U.S. Department of Energy
Energy Efficiency and Renewable Energy

freedomcar & vehicle technologies program

Chair's Overview of High Efficiency Thermoelectrics and Potential Applications

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U.S. Department of Energy

High Efficiency Thermoelectrics Workshop
San Diego, California
February 17-20, 2004

Outline

- Introduction
- Thermoelectric (TE) Energy Conversion
  - Potential Opportunities
  - Potential Applications
    - Seebeck Effect
    - Peltier Effect
  - Recent Breakthrough in Efficiency of TE Materials
  - Long-term Potential
  - European Programs
  - Upcoming RFP
- Conclusion

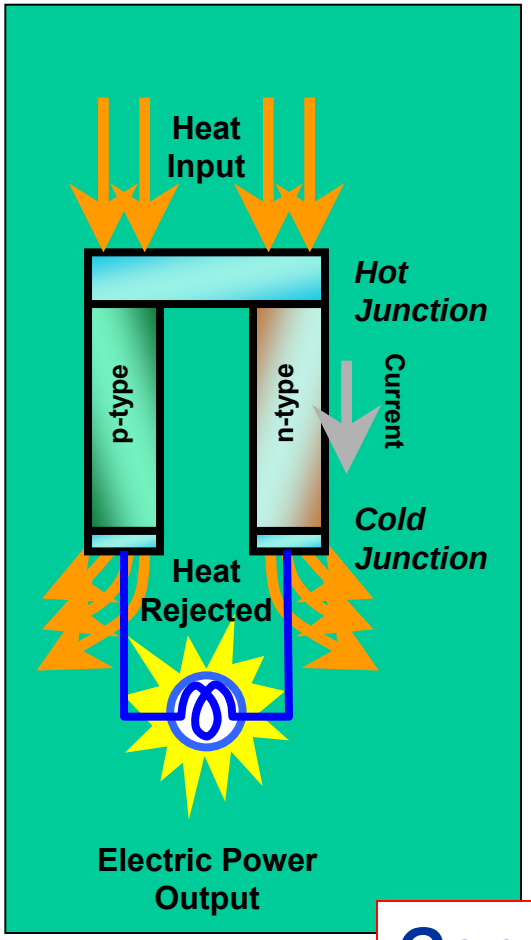
Introduction

Thomas Johann Seebeck (1770-1831)

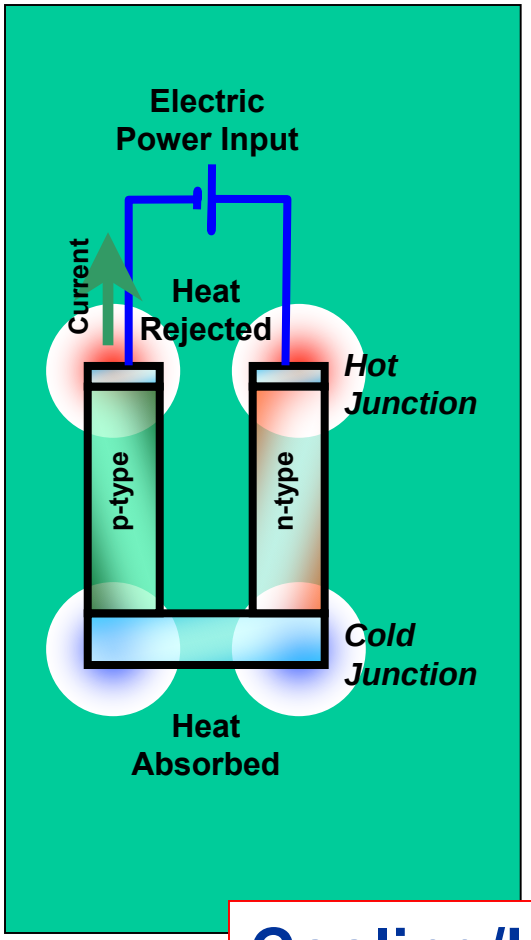
Thomas Johann Seebeck conducted research applying a ΔT across a large number of material couples in 1820's

- Looking for magnetic effect
- Some of his couples later proved to be 3% efficient in converting heat to electricity
  - Essentially the efficiency of contemporary steam engines
  - Imagine what could have happened, had Seebeck fully understood what he had discovered
- Mechanically-driven electrical generators would not appear till about 40 years later.

