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--

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Energy Efficiency
and Renewable Energy
Bringing you a prosperous
is clean, abundant, reliable

hnologies Program

reduce
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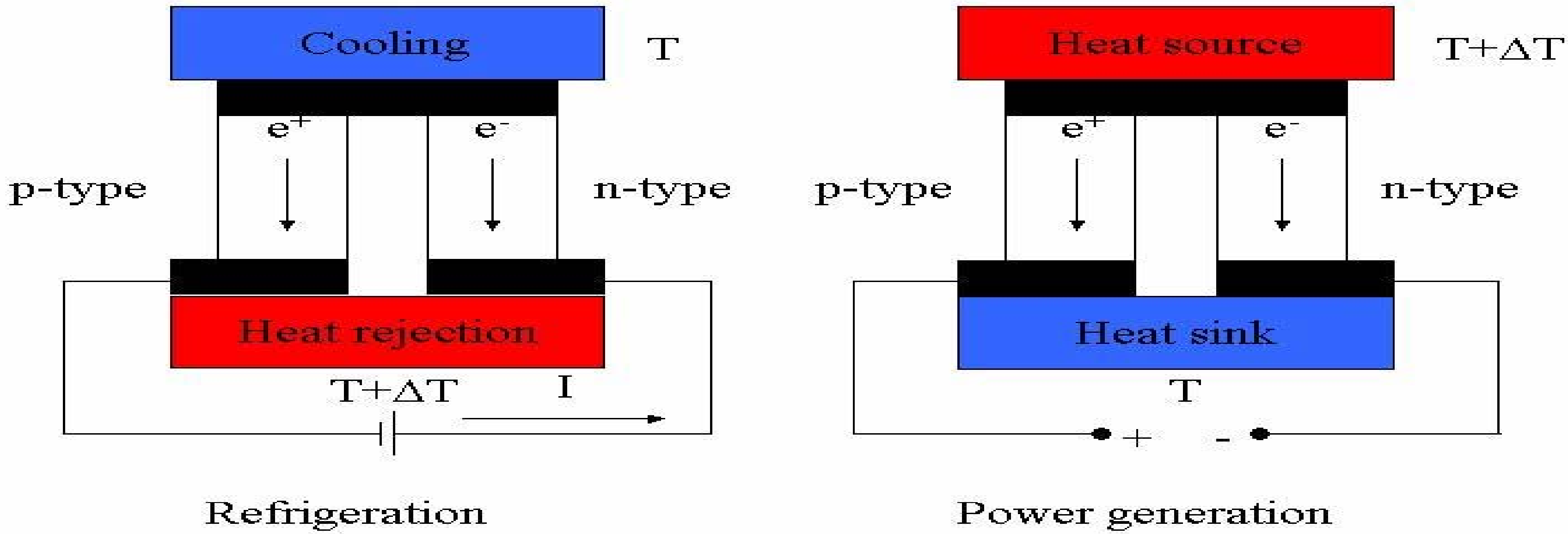
Introduction

- This presentation includes a broad brush review of the thermoelectric technology, near term vehicular applications and potential long term applications

