIT- Lincoln Laboratory, University of Michigan, University of South Florida, Oak Ridge National Laboratory, and RTI International |
| BSST, LLC. | Visteon, BMW-NA, and Teledyne |
| United Technologies Corporation | Pratt & Whitney, Hi-Z Technology, Pacific Northwest National Laboratory, and Caterpillar, Inc. |
| Michigan State University | Jet Propulsion Laboratory and Cummins Engine Company |
Available Energy in Engine Exhaust
Potential Thermoelectric Heat Sources

Combustion

38% Engine

33% Exhaust Gas

24% Coolant

5% Friction & Radiated

Diesel (Light Truck or Passenger Vehicle)

Vehicle Operation

33% Mobility & Accessories

Diesel Engine (Light Truck or Passenger Vehicle)
Current 6-Team Program

- Define commercial viability of TEG and Electric Turbocompounding (ETC) for vehicles in the 2005-2009 time frame
  - Identify challenges for TE commercialization
    target cost at $0.15/watt (not show stopper)
  - Availability
  - Durability
  - Degradation

- Follow-on 60% efficient diesel engine program start decision in 2008
  - Convert waste heat to electricity from components with adequate Delta T
  - Power conditioning
  - Integrate with beltless engine concept

Vehicular Peltier Thermoelectric Air Conditioning System Project being considered
- Requires a COP of 2.0 to 3.0
**FEATURES**

- Lower Fuel Consumption
- Flexibility in Turbo Operation
- Provides Turbo-Assist Capabilities
- No Mechanical Coupling

Electric Turbocompound
Electric Turbocompound (ETC) Technology

Potential for 5 to 10% Reduction in Fuel Consumption
- Currently a 10% fuel economy gain is the objective being sought through the use of a Thermoelectric Generator converting ICE engine waste heat directly to electricity.

- A follow on program using 6 Thermoelectric units could recover about 20 to 25 per cent of the powertrain’s waste heat.

- This electrical energy would be routed through power conditioning equipment then integrated with the “beltless or more electric” engine concept or the integrated motor/alternator/starter.

- Theoretically this approach has the potential of achieving a nominal 60% efficiency.
### Fuel Savings from Energy Recovery in Diesel Powered Vehicles

<table>
<thead>
<tr>
<th></th>
<th>ISB Dodge Pickup</th>
<th>ISX Class 8 Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions Useful Life</td>
<td>185,000 miles</td>
<td>435,000 miles</td>
</tr>
<tr>
<td>Typical Fuel Consumption</td>
<td>16 mpg</td>
<td>5 mpg</td>
</tr>
<tr>
<td>Fuel Consumed During the Useful Life</td>
<td>11,500 Gallons</td>
<td>87,000 Gallons</td>
</tr>
<tr>
<td>Fuel Consumed with Improved Efficiency</td>
<td>10,500 Gallons</td>
<td>79,100 Gallons</td>
</tr>
<tr>
<td>Fuel Saved</td>
<td>1000 Gallons</td>
<td>7900 Gallons</td>
</tr>
<tr>
<td>Money Saved ($2.00 gallon)</td>
<td>$2000</td>
<td>$15,800</td>
</tr>
</tbody>
</table>
10 % engine brake efficiency means:

- 100 million gallons of fuel saving per year for conventional vehicles
  -- using GM’s 2003 NA model year volumes (2.0 million cars & 2.8 million trucks)
  and CAFE standards, assuming 15000 miles per vehicle per year

- 1.5 million gallons of fuel saving per year at 2010 for hybrids
  -- GM anticipate 50,000 hybrids per year (1% of GM’s NA total sales).

Dr. Jhui Yang - GM
10 % engine brake efficiency means:

- 707,000 fewer tons of CO₂ per year from conventional vehicles (2010)
- 550,000 fewer tons of CO₂ per year from hybrids (2010)
- Regulated emissions will be decreased proportionally to the reduction in fuel consumption

Dr. Jhui Yang - GM
Generic Concept for a Thermoelectric Automotive Propulsion Drivetrain
Japanese Diesel Engine Co-Generation Using Thermoelectric Generator

This Project is funded at 2 times the level of DOE’s 4 Team Thermoelectric Generator 10 % Fuel Economy Improvement Program
### Typical Diesel Engine Waste Heat $\Delta T$'s

<table>
<thead>
<tr>
<th>Component</th>
<th>$\Delta T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator</td>
<td>$\approx 70^\circ C$</td>
</tr>
<tr>
<td>Lube Oil Sump</td>
<td>$\approx 70^\circ C$</td>
</tr>
<tr>
<td>Brakes</td>
<td>$\leq 350^\circ C$</td>
</tr>
<tr>
<td>Exhaust System</td>
<td>$\leq 400^\circ C$</td>
</tr>
<tr>
<td>EGR Loop</td>
<td>$\approx 250^\circ C$</td>
</tr>
<tr>
<td>Turbocharger Compressor (Output)</td>
<td>$\approx 33^\circ C$</td>
</tr>
</tbody>
</table>
Objective: 60 percent efficient diesel engine powertrain

