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

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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)

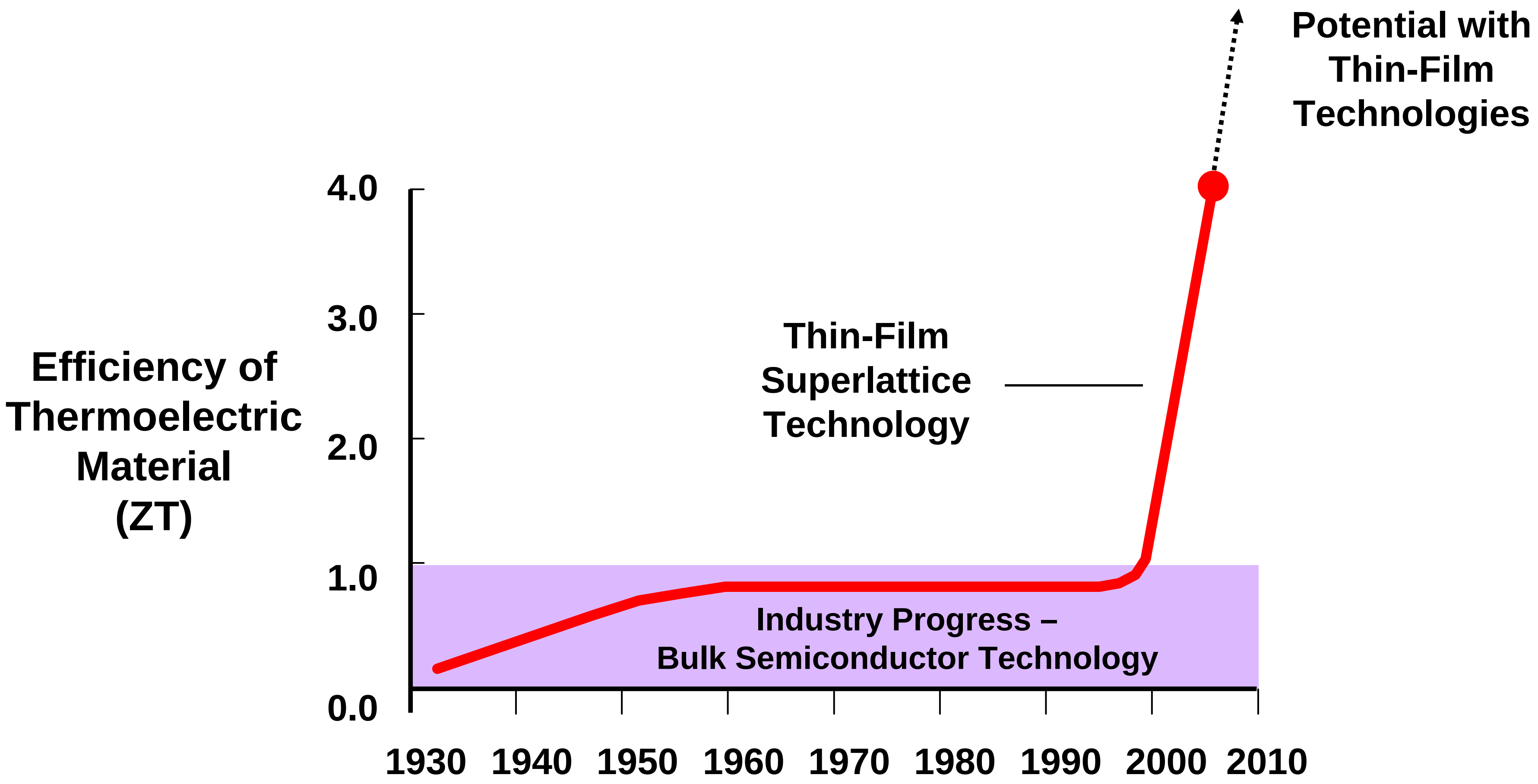
> Long-Term:

Replace Vehicular ICE Propulsion Engine with Thermoelectric Generator

Brief Review of Thermoelectric Efficiency

- 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



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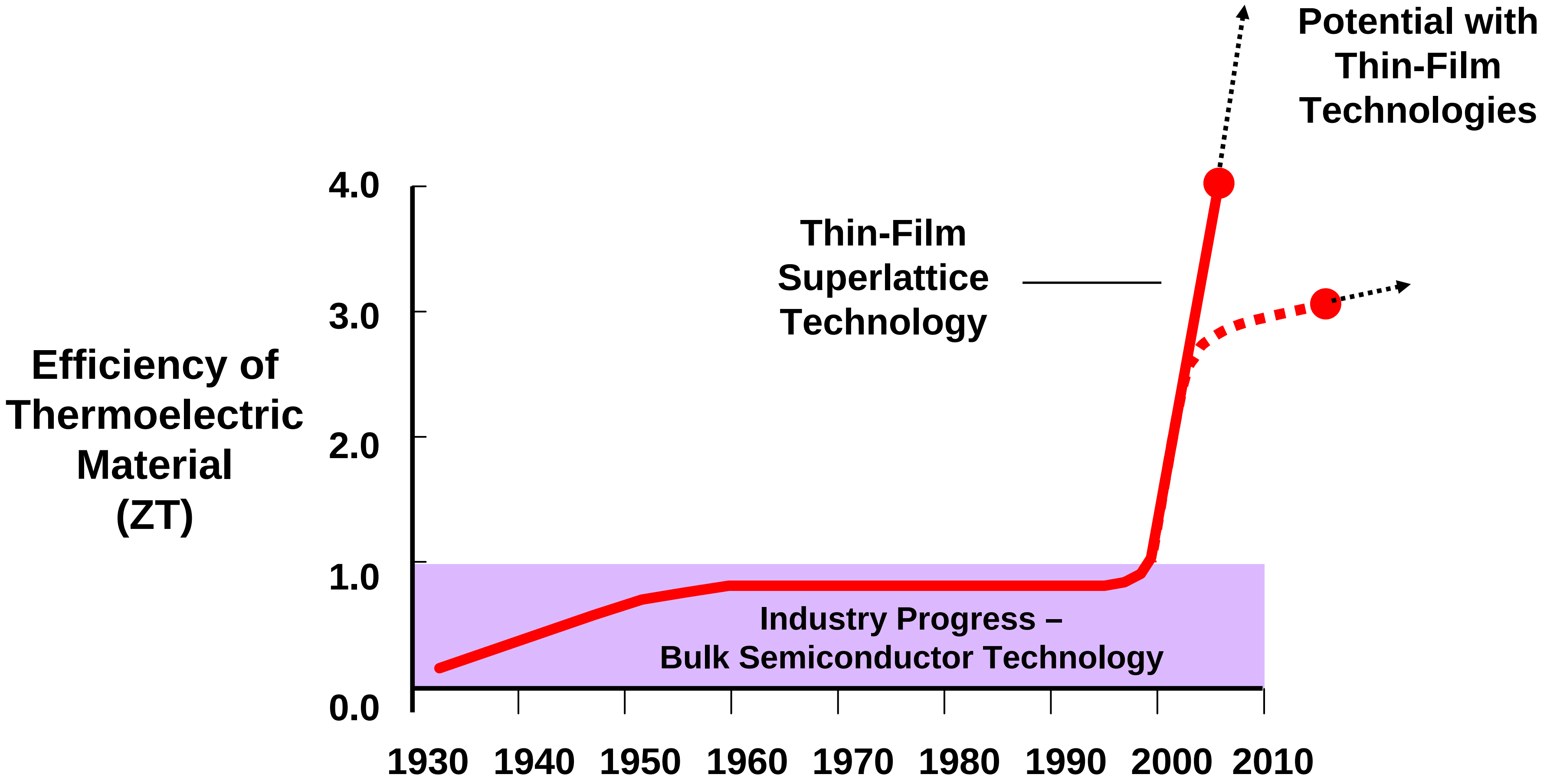
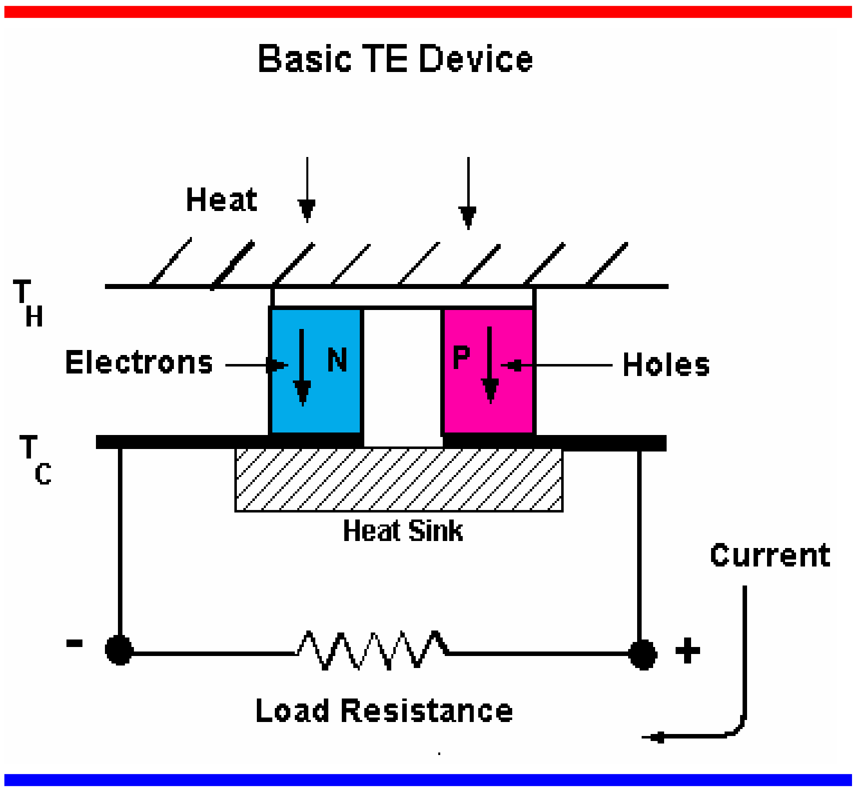