Thermoelectric Modules



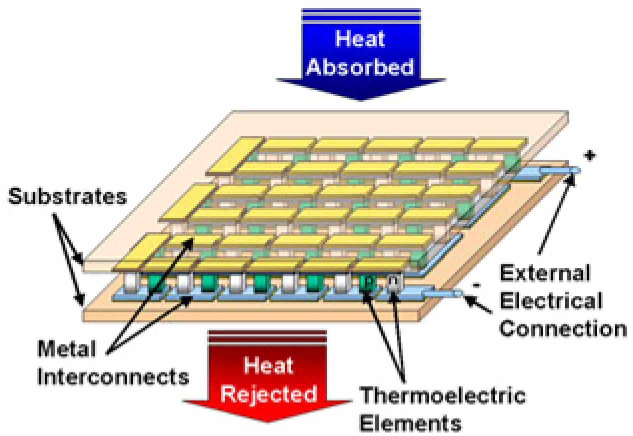


Figure of Merit, ZT

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

where: S = Seebeck coefficient = $(\Delta V/\Delta T)$

V = voltage,

T = absolute temperature,

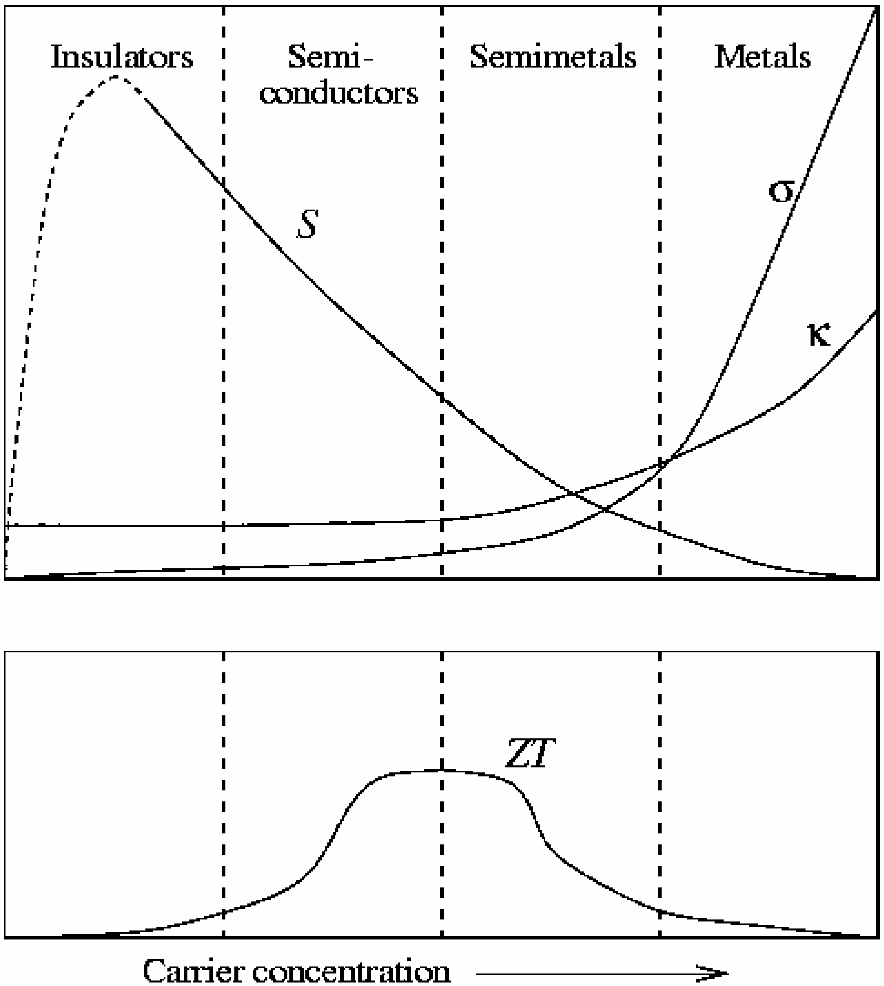
σ = electrical conductivity

κ = thermal conductivity, which consists of:

κ_E = electronic thermal conductivity, and

κ_L = lattice thermal conductivity.

Thermoelectric Properties of Conventional Materials



To increase Z, we want

$$S\uparrow,\quad \sigma\uparrow,\quad \kappa\downarrow$$

but

$$S\uparrow \Leftrightarrow \sigma\downarrow$$

$$\sigma\uparrow \Leftrightarrow \kappa\uparrow$$

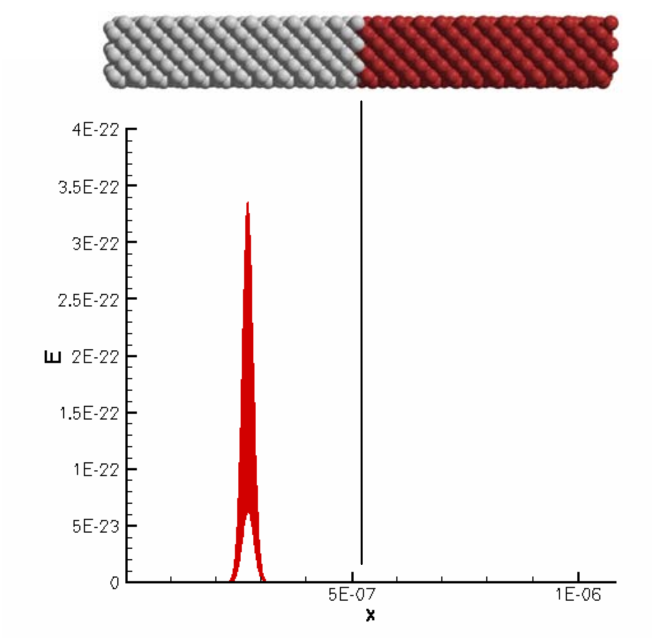
With known conventional solids, a limit to Z is rapidly obtained.