TE Generator and Cooler/Heater

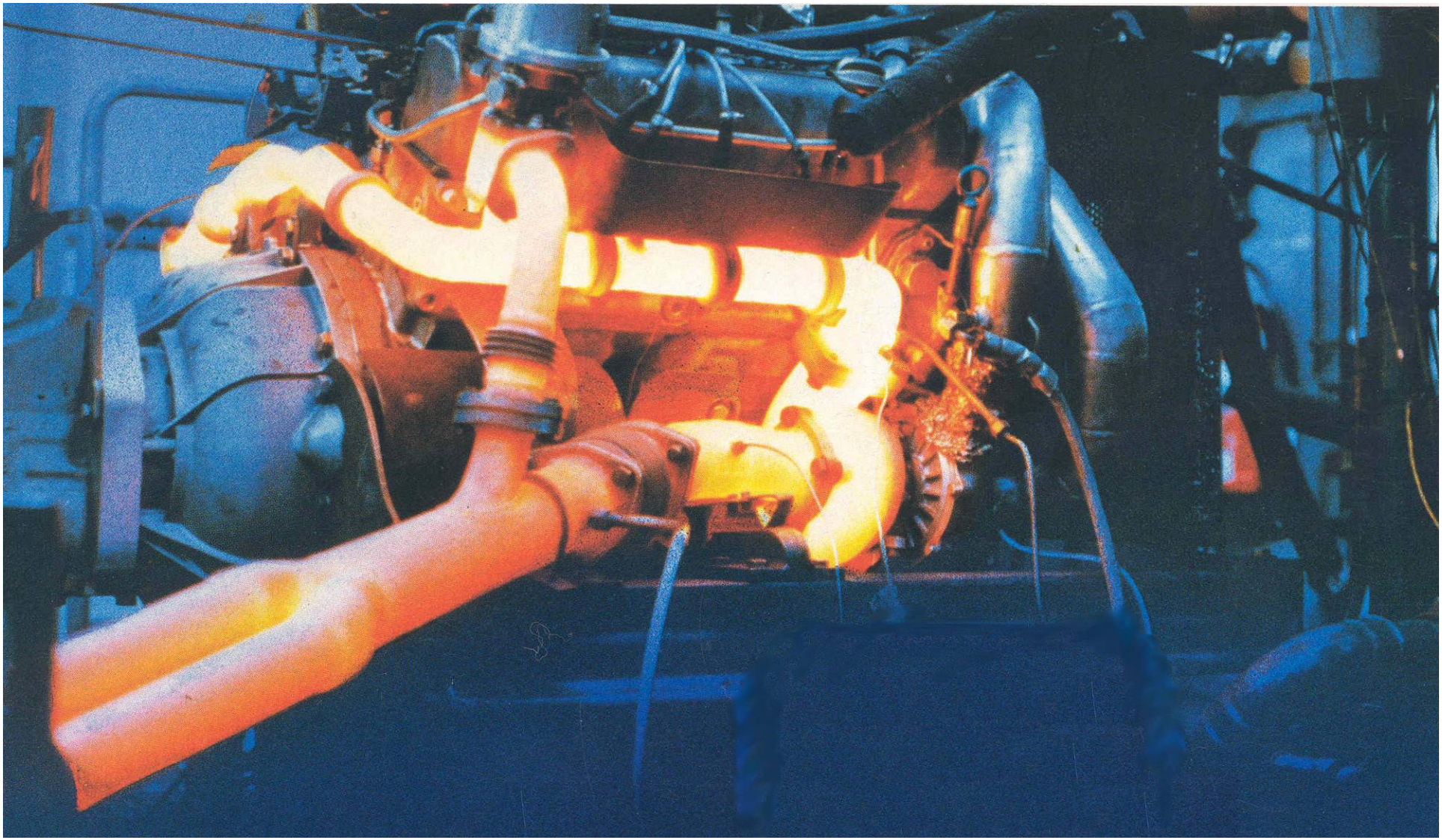


Generator

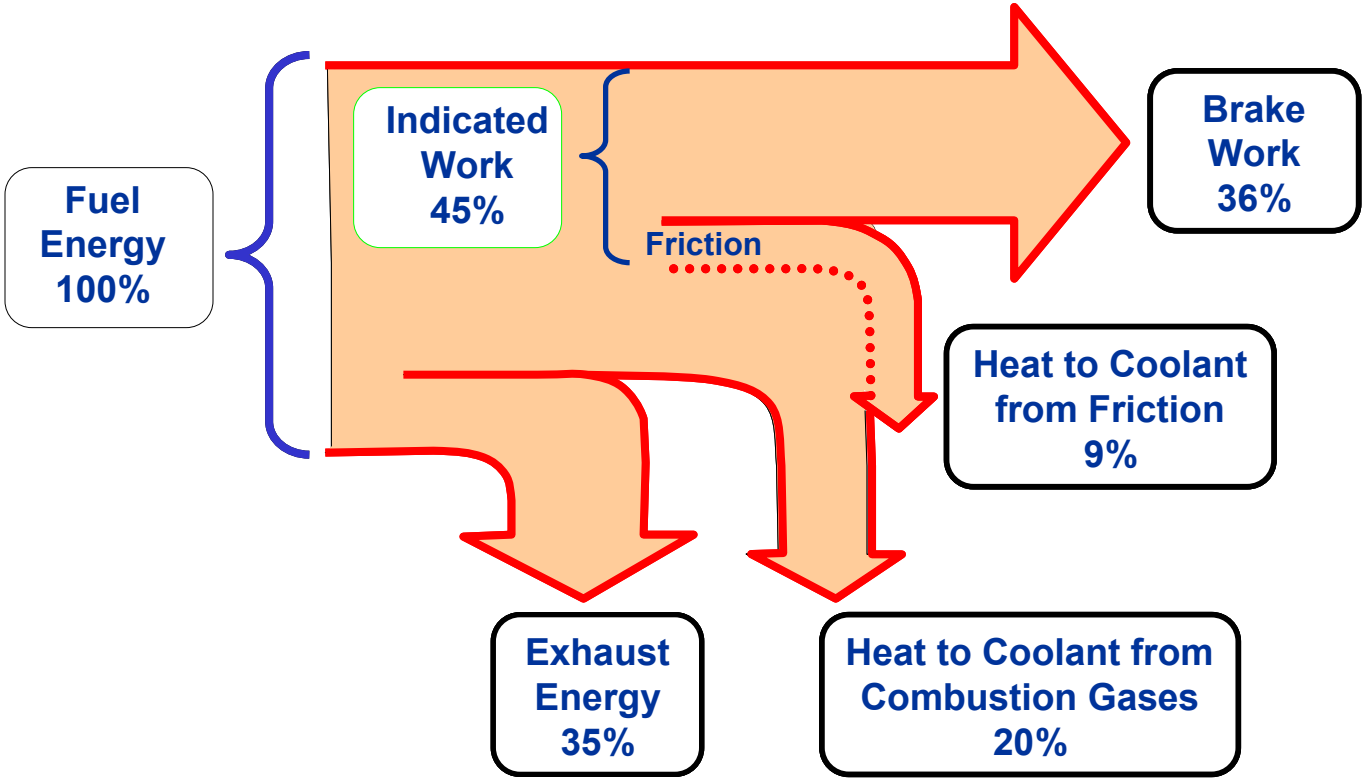


Cooling/Heating

Available Energy in Engine Exhaust

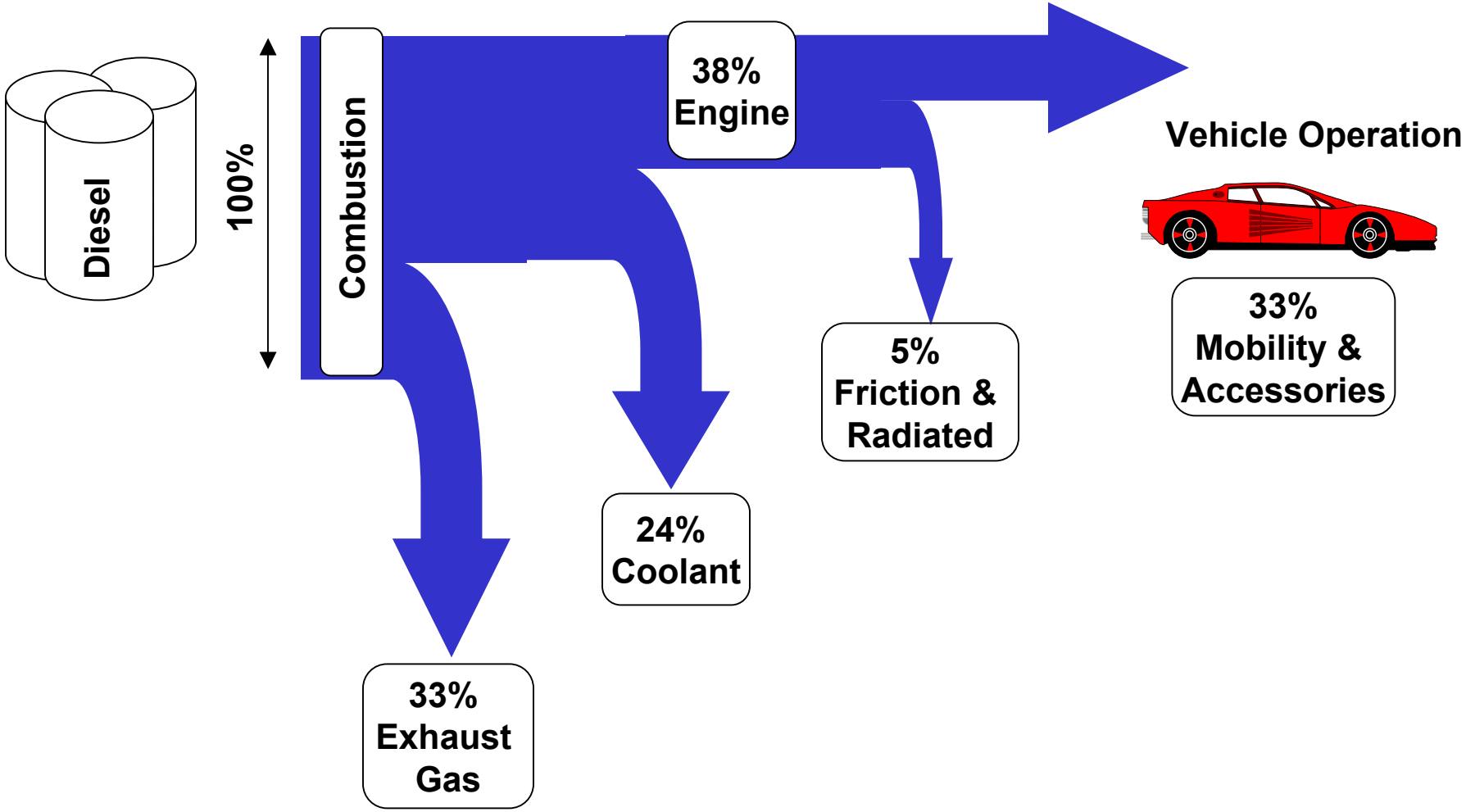


Potential Thermoelectric Heat Sources



Diesel Engine (Class 7 and 8 Heavy-Duty Truck)

Potential Thermoelectric Heat Sources (Cont'd)



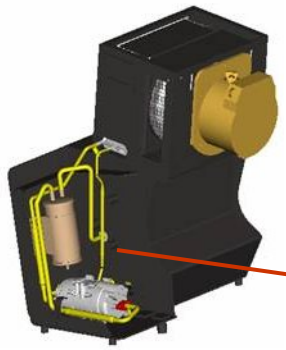
Diesel Engine (Light Truck or Passenger Vehicle)