Thermoelectric (TE) Energy Conversion

Hot Side ("Waste Heat")



Cold side

Waste heat >> Electricity

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

$Z = S^2\sigma/k$

S = Seebeck Coeff = dV/dT

σ = Electrical Conductivity

k = Thermal Conductivity

$$\eta = \frac{T_{hot} - T_{cold}}{T_{hot}} * \frac{\sqrt{1+ZT_{avg}} - 1}{\sqrt{1+ZT_{avg}} + \frac{T_{cold}}{T_{hot}}}$$

Carnot efficiency

Thermal Considerations for TE Generators

- Heat transfer different for nanostructures
- Thermoelectric materials

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

$$\mathbf{ZT = S^2 \rho T / k}$$

where: S = Seebeck Coeff = dV/dT
ρ = Electrical Conductivity
k = Thermal Conductivity

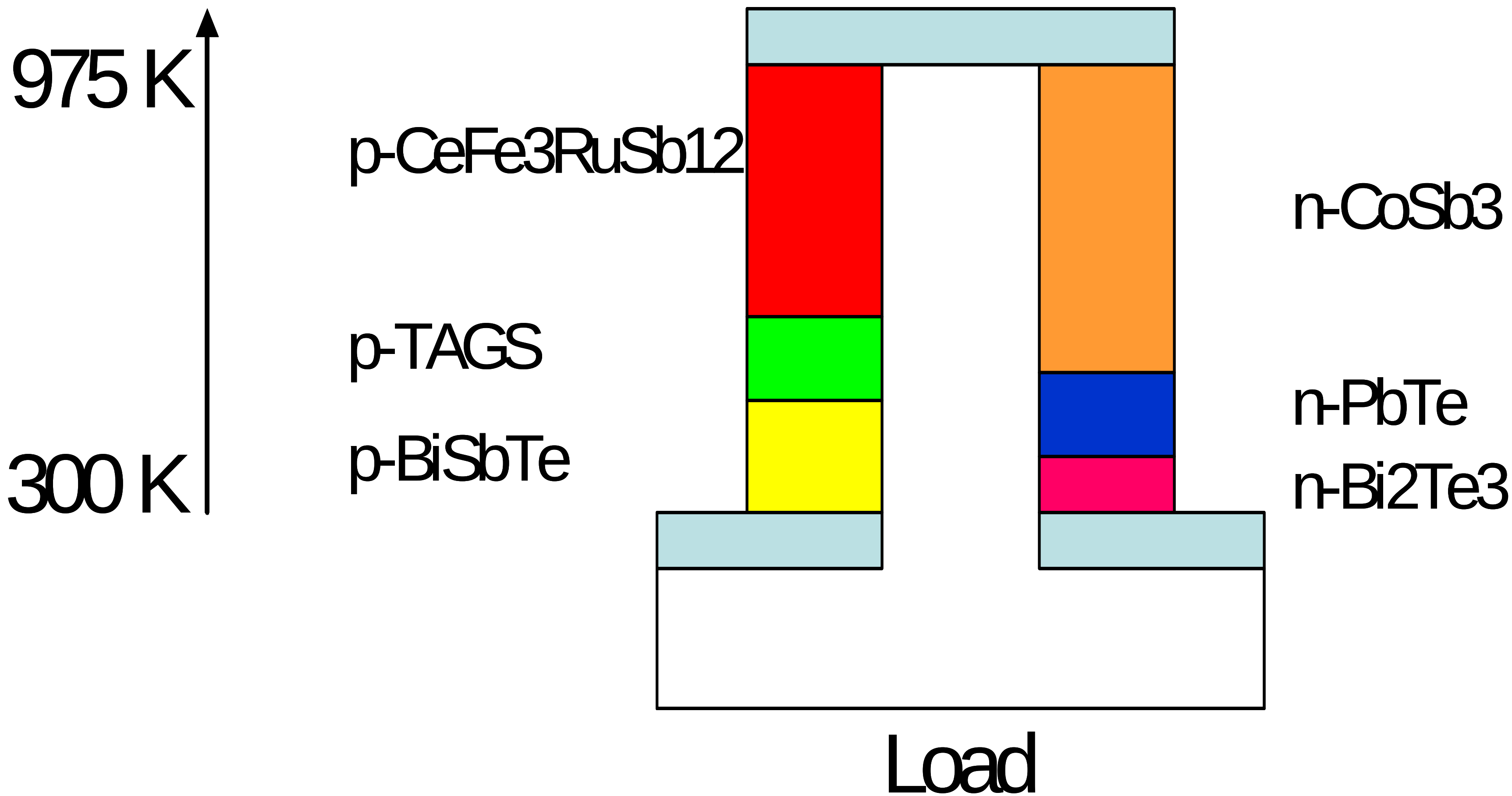
In macrostructures: $\uparrow\rho \Rightarrow \uparrow k$

In microstructures: $\uparrow\rho$ [increase electron mean free path]

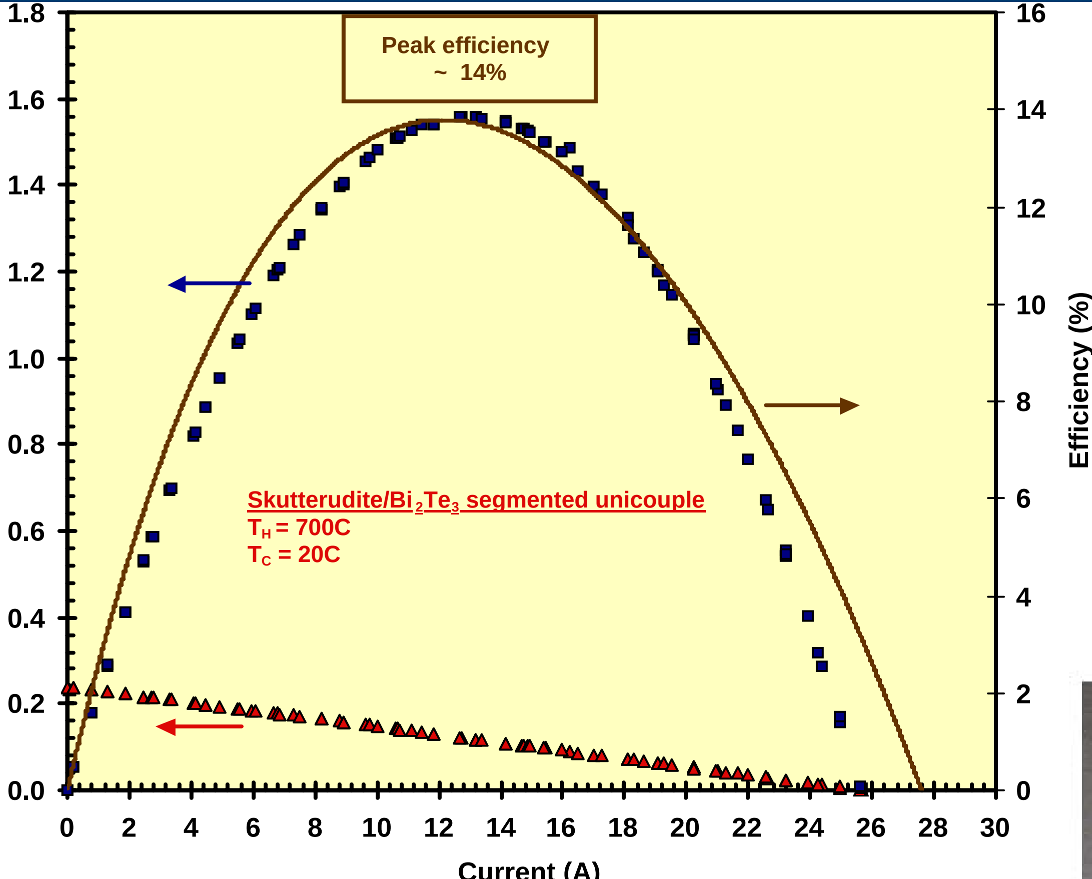
$\downarrow k$ $[\, k_{phonons} + k_{electrons} \,]$