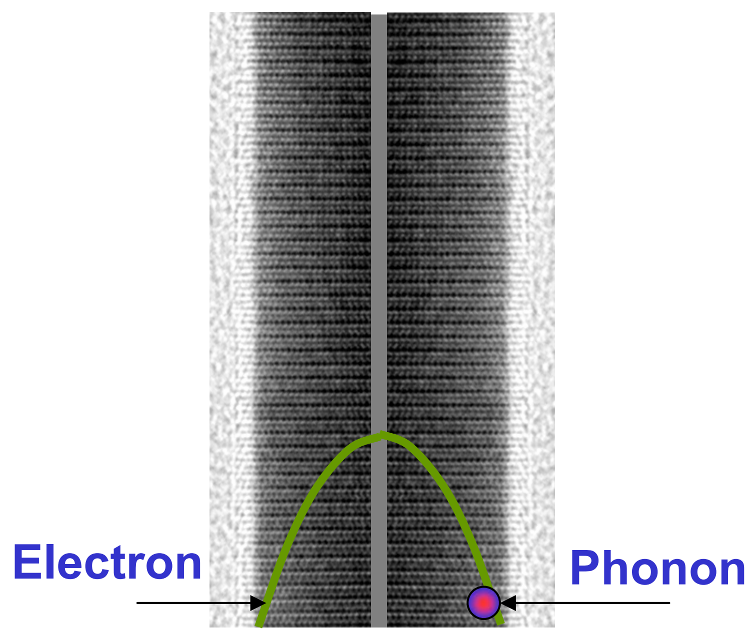
Best alloy: $Bi_{0.5}Sb_{1.5}Te_3$

$ZT \sim 1$ @ 300 K

Interfaces that Scatter Phonons but not Electrons

	Electrons	Phonons
Mean Free Path	Λ=10-100 nm	Λ=10-100 nm
Wavelength	λ=10-50 nm	λ=1 nm