Typical Diesel Engine Waste Heat ΔT's

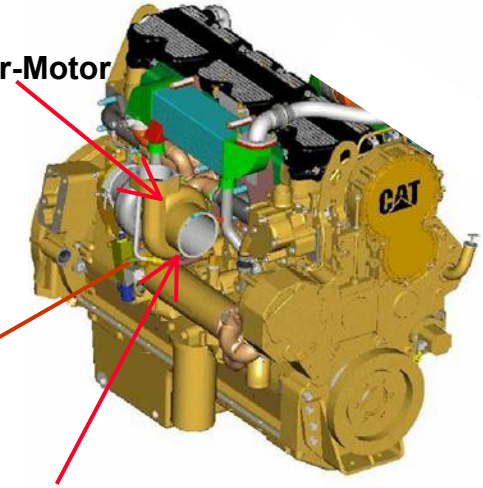
Component	ΔT
Radiator	≈ 70°C
Lube Oil Sump	≈ 70°C
Brakes	≤ 350°C
Exhaust System	≤ 400°C
EGR Loop	≈ 250°C
Turbocharger Compressor (Output)	•≈ 33°C

Increasing Electric Loads in Trucks

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



Motor/Generator on Turbo
recover exhaust energy improve fuel economy improve turbo response



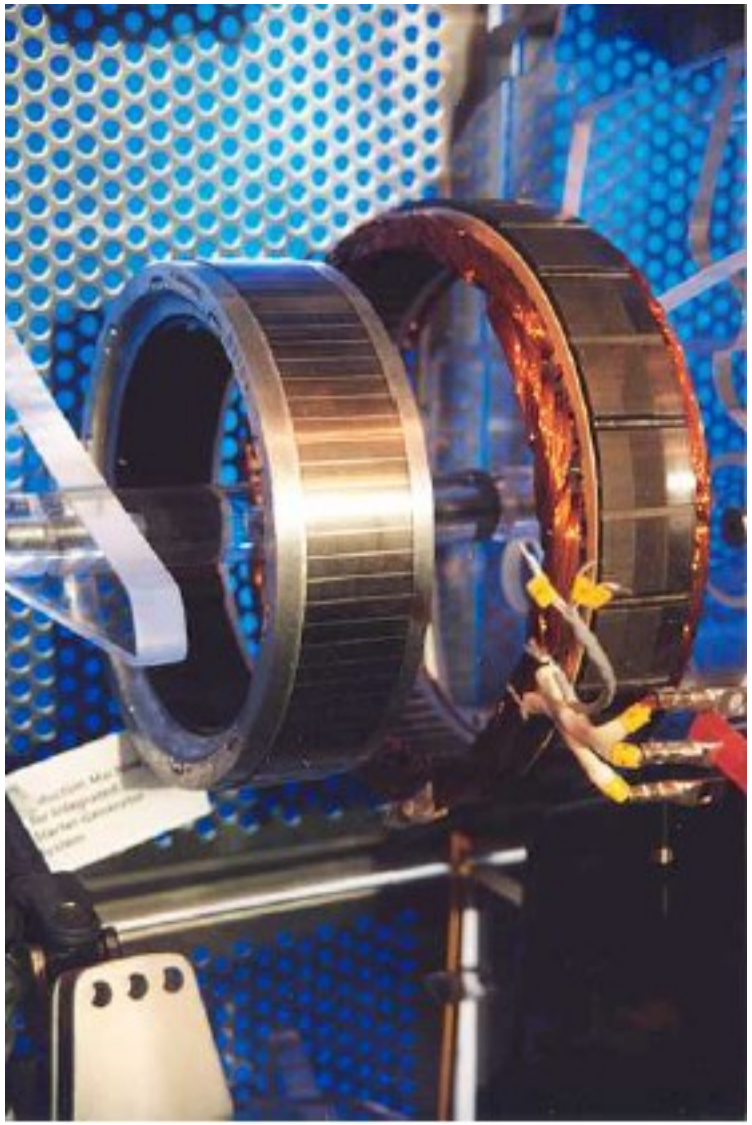
Electric Cooling Fan Drives
variable speed motors
speed on-demand
highly efficient and reliable
power saving mode

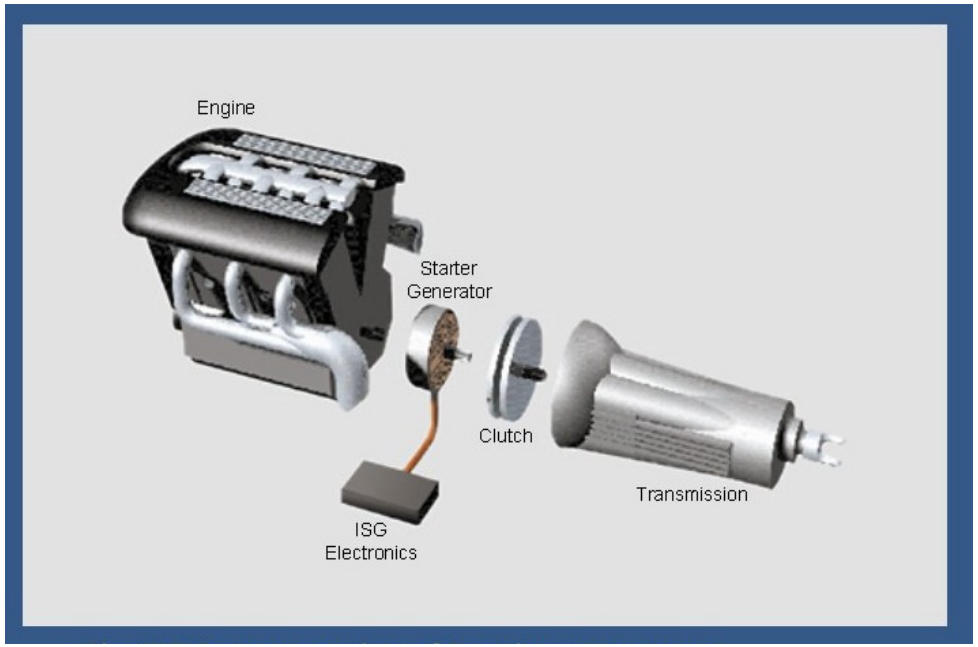
Electrical Outlets
120/240 Vac 50/60 Hz
for tools , attachments, and cab appliances

Electric Water Pump
higher reliability
variable speed
faster warm-up
extended oil life
less white smoke
less carbon buildup
lower cold weather emissions

Starter/Generator/Motor
beltless engine
product differentiation
improve systems design flexibility
more efficient & reliable accessories
supplies 12 Vdc & 120/240 Vac

Integrated Motor/Alternator Starter





Carbon Balance Through Internal Combustion Engine

Gasoline C_7H_{16}

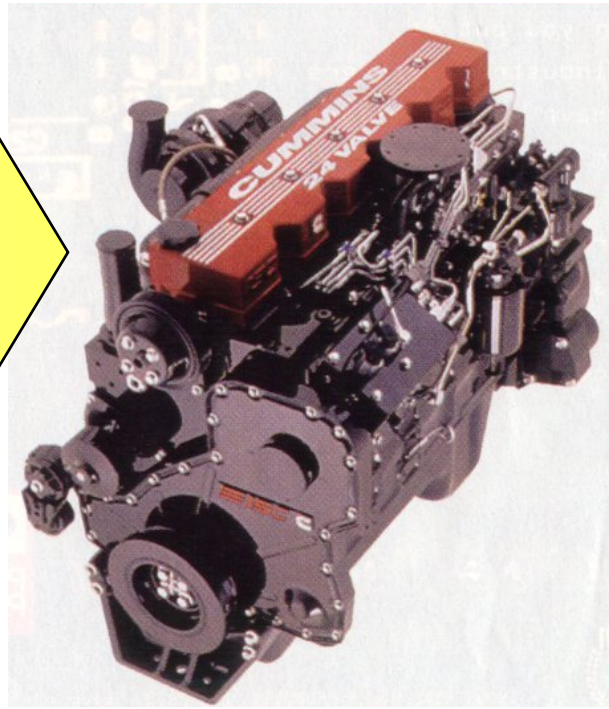
Diesel $C_{18}H_{30}$

Methanol CH_3 OH

Ethanol C_2H_5OH

Natural Gas (Primarily Methane, CH_4)