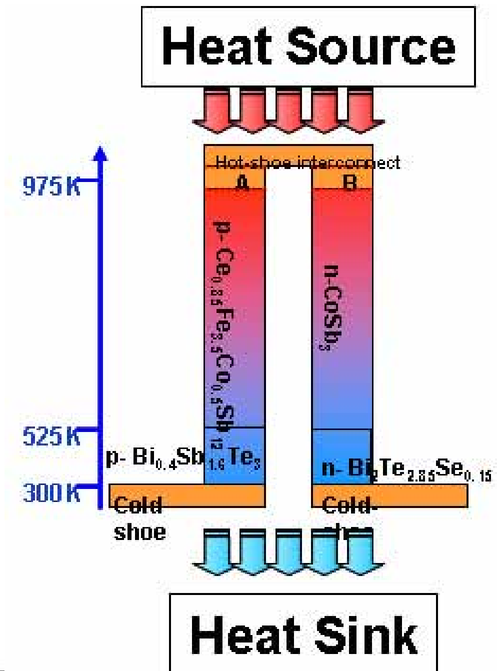
- Low dimensional thermoelectrics need substrate support
  - High temperature capability, low k, strong and thin
  - Kapton is a candidate
- Increase ΔT across thermoelectric generators
  - Improve cooling at the cold side

Segmented TE Couple



Thermal and electrical testing - Segmented unicouple

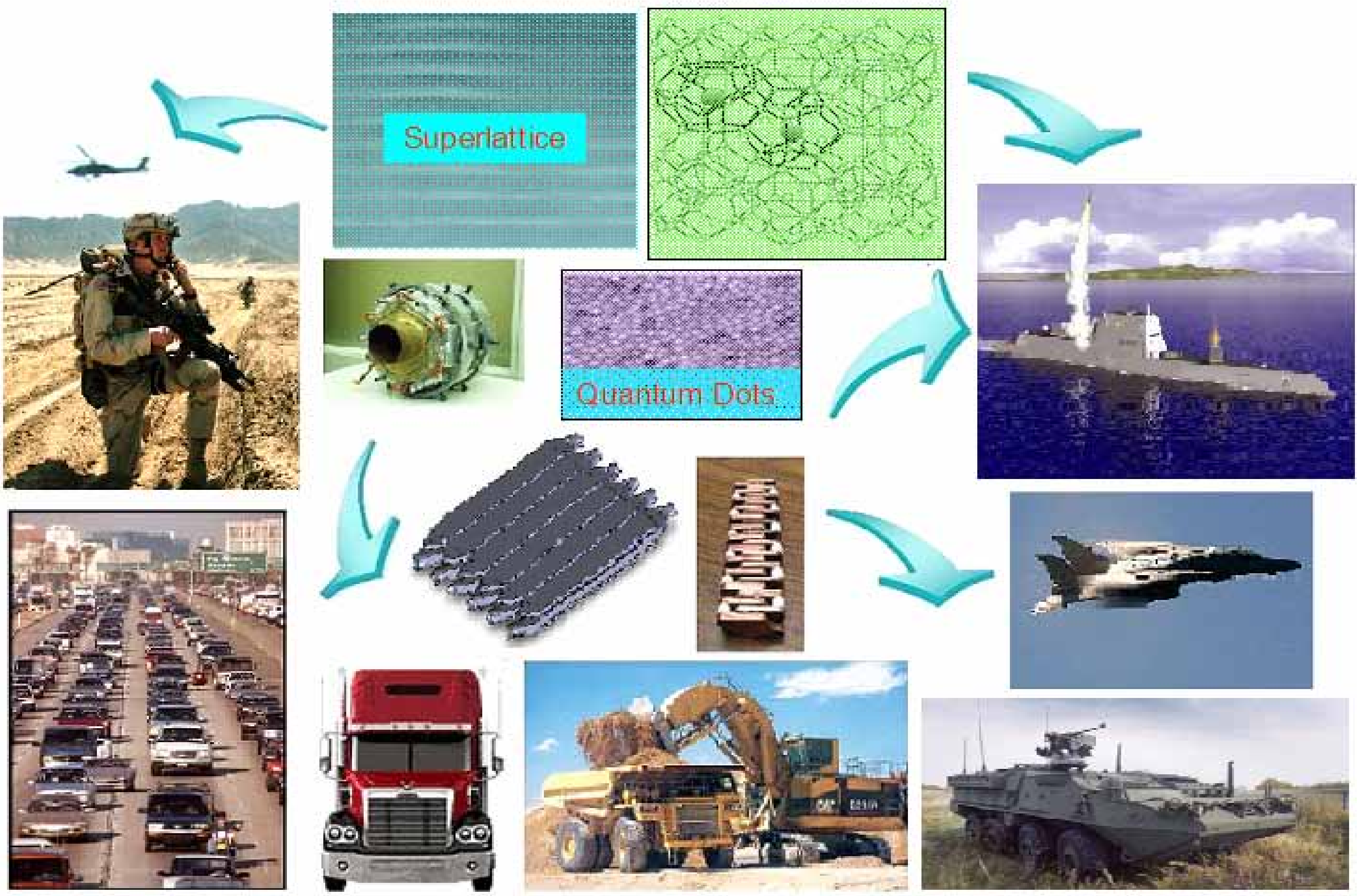




- Experimental I-V curves fully validate projected performance
  - Translate into ~ 14% efficiency for 975K-300K ΔT
- Results independently confirmed at the University of New Mexico

Skutterudite unicouples fabricated by diffusion bonding

HETE Applications



Thermoelectric Watch

CITIZEN Eco-Drive Thermo 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)**

Advanced Thermal Management for Tomorrow Soldier

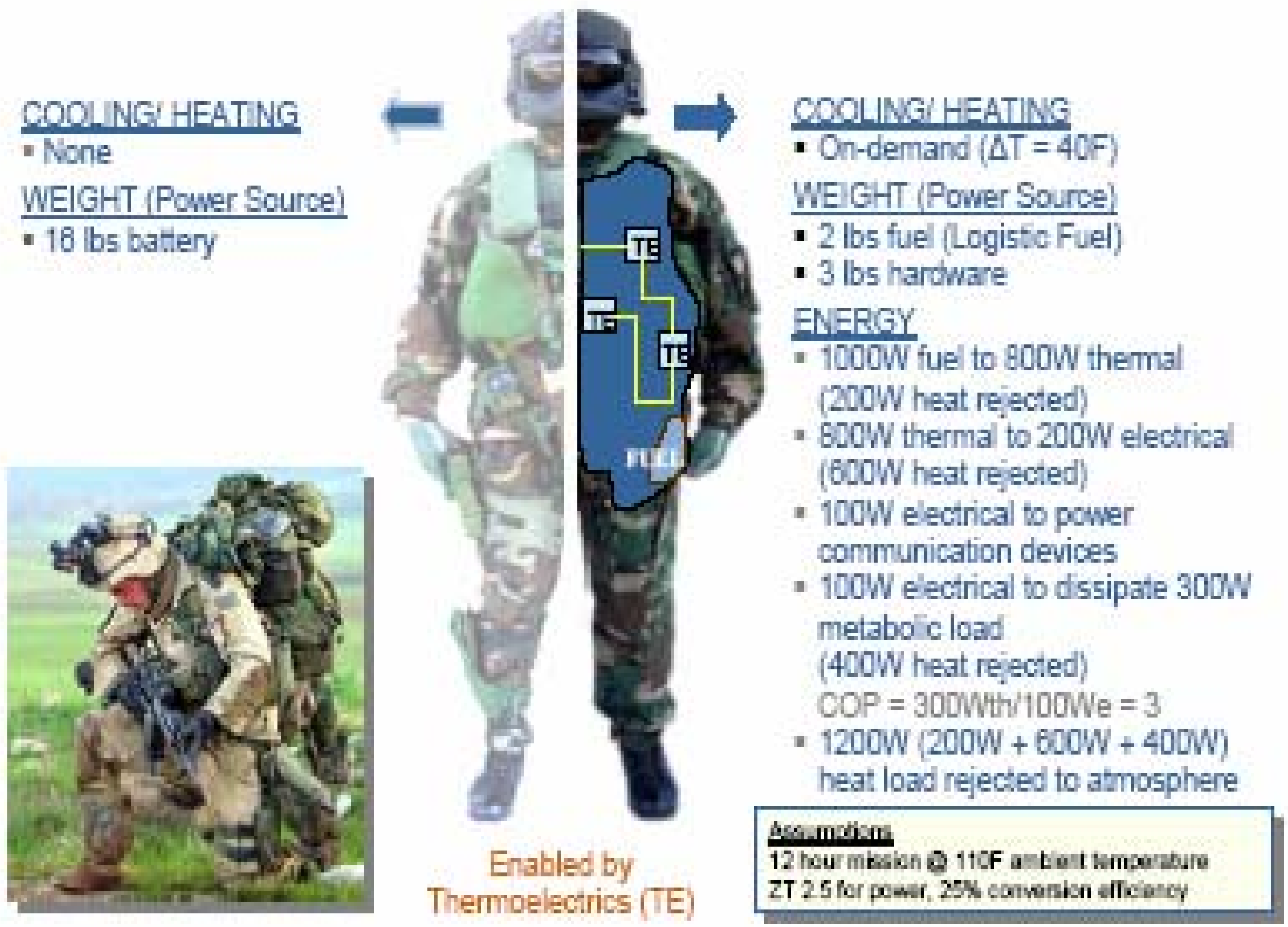
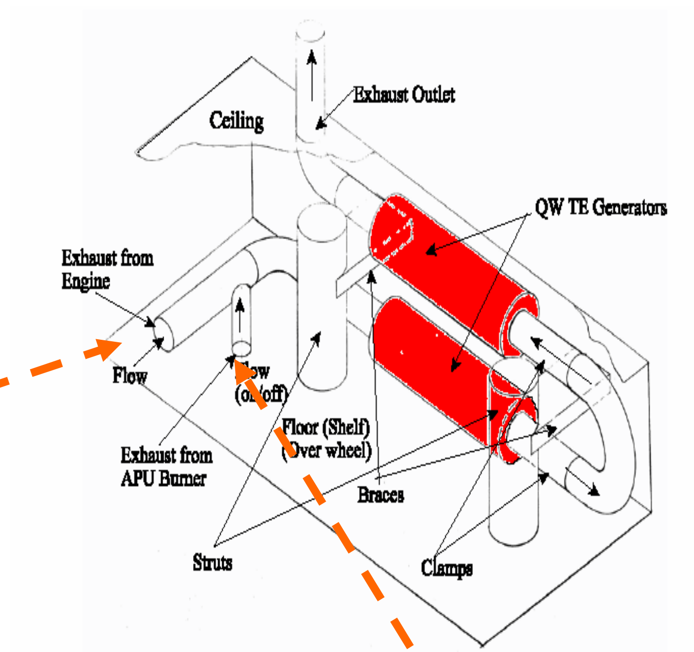