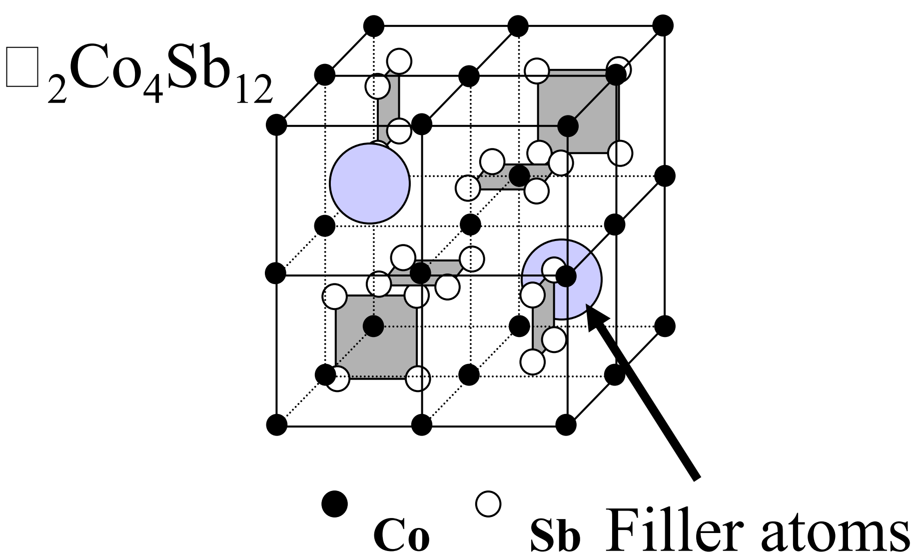


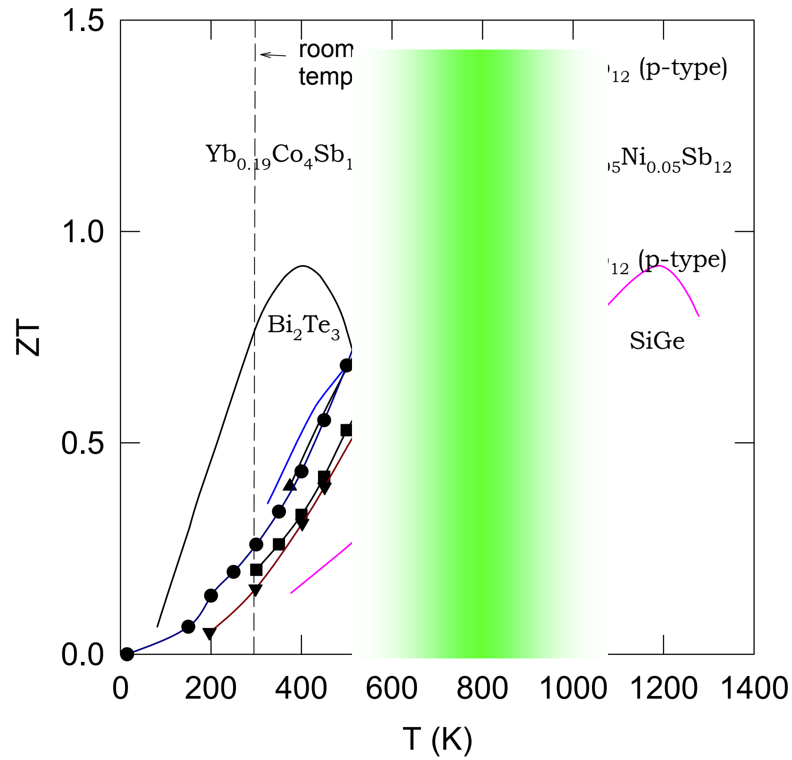


Filled Skutterudites: Phonon-Glass-Electron-Crystal Materials

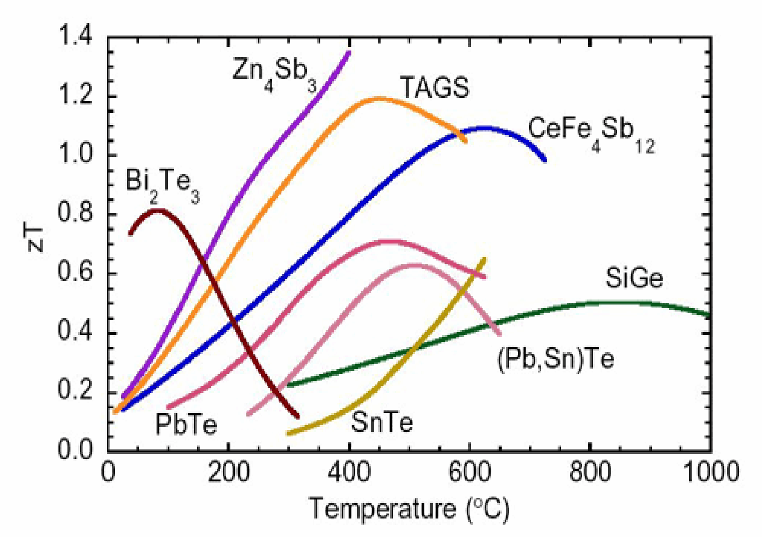
- TE power generation materials for hot-side temperature between 700 K (427^{o}C) and 1000 K (727^{o}C)