Propane C_3H_8



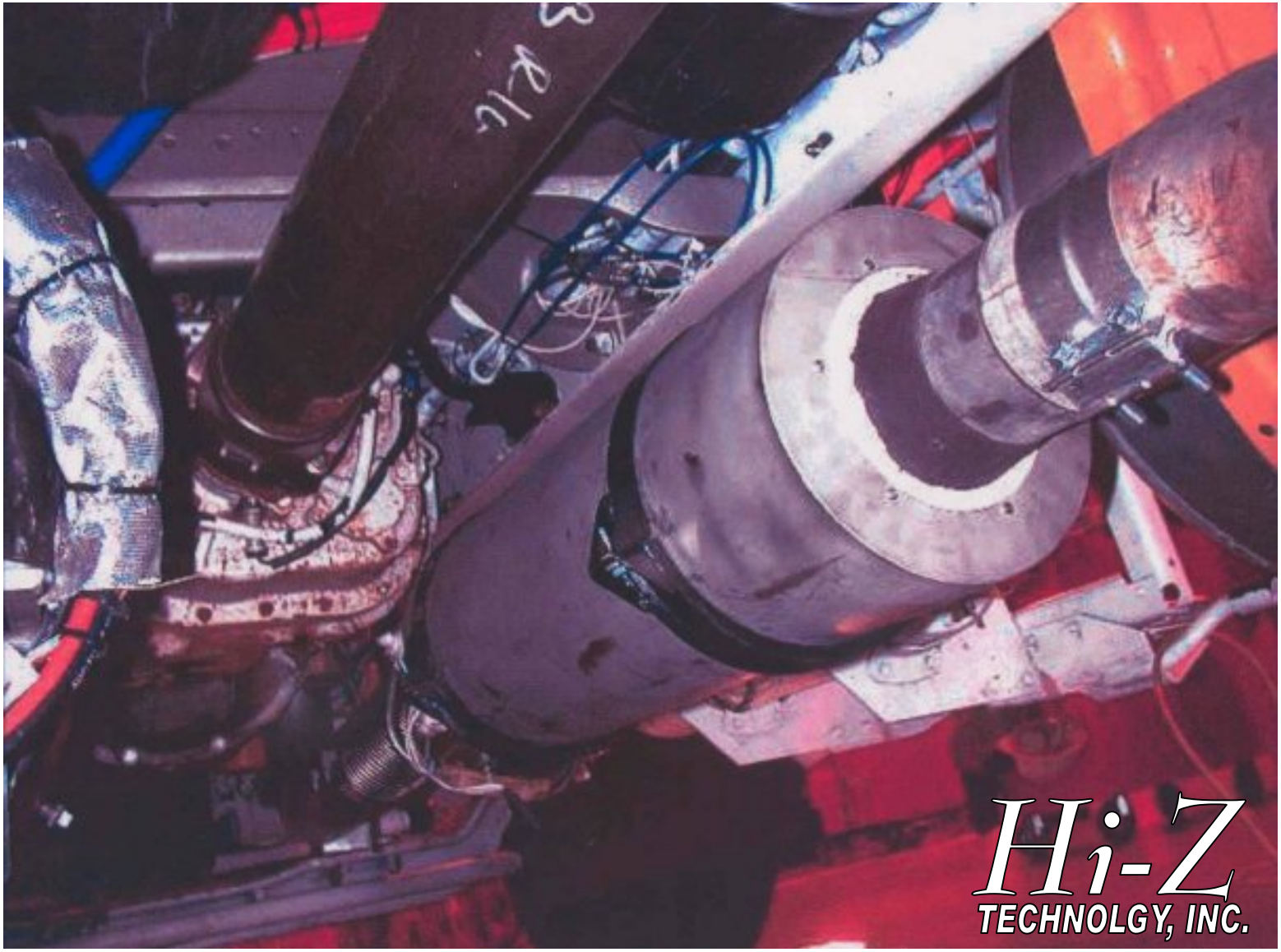
Carbon

- PM
- HC
  Unburned
  Fuel, Lube Oil
- CO
- CO_2

550 HP Truck Equipped With the TEG

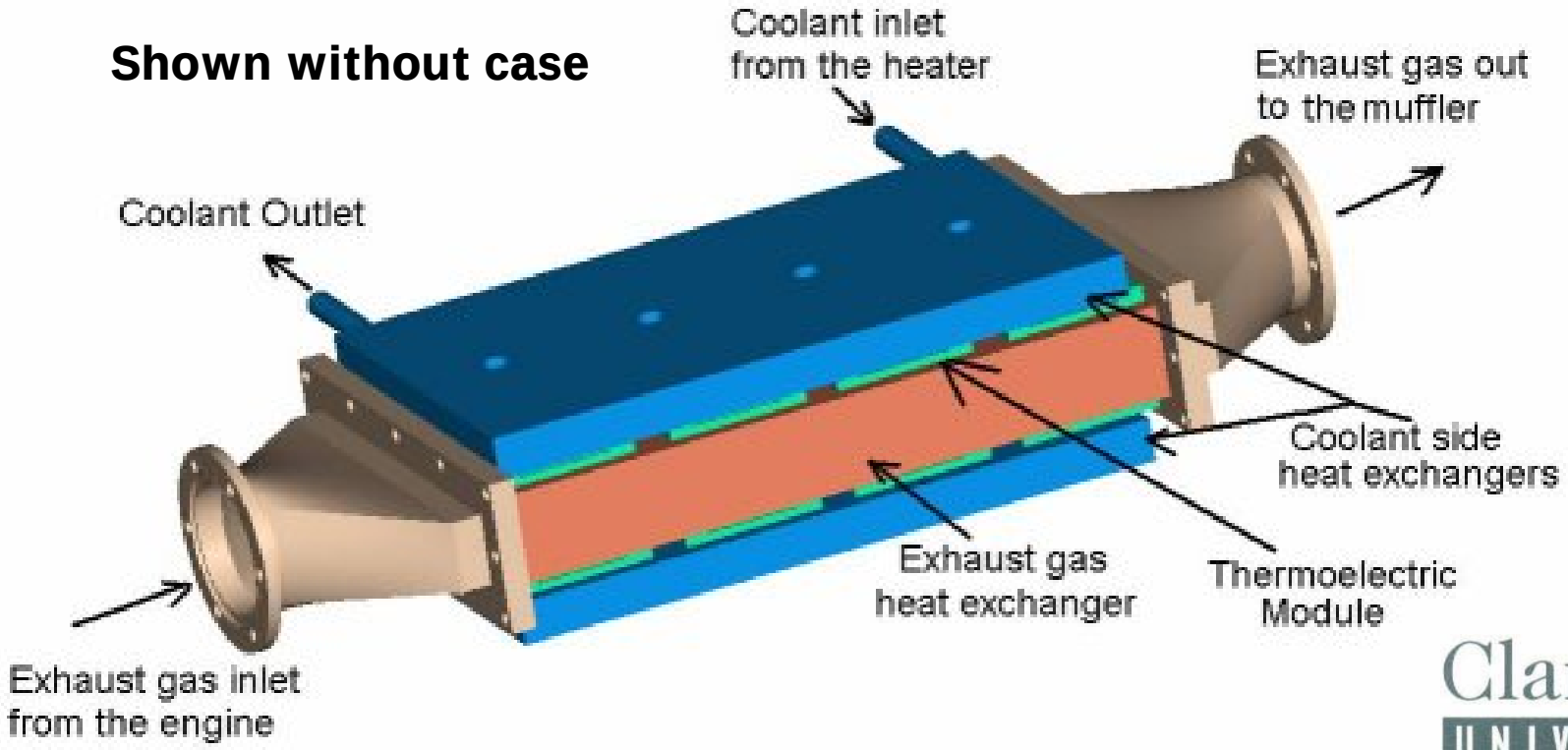
Engine – Caterpillar 3406E, 550 HP
PACCAR's 50 to 1 Test Track
(Note Speed Bumps and Hill)
Standard Test Protocols Used or Each Evaluation
Heavy Loaded (over 75,000 lbs)
TEG Installed Under the Cabin