Approach: recover electrical energy from waste heat
- Integrate with beltless engine and/or integrated starter/motor-alternator

Potential sources for TE generator ΔT’s
- Radiator
- Lube oil sump
- EGR loop
- Turbocharger air discharge
- Brakes
- Exhaust gas

Note: high efficiency TE generator will significantly reduce the water pump, radiator fan, intercooler pump loads

Thermally managed diesel (TMD-60)
- Integrate with other emerging technologies
Potential Thermoelectric Applications

HVAC - Home and Industrial
Fuel Cell Waste Heat Recovery
Battery Thermal Control
Industrial Process Waste Heat Recovery
Ocean Thermal Thermoelectric Energy Conversion
Geothermal Energy Recovery
Power Plant and Industrial Process Waste Heat Recovery
Wireless Sensors
Computer Chip Cooling
Personal Cooling/Heating Systems
Marine Propulsion (Surface and Submarine)
Vehicle Propulsion
Vehicle and Building Air Conditioning/Heating
High Efficiency Thermoelectric Materials and Devices for Solid State Power Generation & Cooling

Dr. Mihal E. Gross
Office of Naval Research

Naval Applications
- Power generation
- Auxiliary power
- Energy recovery from waste heat
- Alternator replacement
- Distributed power systems
- Solid state cooling
- Unattended/remote power supplies

Naval Benefits
- High reliability (>230,000 hrs.)
- Improved stealth
- Low noise
- No vibrations
- Small
- Lightweight
- No compressed gases/chemicals
- Decreased life cycle costs
DoD Investments in TE Technologies

ONR 1994-1997

Quantum dots

DARPA/ONR 1996-2002

ONR MURI 1998-2003

ONR/DARPA DTEC 2003-?


Microdevices

ONR MURI 2003-2007

Bulk materials

Palm Power 2001-2005

ONR/OSD/ARO SBIRs 2005-2007

P-type Bi0.1Sb1.9Te3

n-type Bi2Te3

Superlattices

n-type Bi2SbTe3
Direct Thermal-to-Electrical Energy Conversion

Dr. Mihal E. Gross
Office of Naval Research

ONR Program Participants

- Michigan State University
- UC Santa Cruz
- North Carolina State University
- Clemson University
- Harvard University
- MIT
- University of Michigan
- Purdue University
- UC Berkeley
- UC Santa Barbara
- University of Oregon
- University of South Florida
- University of Texas, Austin
- MIT Lincoln Labs
- Ames Lab

- RTI
- BSST
- Lockheed Martin
- Northrup Grumman/Newport News
- Pratt & Whitney/UTC
- Rockwell Scientific
- Tellurex
- MetaMateria

Mihal_Gross@onr.navy.mil
60% Efficient Vehicular Diesel Engine -

Probable, Possible or Fantasy?
Predicted Efficiency of Quantum Well Thermoelectric Module

- N-Type Si/SiC & P-type B4C/B9C
- Cold side at 50°C
- Based on measured $a$ & $r$, and literature $k$ (bulk thermal conductivity)
- Efficiencies compete with gasoline & diesel engines, & fuel cells.
Radiation coupling is practical design for high temperature; conduction or convection higher power

- N-Type Si/SiC & P-type B4C/B9C
- Cold side at 50°C
- Module is 2.5 x 2.5 in.
  - Thickness changed to match heat flux from source
    - Conduction
    - Convection
    - Radiation
- Based on measured a & r, and literature k (bulk thermal conductivity)
- Requires high temperature eggcrate

![Graph showing module power vs hot side temperature for conduction, convection, and radiation](image)
Quantum Well delivers $5 \text{ W/cm}^2$ at $800^\circ\text{C}$ with thermal radiation from source to thermoelectric.

- N-Type Si/SiC & P-type B4C/B9C
- Cold side at $50^\circ\text{C}$
- Represents practical design
  - Radiation coupling simplifies design and reduces thermal contact losses
- Based on measured $a$ & $r$, and literature $k$ (bulk thermal conductivity)
Vehicle Thermoelectric Technologies Possibilities

Near Term (3-5 yrs)
- Thermoelectric Generator providing 10% fuel economy gain
- “Beltless” or more electric engine
- Integrated Motor/Alternator/Starter

Mid Term (10-15 yrs)
- 5 Thermoelectric Generators mated diesel engine $\Delta T$’s
  - 60% efficient heavy duty truck engine
  - 55% efficient light truck (SUV’s, Pick-ups, Mini-vans), auto
- Thermoelectric air conditioner/heater for vehicles
- Aluminum/Magnesium frame & body replacing steel (Process waste heat recovery)

Long Term (15-25 yrs)
- 35% efficient Thermoelectrics with 500 $^\circ$C $\Delta T$
  - Replace Internal Combustion Engine
  - Combustor burns any fuel

Very Long Term (40+ yrs)
- Radioisotope replaces combustor for vehicle propulsion
  - 30+ years life powertrain
  - Replace vehicle body periodically