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

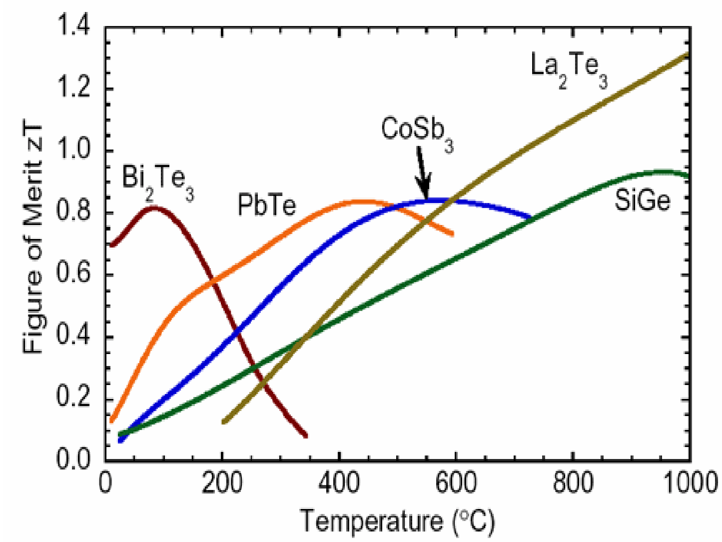




Current TE Materials



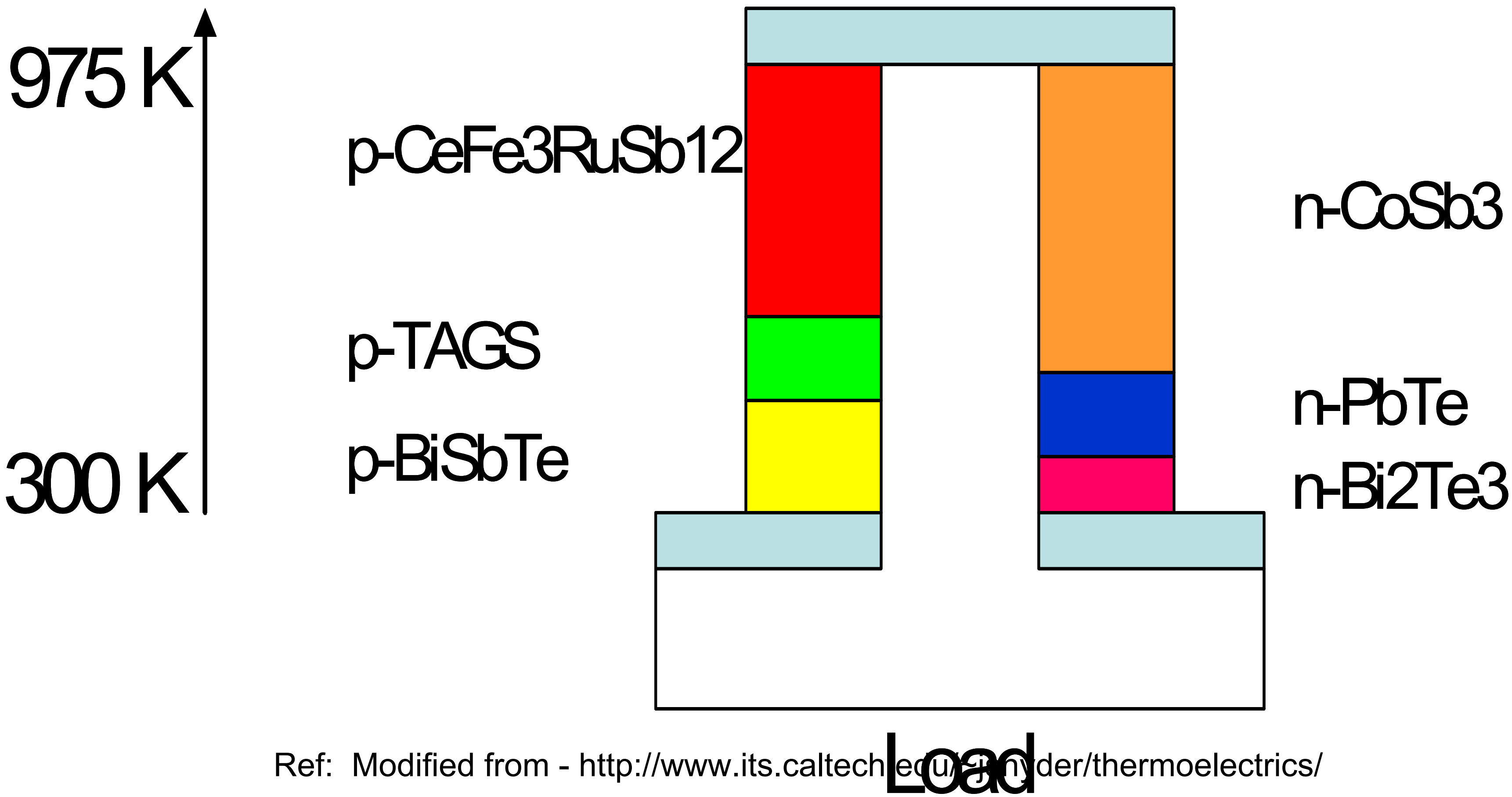
P-type TE material



N-type TE material