Figure 1. Today's soldier highlighting the lack of climate control and heavy battery weight compared to tomorrow's soldier which will provide a lightweight system of cooling, heating, flexible armor and portable power.

Army Stryker Vehicle

Stryker Vehicle Has Space for Under armor Quantum Well Thermoelectric Generators

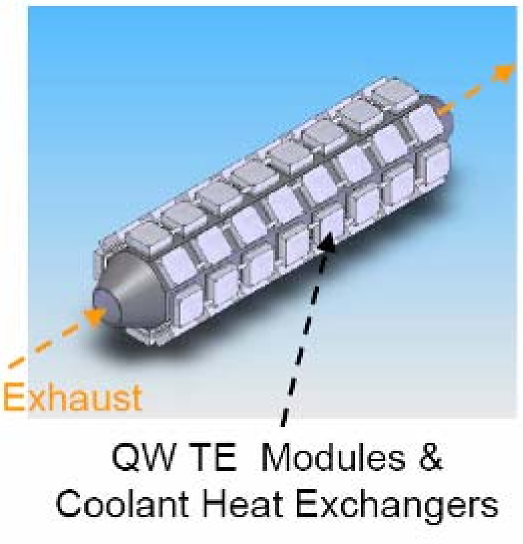
15% Efficiency Predicted with two 5 kW_e QW TE Generators Driven by Vehicle Exhaust



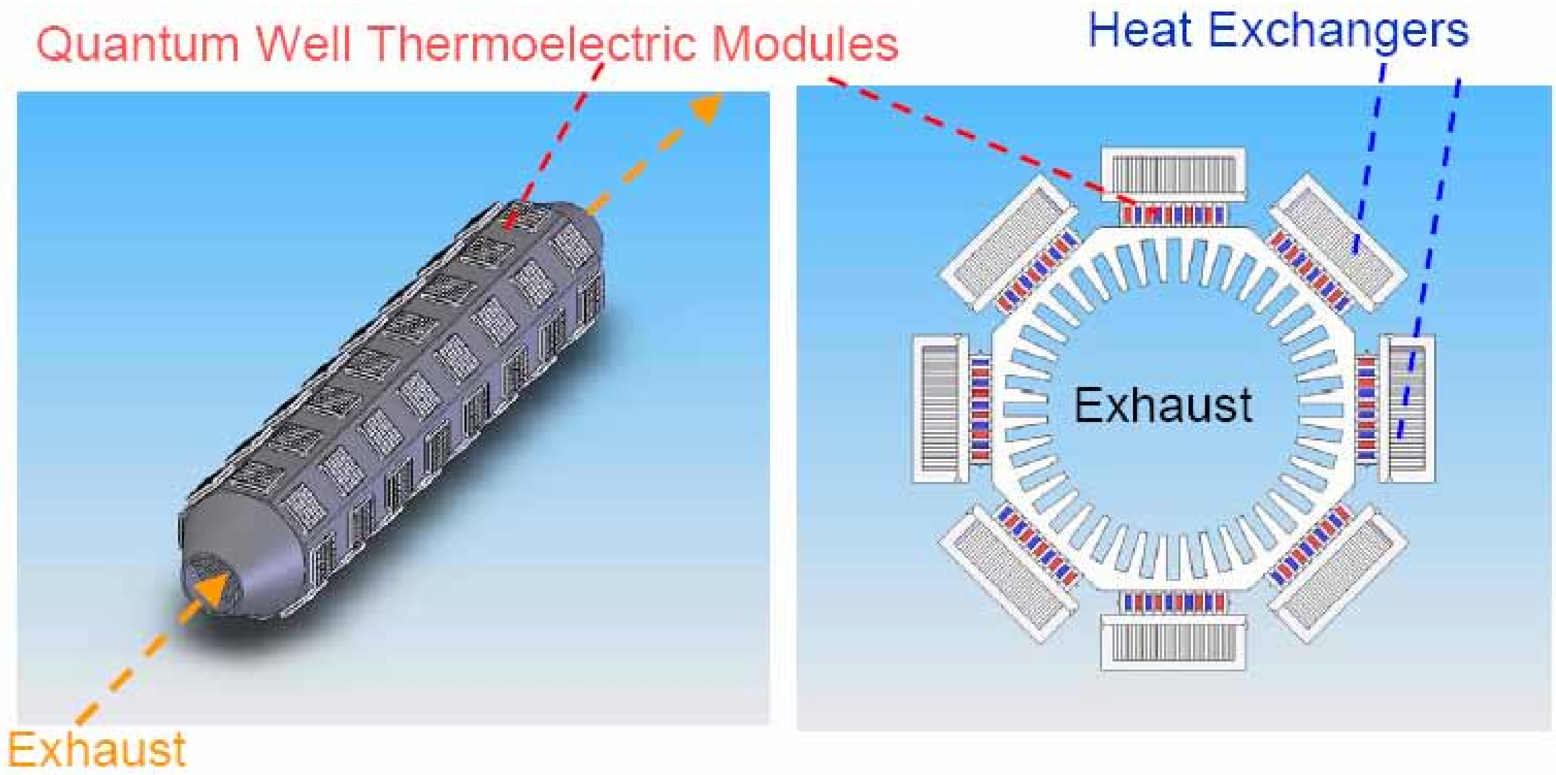
When Parked APU Burner to Provide Power Using Same Thermoelectric Generator

5-Kwe Quantum Well 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, CO_2, or Thermoelectrics

- U.S. probably will stay with R-134a
- Europe apparently going to CO_2
  - R-134a has 1,300 greenhouse gas effect as CO_2
  - 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

Global Climate Warming

- R-134a has 1,300 times greater greenhouse gas impact than CO_2.
- 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 ($1.5\ ft^3$)

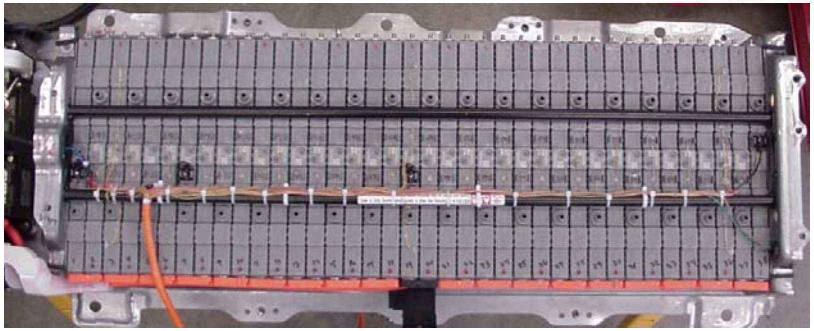
FUTURE ?

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

Battery Temperature Impacts HEV/EV

Temperature affects battery operation

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

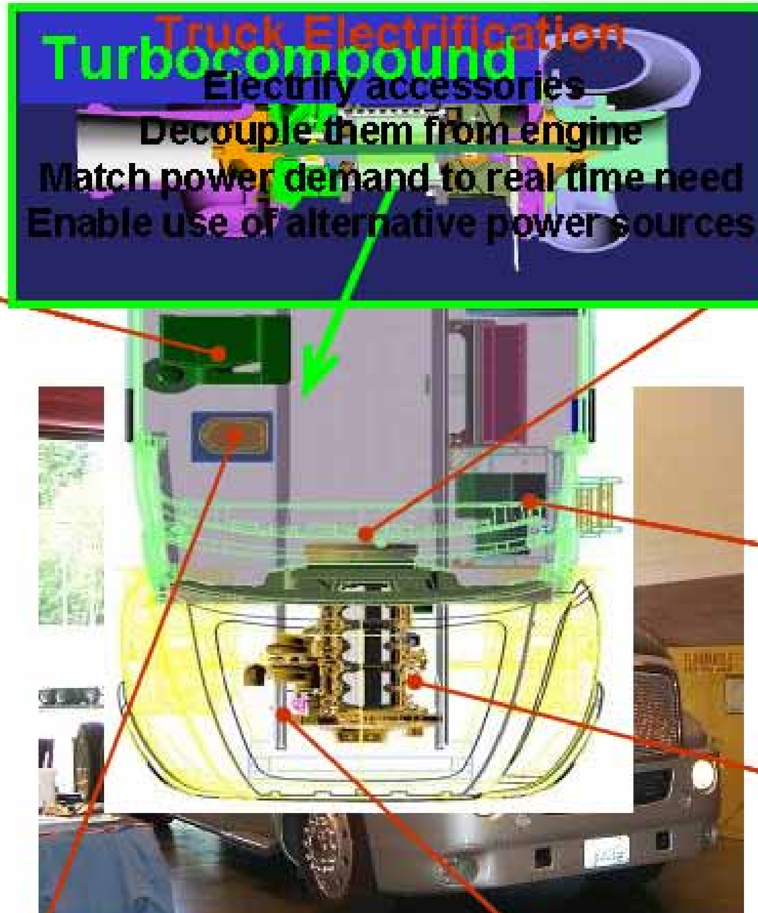


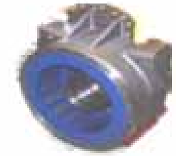
Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost

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





Starter Generator Motor

Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

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

Auxiliary Power Unit

Supplies DC Bus Voltage when engine is not running - fulfills hotel loads without idling main engine overnight

Down Converter

Supplies 12 V Battery from DC Bus

Compressed Air Module

Supplies compressed air for brakes and ride control

Electric Water Pump

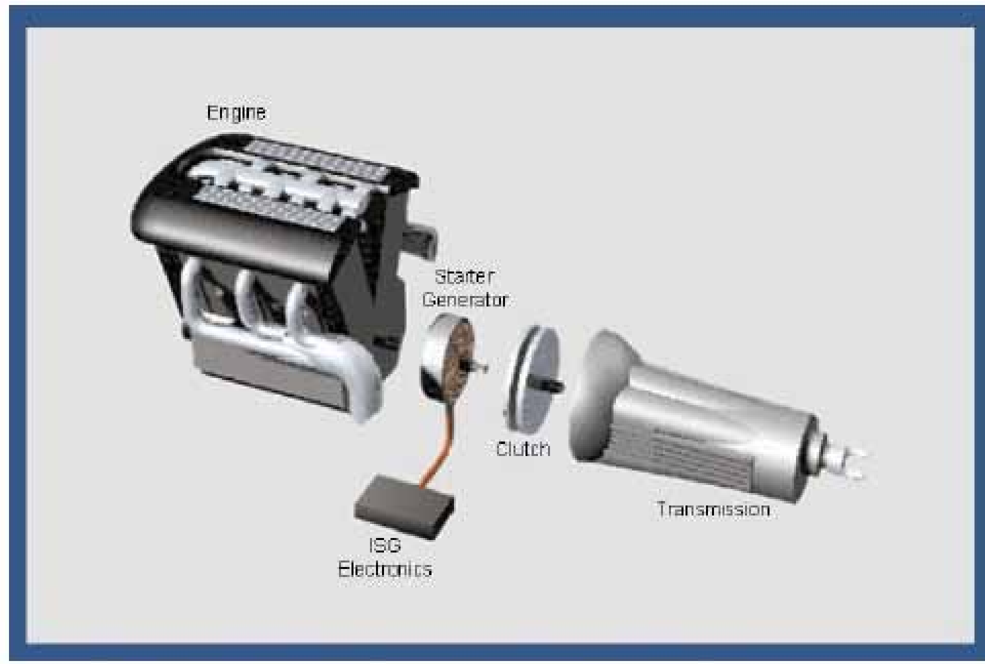
Higher reliability variable speed faster warm-up less white smoke lower cold weather emissions

Electric Oil Pump

Variable speed
Higher efficiency

CAT®

Integrated Motor/Alternator Starter



TE Energy Recovery Benefit

2004 Jaguar XJ

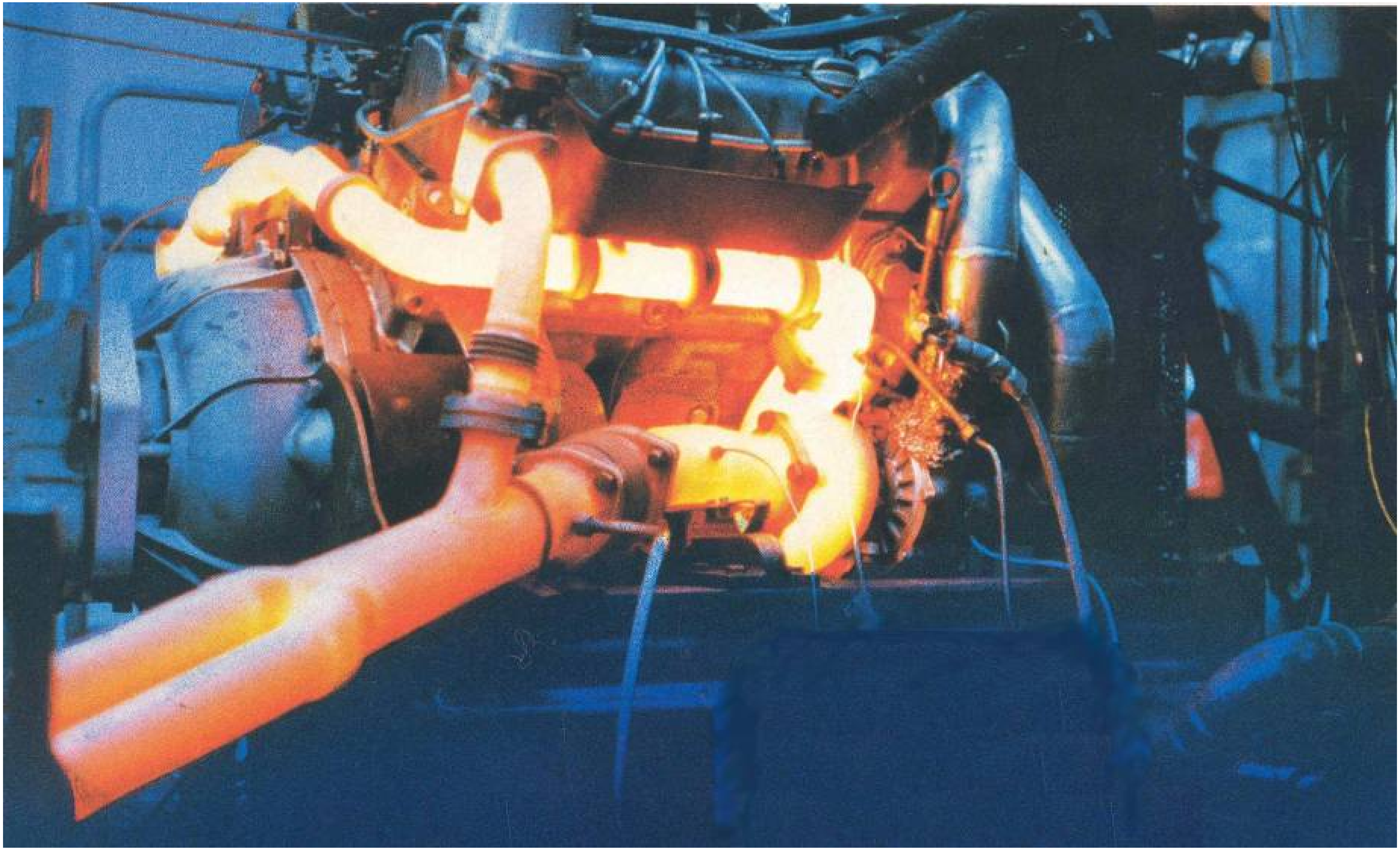
- Use of aluminum results in a 500-lb weight reduction, with consequent fuel saving
- Currently, only luxury cars use aluminum frame and body, due to high cost
- If we can recover sufficient energy from the aluminum manufacturing process, it may become feasible to use it for mass-produced cars, due to 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