Potential Location for the Thermoelectric Generator



330 W Thermoelectric Generator for Light-Truck

Shown without case



Clarkson
UNIVERSITY
Potsdam, New York 13699

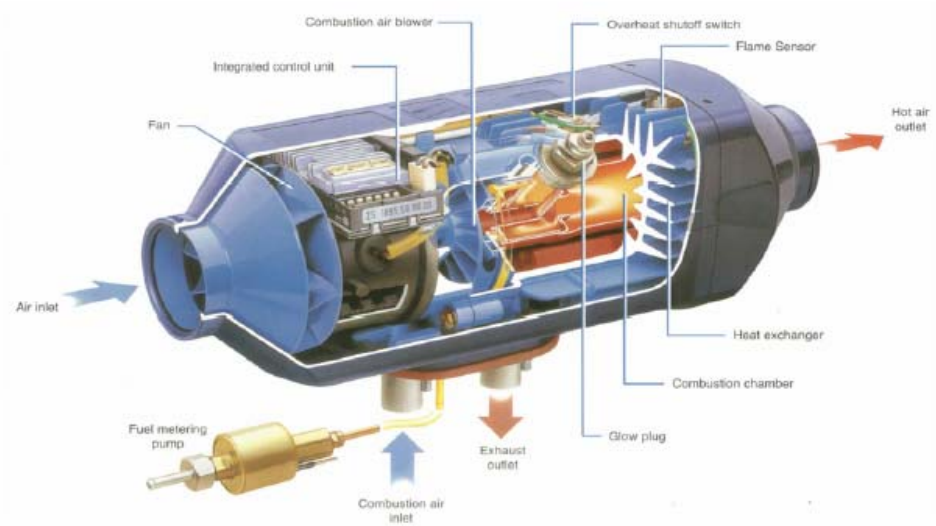
NYSERDA

Hi-Z TECHNOLOGY, INC.

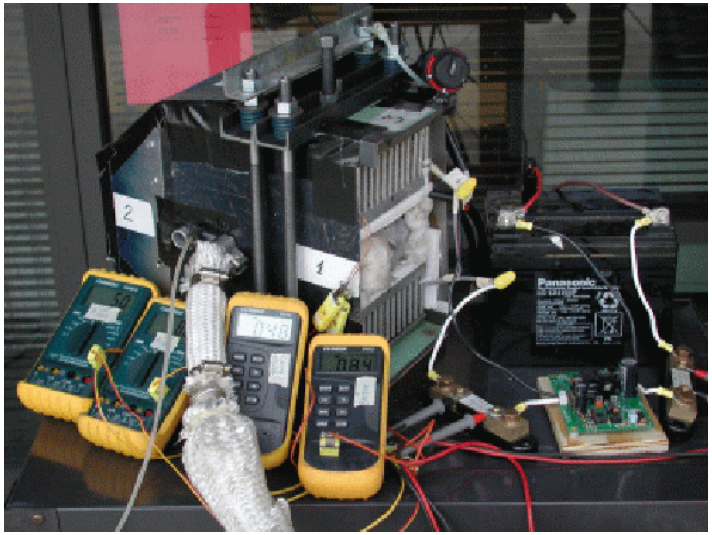
DELPHI
Driving Tomorrow's Technology

GM

Self-Powered Diesel Fired Heater
U.S. Patent 6,527,548



Diesel Firing Heater

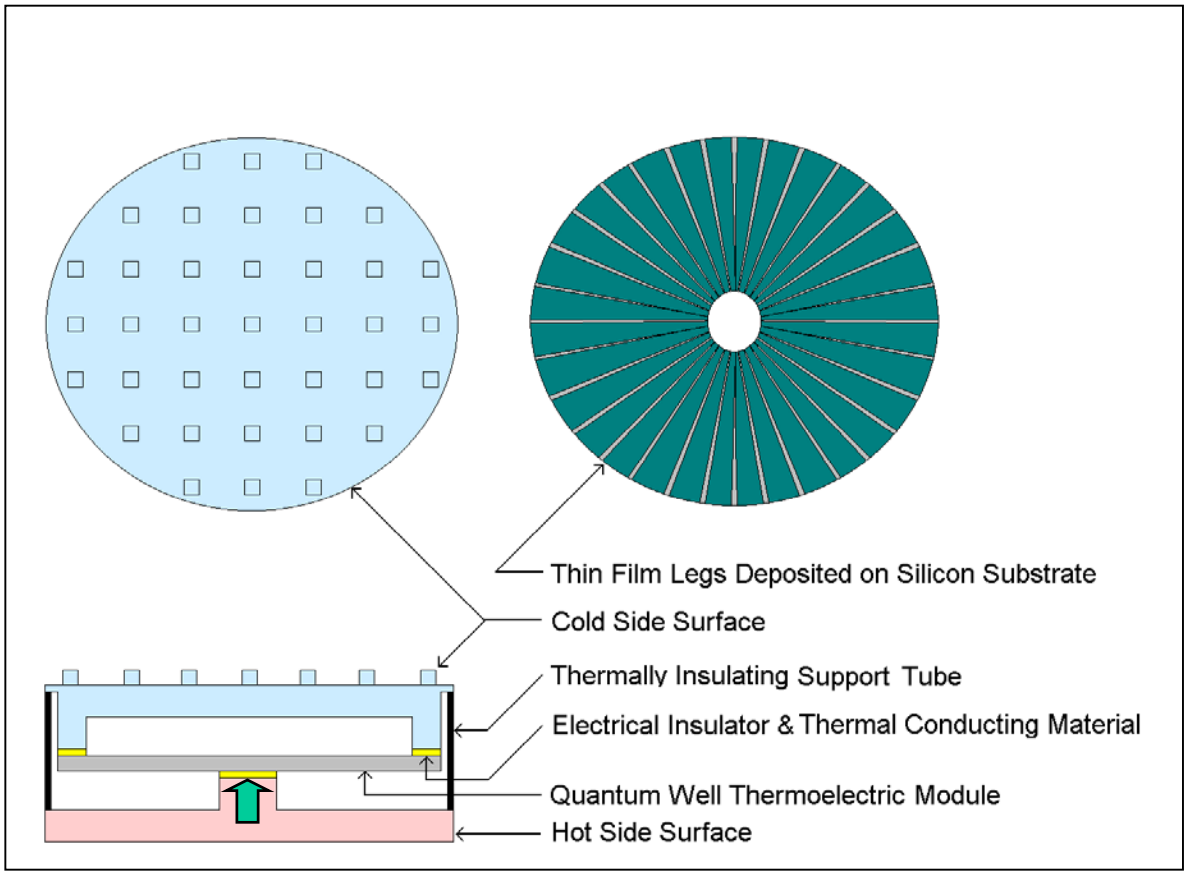


Self Powered Heater Prototype

Aircraft Gas Turbine

Ship Sensor

Power Harvesting QW TEG Concept for Navy Shipboard Wireless Sensors



Generator dimensions: 1 in^2 footprint, ½ cm height

Small size (1 in^3) requirement satisfied using QW TEG

Provides power for wireless sensors: 5 mW at 3 V using 41°C ΔT from ship interior thermal environment