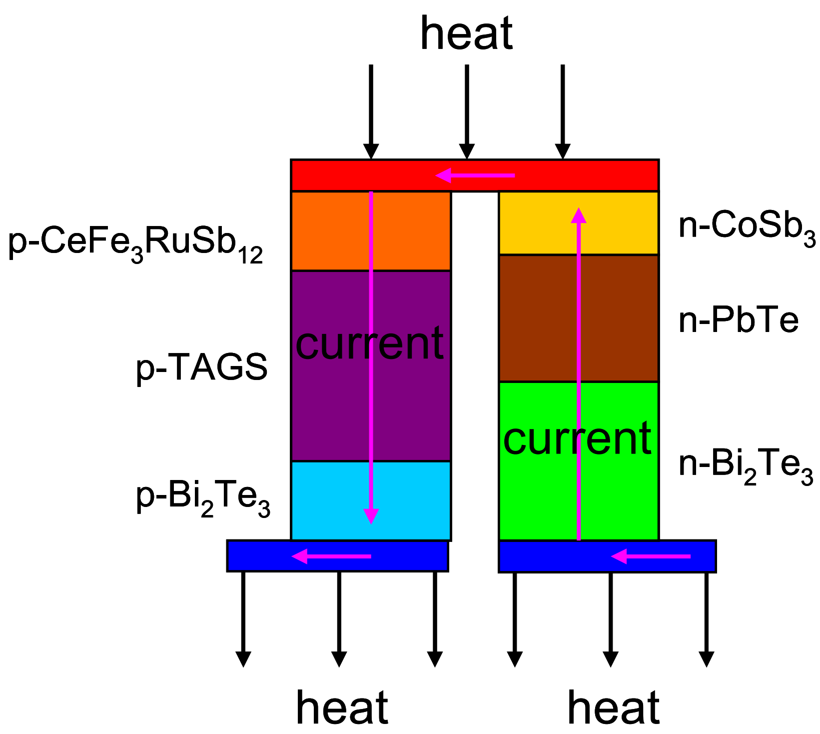
Ref: http://www.its.caltech.edu/~jsnyder/thermoelectrics/

Segmented TE Couple



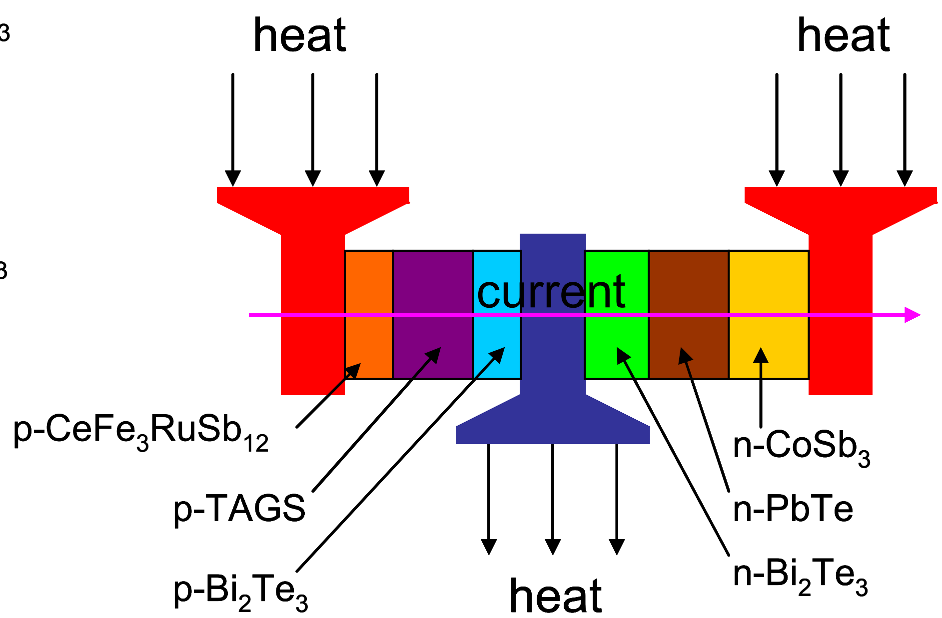
Ref: Modified from - http://www.its.caltech.edu/~jsnyder/thermoelectrics/