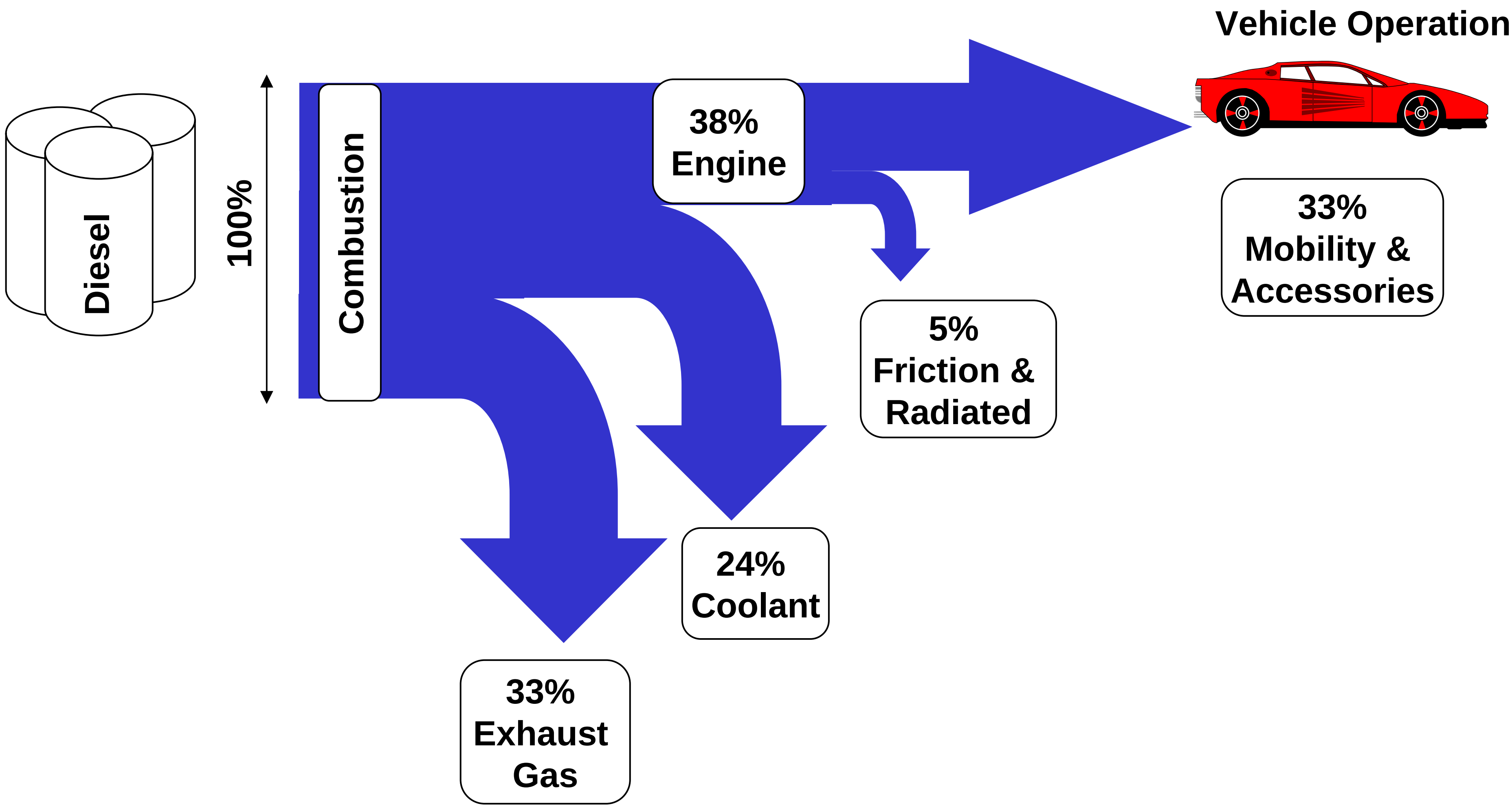
High Efficiency Thermoelectric Teams

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



Diesel Engine (Light Truck or Passenger Vehicle)

Transportation Thermoelectric (TE) & Electric Turbocompound (ETC) Applications Perspective

- **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**

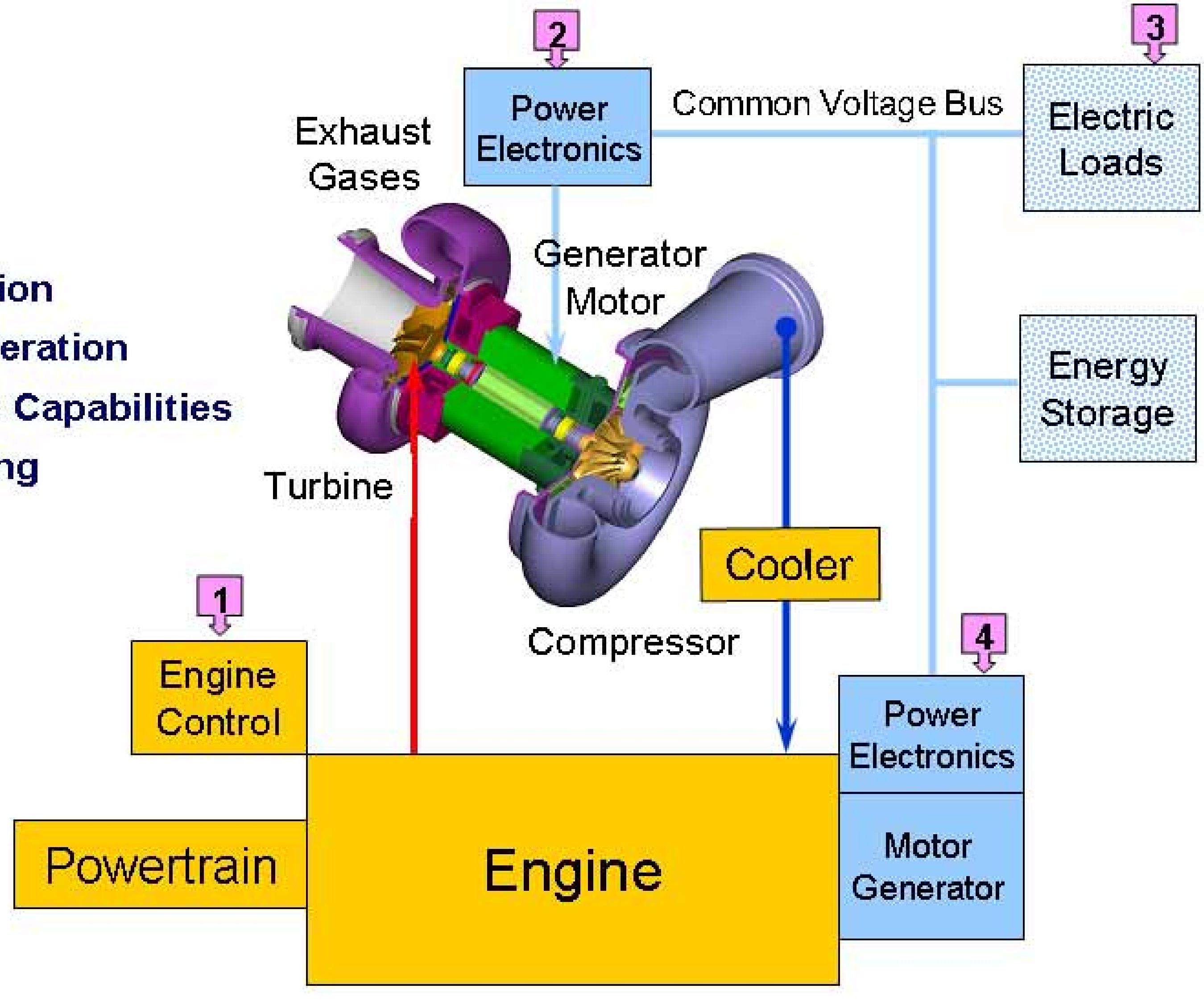
    - Convert waste heat to electricity from components with adequate Delta T
    - Power conditioning
    - Integrate with beltless engine concept

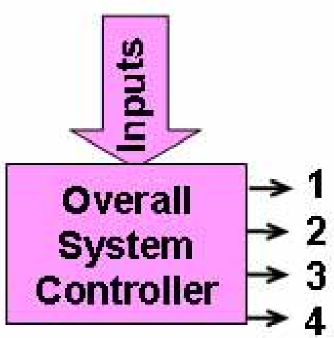
- **Vehicular Peltier Thermoelectric Air Conditioning System Project being considered**
    - Requires a COP of 2.0 to 3.0

Electric Turbocompound

FEATURES

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



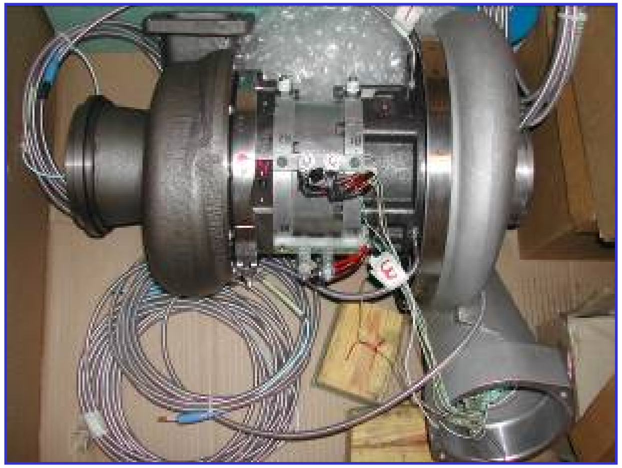


Diesel Engine Waste Heat Recovery Utilizing ETC

Electric Turbocompound (ETC) Technology

Rotor Stator

Windings Rotor Assembly



Electric Turbocompound Turbocharger

Potential for 5 to 10 % Reduction in Fuel Consumption

Thermoelectic ICE Efficiency Road Map

-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 electicity

-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

	ISB Dodge Pickup	ISX Class 8 Truck
Emissions Useful Life	185,000 miles	435,000 miles
Typical Fuel Consumption	16 mpg	5 mpg
Fuel Consumed During the Useful Life	11,500 Gallons	87,000 Gallons
Fuel Consumed with Improved Efficiency	10,500 Gallons	79,100 Gallons
Fuel Saved	1000 Gallons	7900 Gallons
Money Saved ($2.00 gallon)	$2000	$15,800