Spacecraft Solar Panels

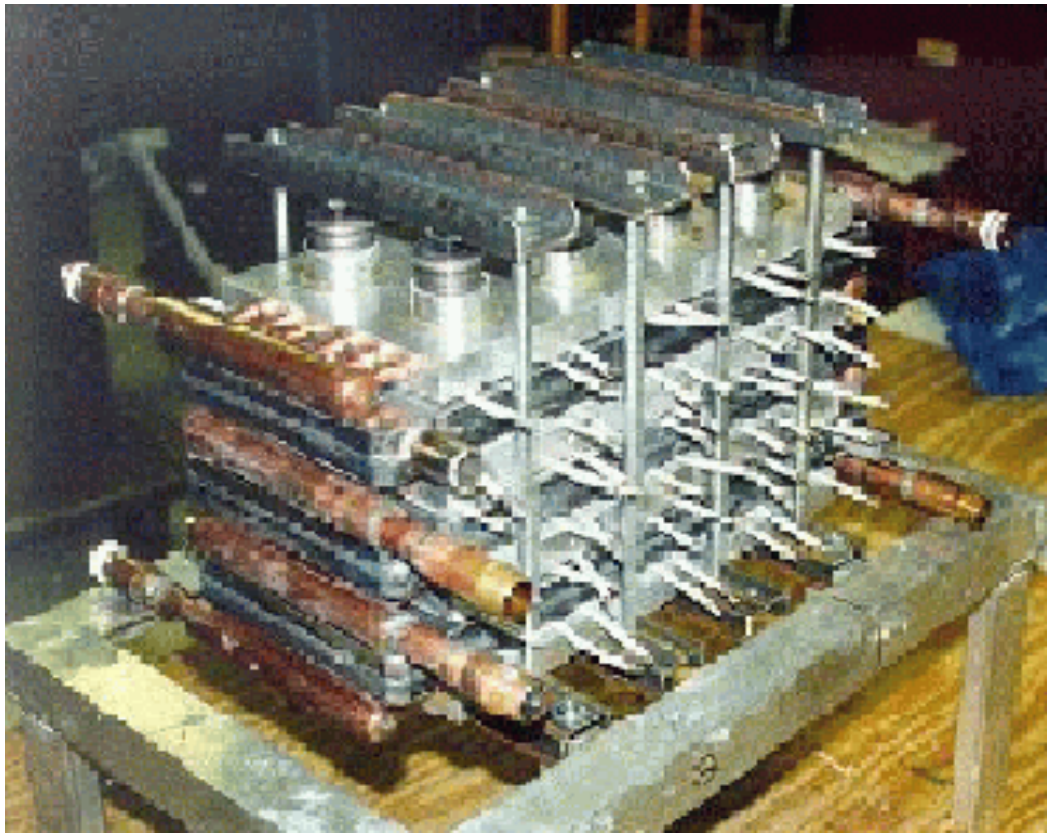
Solar Panels with Concentrators

Thermoelectric Watch

CITIZEN
Eco-Drive Thermo
Watch

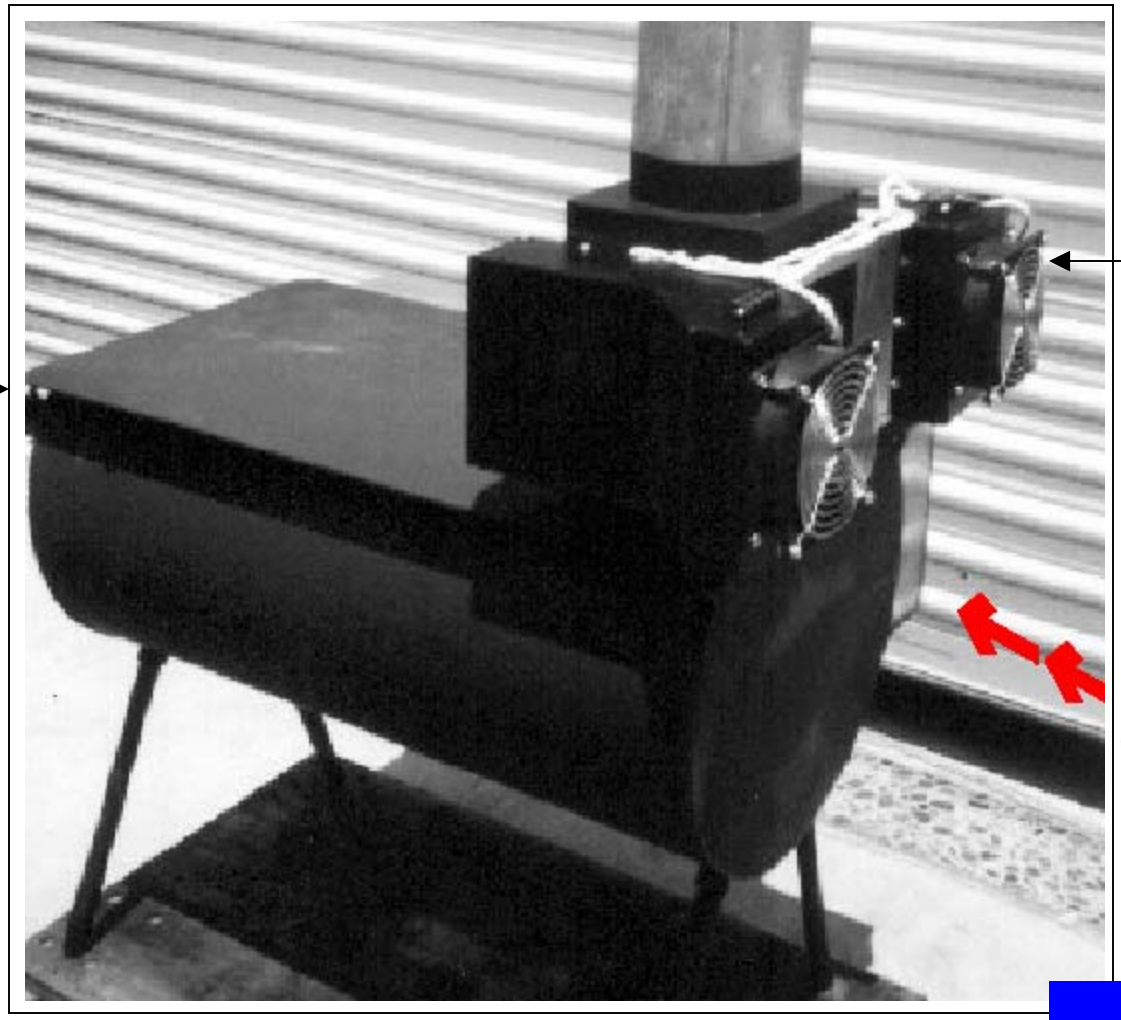
- Converts temperature difference between body and surrounding air into electrical energy
- No battery change needed
- When not being worn, second hand moves in 10-second increments (non-power generation mode), returning to normal when put on (power generation mode)
- No. of semiconductors in thermocouple array: 1,242 pairs
- Operating time from a full charge: Approx. 6 months (approx. 16 months in power saving mode)

Incinerator Plant Waste Heat Recovery Unit



Hi-Z TECHNOLOGY, INC.

Wood Stove



Cooking surface

Exhaust Hot Gases Converted to Electricity

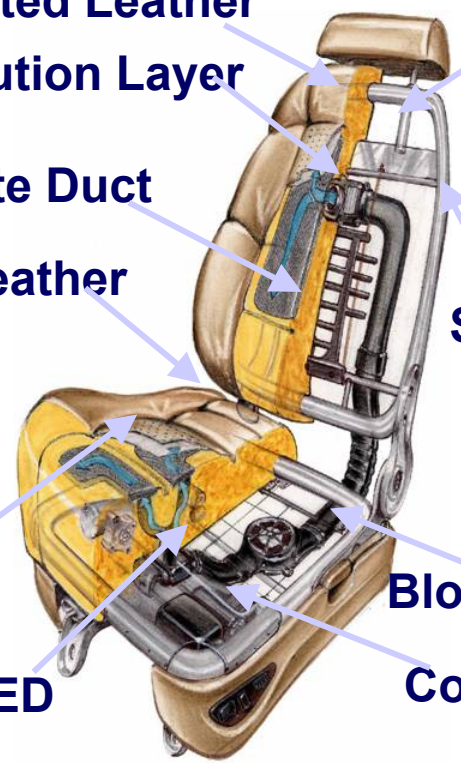
Hot Water Container

Hi-Z Technology, Inc.

Vehicle Seat Application of Thermoelectric Device

CCS™ Vehicle Seat Application

Production CCS™ Assembly



TE Wine Cooler

SPECIALBUY

$139

47 Bottle Wine Cooler

- 4.6 cu. ft. capacity
- Black interior, exterior and shelves
- Reversible double paned amber tinted door
- Light with manual ON/OFF switch
- Temperature range from 39-61 °F

BC130D (562911)

THE HOME DEPOT

You can do it.
We can help.