Program Fuel Savings Potential

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

Greenhouse Gas and Emissions Reduction

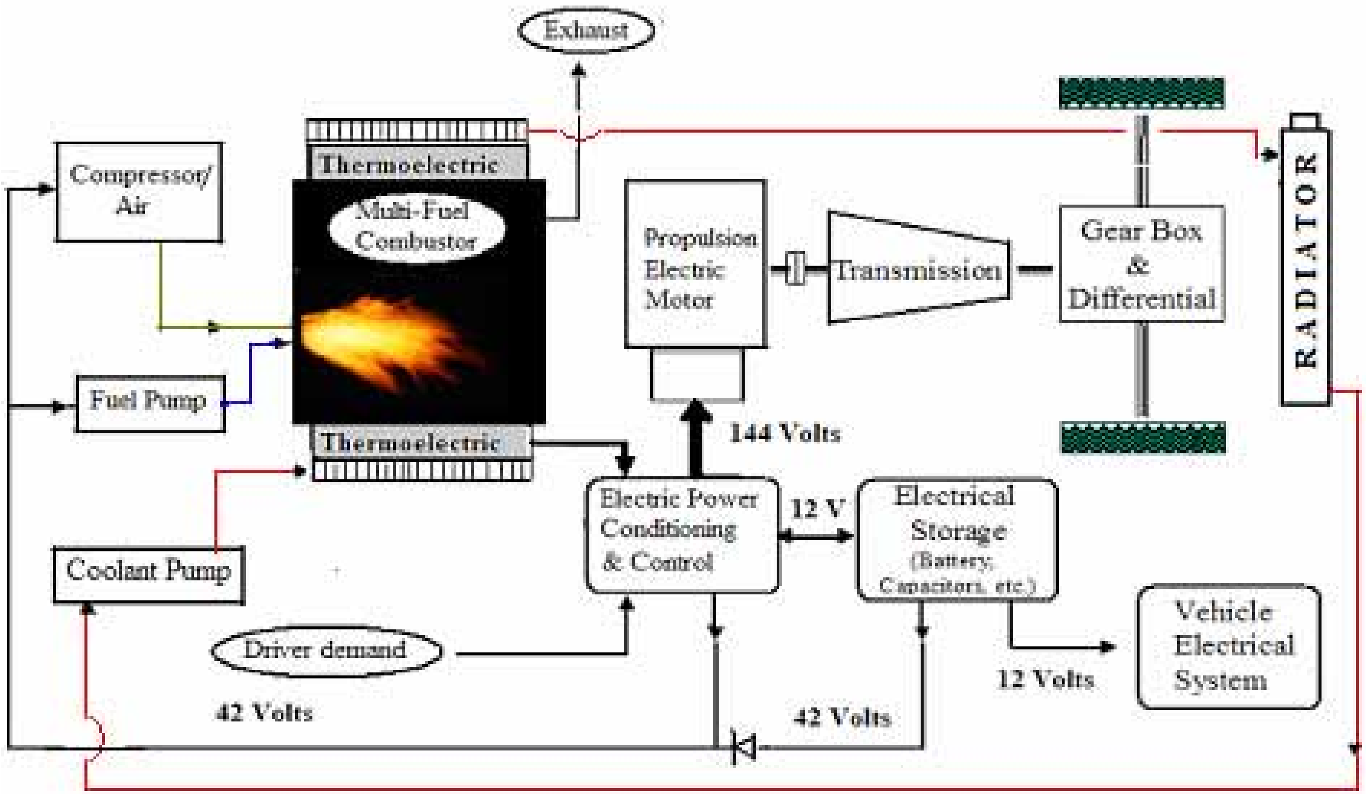
10 % engine brake efficiency means:

- 707,000 fewer tons of CO_2 per year from conventional vehicles (2010)
- 550,000 fewer tons of CO_2 per year from hybrids (2010)
- Regulated emissions will be decreased proportionally to the reduction in fuel consumption

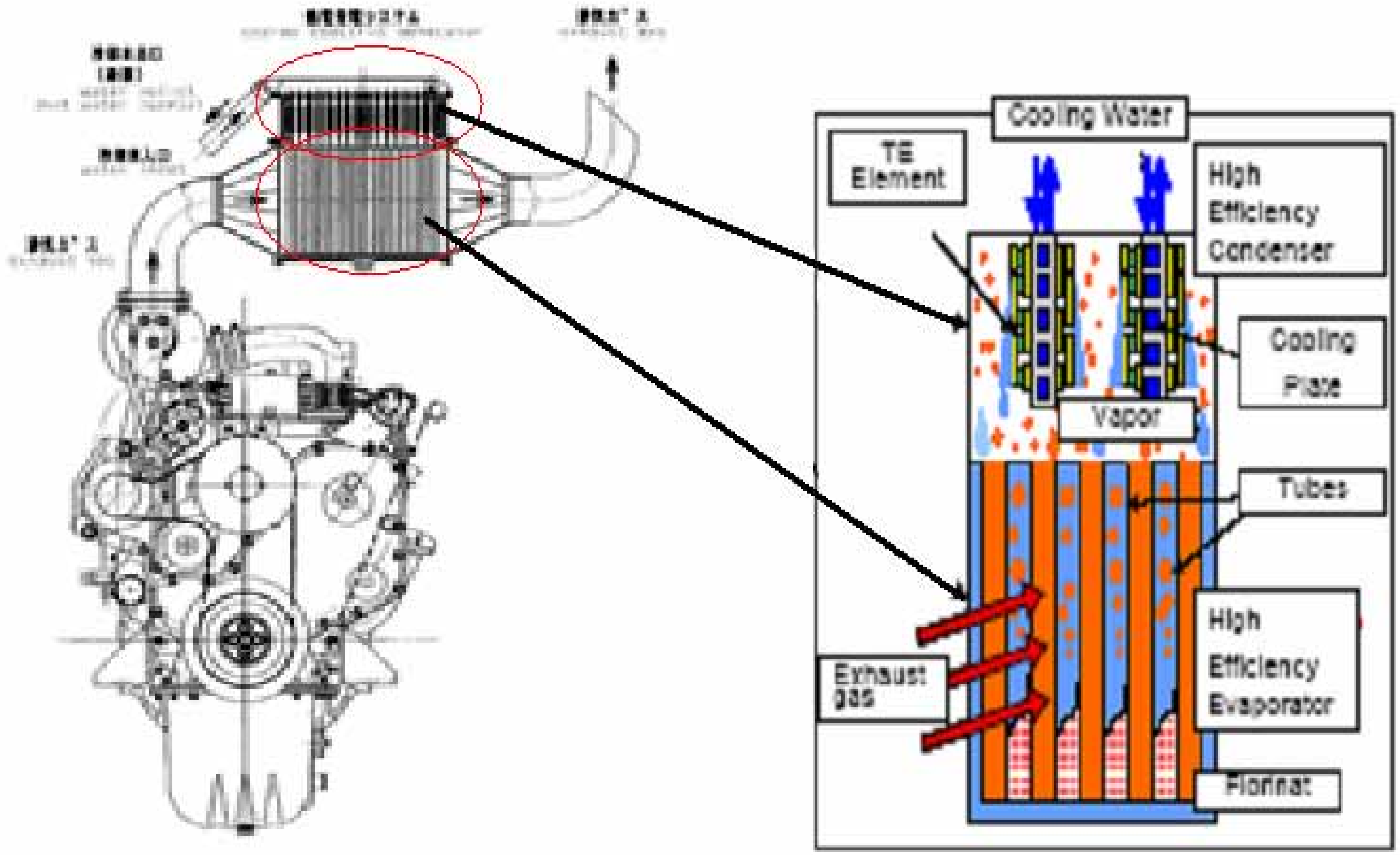
Dr. Jhui Yang - GM

Schematic of TEG Replacement for Vehicular ICE

Generic Concept for a Thermoelectric Automotive Propulsion Drivetrain



Japanese Diesel Engine Co-Generation Using Thermoelectric Generator



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Courtes
on Development for Advanced Thermoelectric Energy Conversion Systems

This Project is funded at 2 times the level of DOE’s 4 Team Thermoelectic Generator 10 % Fuel Economy Improvement Program

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

Follow-on Thermoelectric Program Thermally Managed Diesel (TMD-60)

- 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

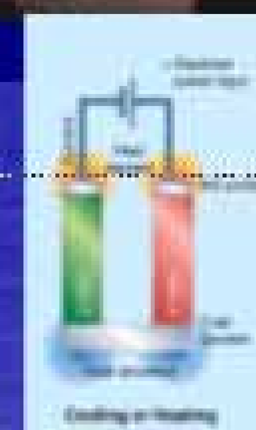
Dr. Mihal E. Gross
Office of Naval Research

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

1990 | 1995 | 2000 | 2005 | 2010

ONR 1994-1997

DARPA/ONR 1996-2002

ONR MURI 1998-2003

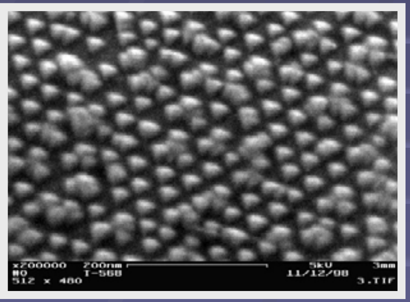
DARPA/ARO Palm Power 2001-2005

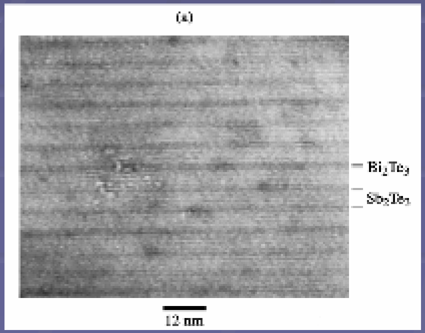
ONR MU
2003-2007

ONR/DARPA DTEC 2003-?

ONR/OSD/ARO SBIRs 2005-2007

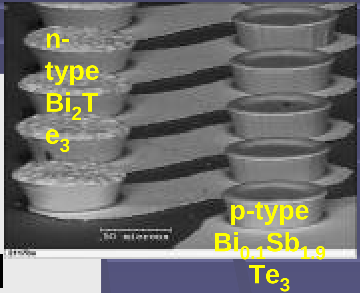
Quantum dots





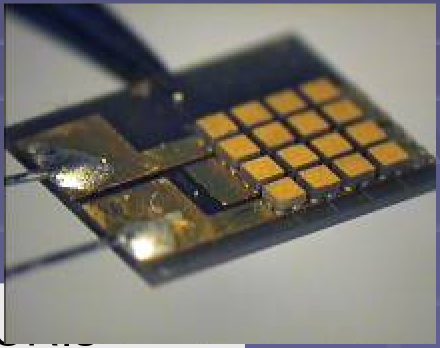
superlattices

Bulk materials



microdevices

nanodevices



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

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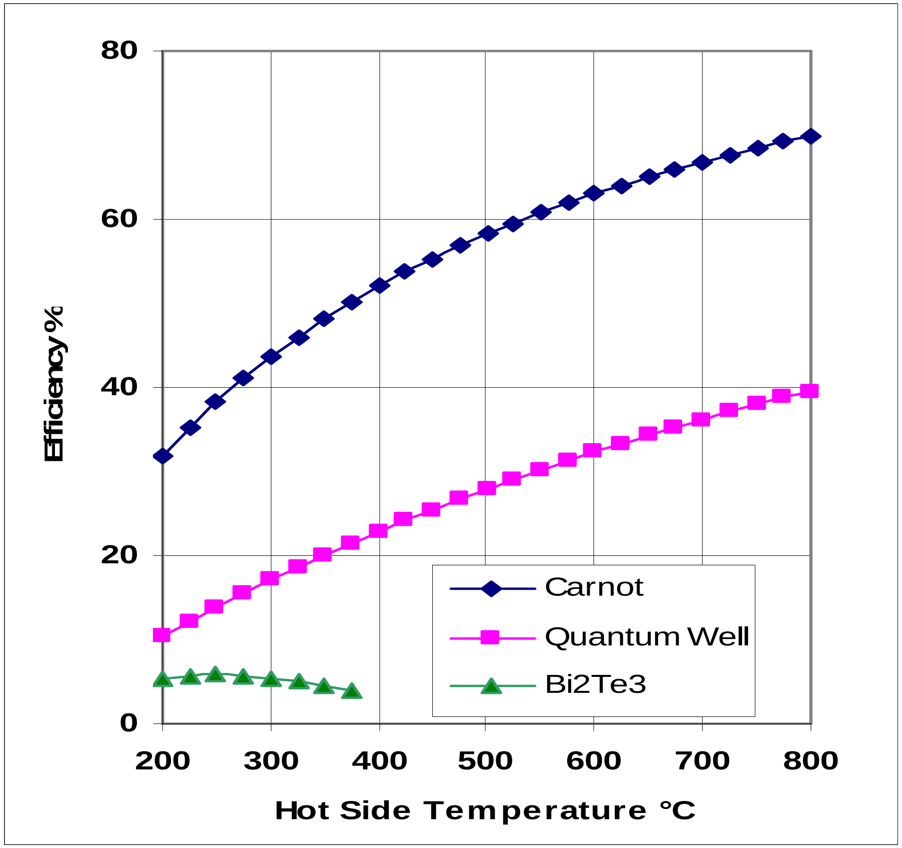
60% Efficient Vehicular Diesel Engine -

Probable, Possible or Fantasy?

Predicted Efficiency >50% Carnot at higher temperatures

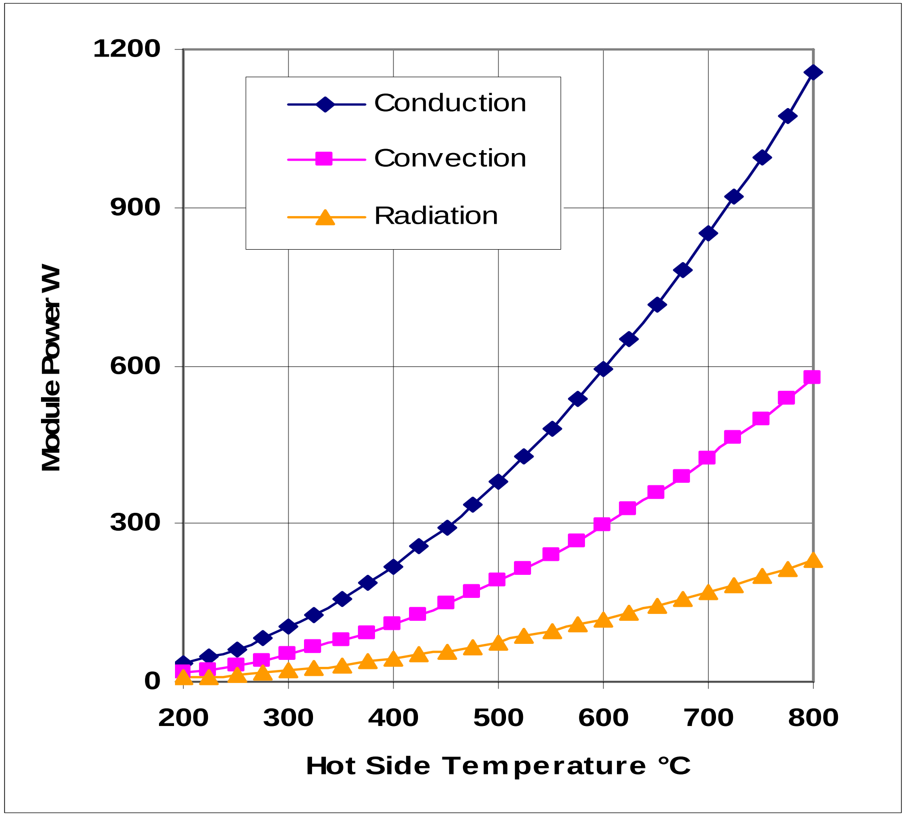
Predicted Efficiency of Quantum Well Thermoelectric Module

- 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.



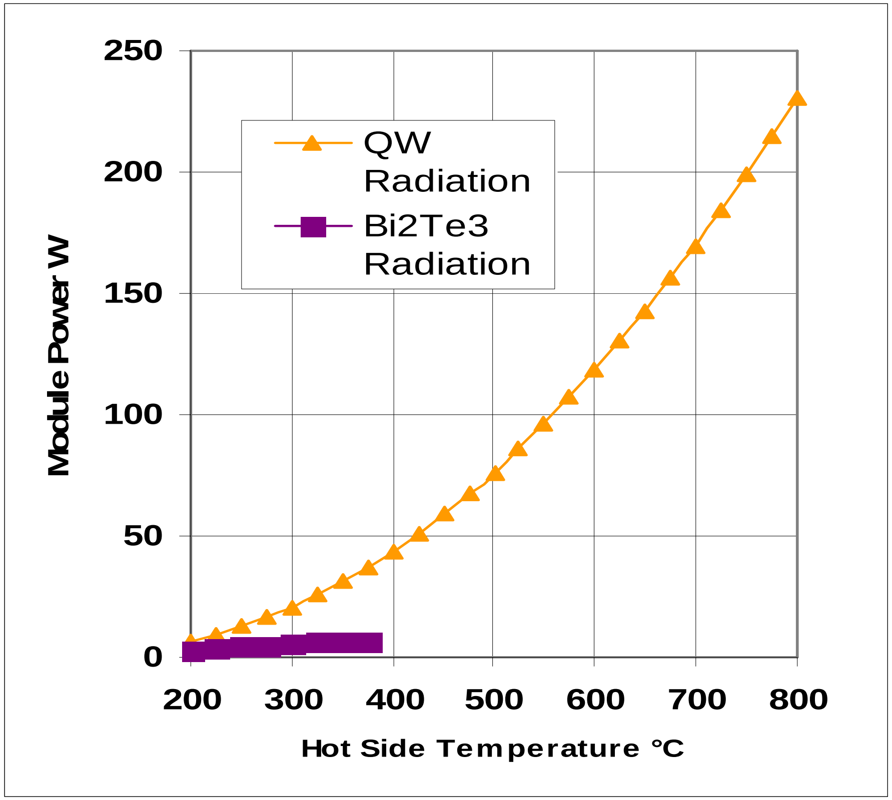
Radiation coupling is practical design for high temperature; conduction or convection higher power

- 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



Quantum Well delivers 5 W_e/cm^2 at 800°C with thermal radiation from source to thermoelectric

- N-Type Si/SiC & P-type B4C/B9C
- Cold side at 50°C
- Represents practical design
  - Radiation coupling simplifies design and reduces thermal contact losses
- Based on measured a & r, and literature k (bulk thermal conductivity)



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 ΔT'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 ^{0}C ΔT
  - 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