SE NE SW MW NW PW

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HDCLAMP1203A

TE Fruit Saver

Thermoelectric Cooling Fruit Saver

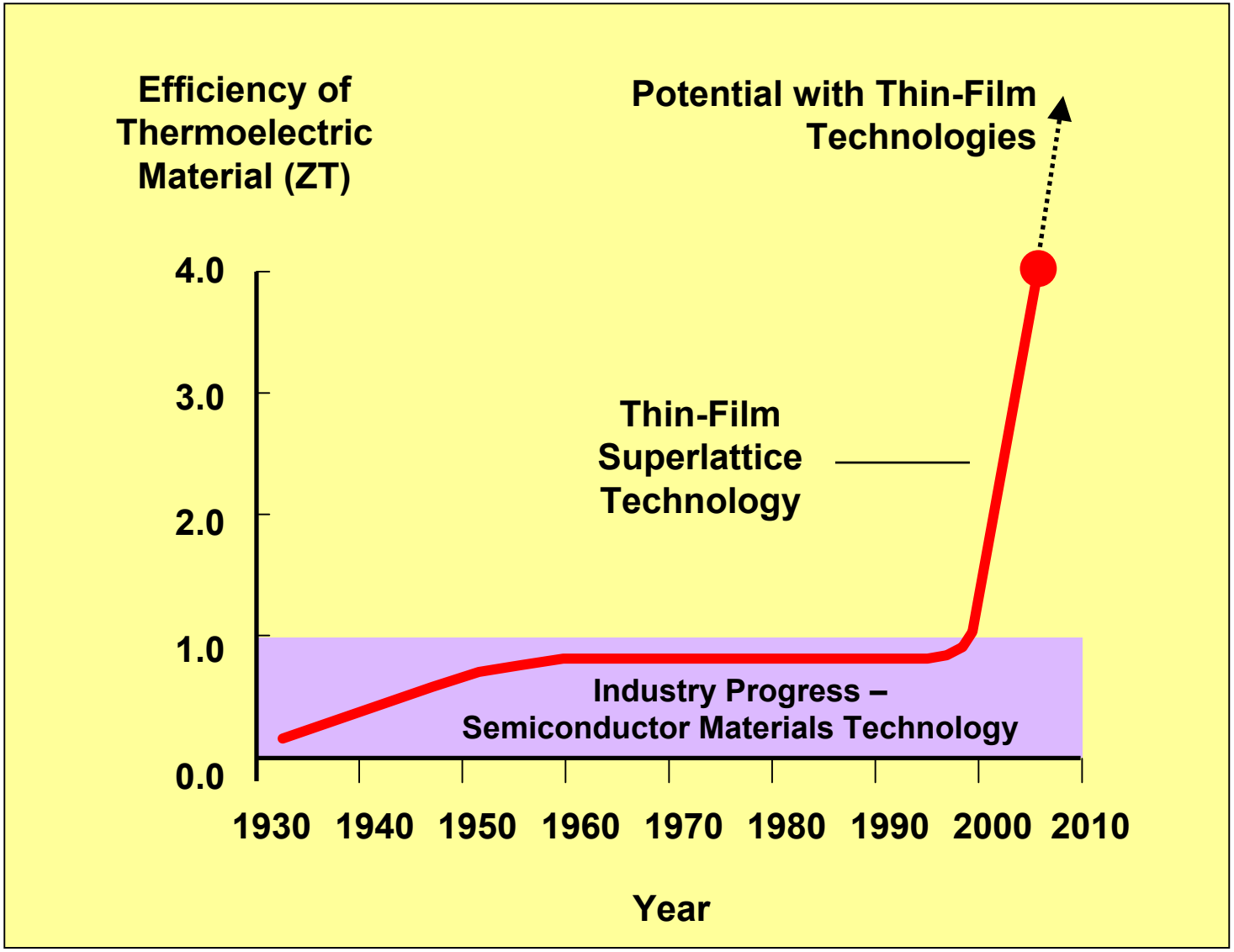
Environmental Benefits

- Utilization of thermoelectrics would provide the benefit of reducing R-134a refrigerant usage, the most common working fluid, in heating/cooling systems.
- R-134a has 1,800 times greater greenhouse gas impact than CO_2 on a per molecule basis.

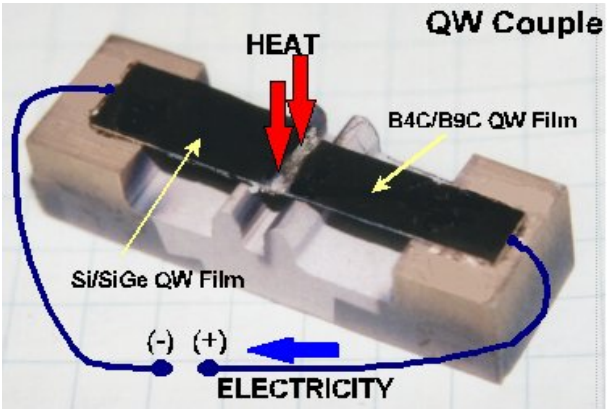
Recent Breakthrough in Efficiency

- Recently, thermoelectric devices based on the quantum well confinement concept were fabricated, and demonstrated measured ZT values of 4.0 (a conversion efficiency of ~20%)
  - Fabricated by sputtering a number of alternate N and P layers about 60 µm each (roughly 1/1000 the thickness of a human hair).
  - Currently still at the laboratory stage.
  - Significant work needed to enhance fundamental understanding, to develop improved devices, to address considerable heat transfer challenges, and to obtain high-rate production volumes

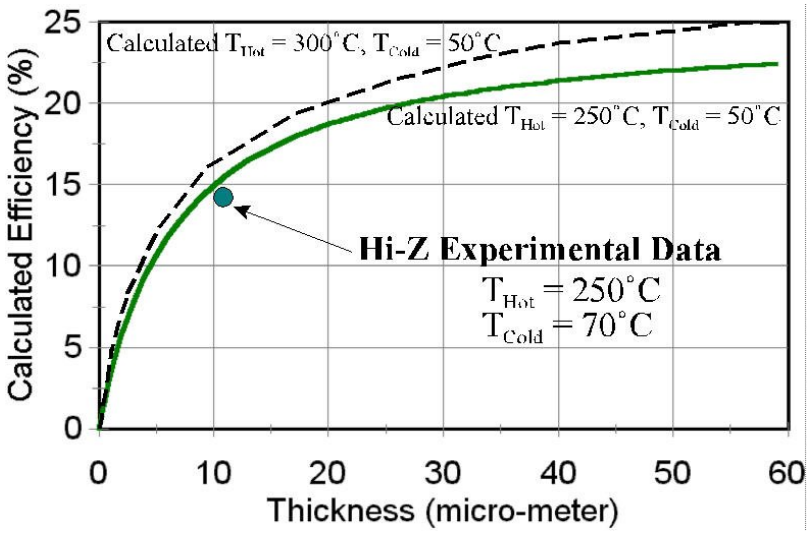
Recent Breakthrough in Efficiency (Cont'd)



Hi-Z TE Device



QW couple made with B_4C/B_9C and Si/SiGe films



Efficiency of QW couple versus film thickness

Source: Hi-Z Technology

Size Comparison of a Nanowire to the Human Hair

Width of the Human Hair

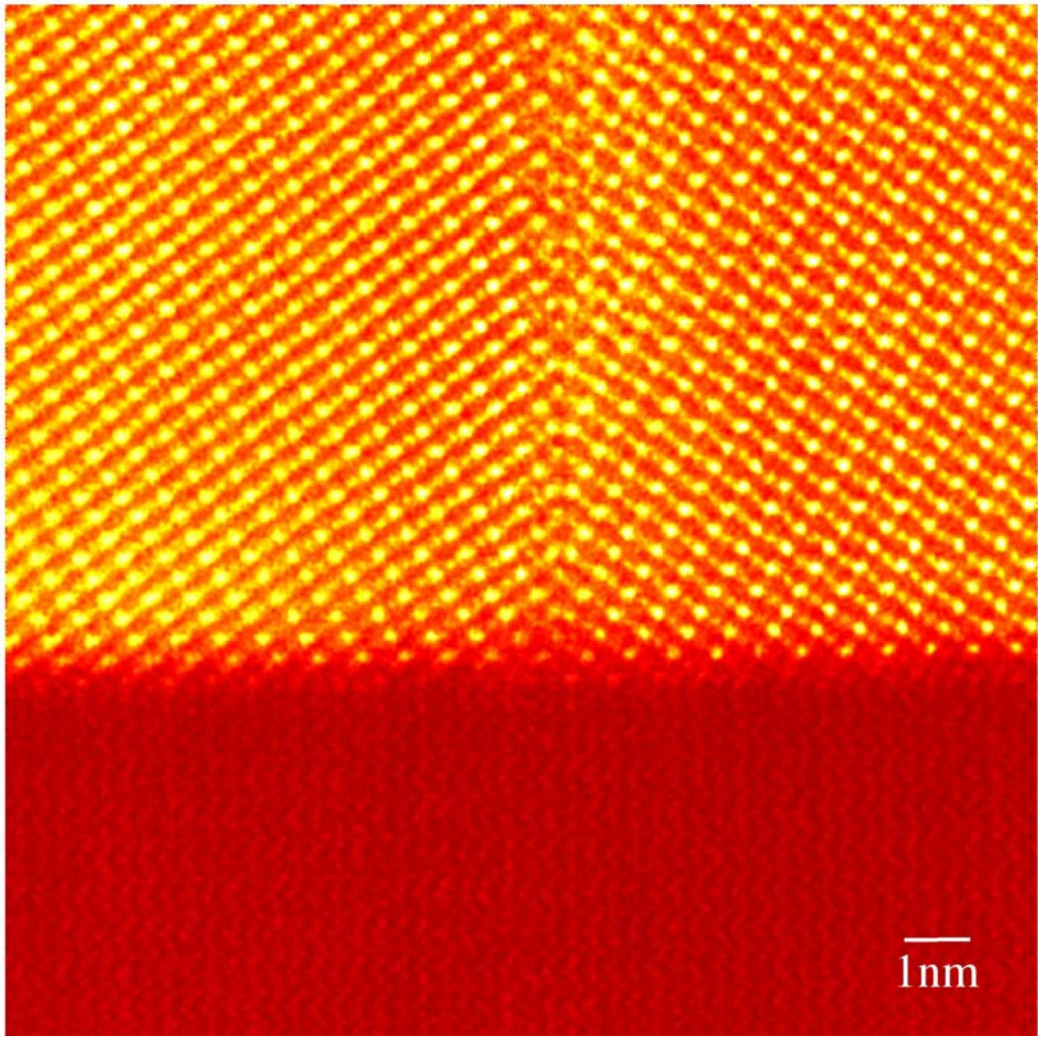
Width of a Nanowire (1,200 times smaller)

	Width
Human Hair	~60 µm (60,000 nm)
Nanowire	~50 nm

ORNL Electron Microscope Resolution

Domain boundary in $SrTiO_3$ (111) on Al_2O_3 (001)

looking down the <$\bar{1}$10> direction of both materials



TE Energy Recovery Benefit

2004 Jaguar XJ

- 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.

Ford's Interest

"Ford is already a consumer of thermoelectric devices for passenger comfort, and we in Ford Research and Advanced [Development] have an interest in waste heat recovery technologies."

Dear Dr. Fairbanks:

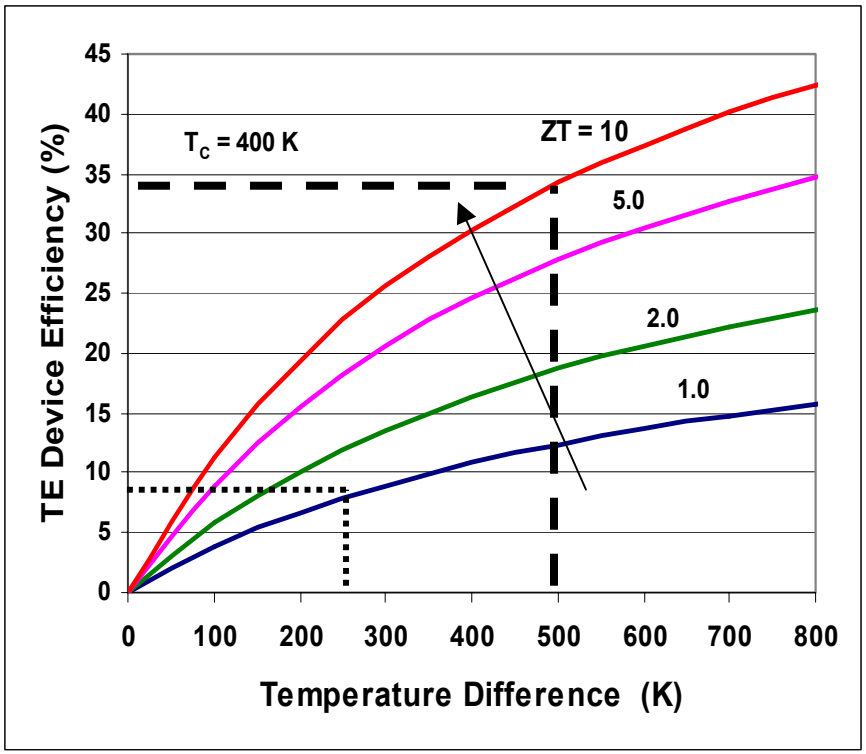
Thank you for the telephone call inviting our input on the 2004 Thermoelectrics Workshop that you are organizing. Ford is already a consumer of thermoelectric devices for passenger comfort, and we in Ford Research and Advanced have an interest in waste heat recovery technologies. Thermoelectric waste heat recovery is not terribly attractive from a cost/benefit standpoint in the short term, but the new materials and systems approaches being studied and the large number of researchers being drawn to this field are very encouraging developments.

It is not clear whether our travel budget will allow us to attend the Workshop, but I would very much like to remain on any (e)mailing lists for this and related events. Thanks again.

Best regards,

John
Dr. John M. Ginder
Technical Leader
Ford Motor Company
Physical and Environmental Sciences Department
Research and Advanced Engineering

Long-term Potential to Replace Vehicular Internal Combustion Engines



For a given ΔT, higher the ZT, higher the heat-to-electric conversion efficiency

If ZT of 10 can be achieved, a theoretical conversion efficiency of ~35% is possible for ΔT of ~500 °C

Cooling Devices of Tomorrow?

Now

Thermoelectric Hot & Cold Mini Fridge (1.5 ft^3)

Future?

Side-by-side Refrigerator/Freezer (27.5 ft^3)

Mechanical Engineer's Perspective

- Figure of Merit (ZT) has been used by the thermoelectrics investigators for years
  - A higher ZT is better, but is the 'T' playing an inordinate role?
  - Measuring nanoscale properties is very challenging.
- Direct energy conversion devices can be better understood as "Percentage of Carnot Efficiency"
  - Suggest this be included for devices in addition to investigator's parameters.

European Union Funding for Thermoelectrics Research

- Major effort: three-year project entitled "Nano-engineering for efficient energy conversion systems," funded under the European Union's Fifth Framework Programme.
- Analogous to the multidisciplinary MURI team in the U.S. (includes universities, research institutions, and commercial enterprises in several European countries).
- Aimed at developing a viable strategy for improving the performance of TE materials using nanotechnology as well as via structural modification.
- Resources
  - Phase I: $1.9 Million (2001 – 2003)
  - Phase II*: $10 – $20 Million (expected, 2004 – 2008)

Private Communication on October 6, 2003, from Prof. Mamoun Muhammed, Project Lead for Phase I and Chairman, Department of Material Chemistry, Royal Institute of Technology, Stockholm, Sweden.

Upcoming Request for Proposals (RFP)

- RFP entitled "Thermoelectrics/Thermionic Approaches for Engine Waste Heat Recovery" expected by the end of March, 2004.
- To be released by the National Energy Technology Laboratory (NETL).

- Resources
  - Phase I: $1.9 Million (2001 – 2003)
  - Phase II*: $10 – $20 Million (expected, 2004 – 2008)

Conclusion

Thomas Johann Seebeck
(1770-1831)

Almost two centuries after Seebeck's work, we are faced with another challenge

- Recognize the potential of emerging high ZT technology
- Understand the fundamentals
- Measure properties
- Determine how to commercialize