TE Couple Configuration Alternatives with Segmented Elements



- Traditional configuration

- Alternative "Y" configuration

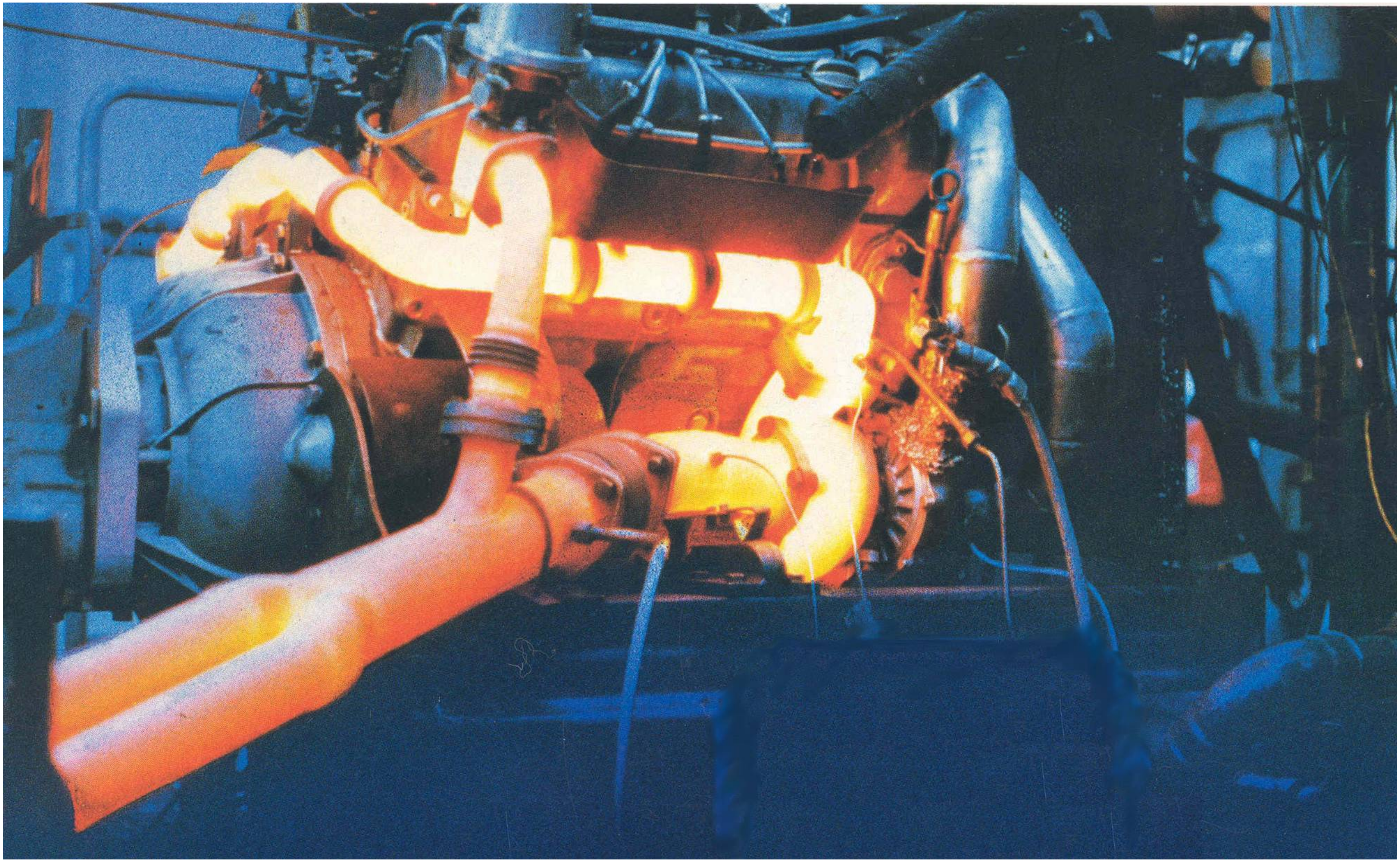


Potential Location for the Thermoelectric Generator

Thermoelectric Markets

- 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

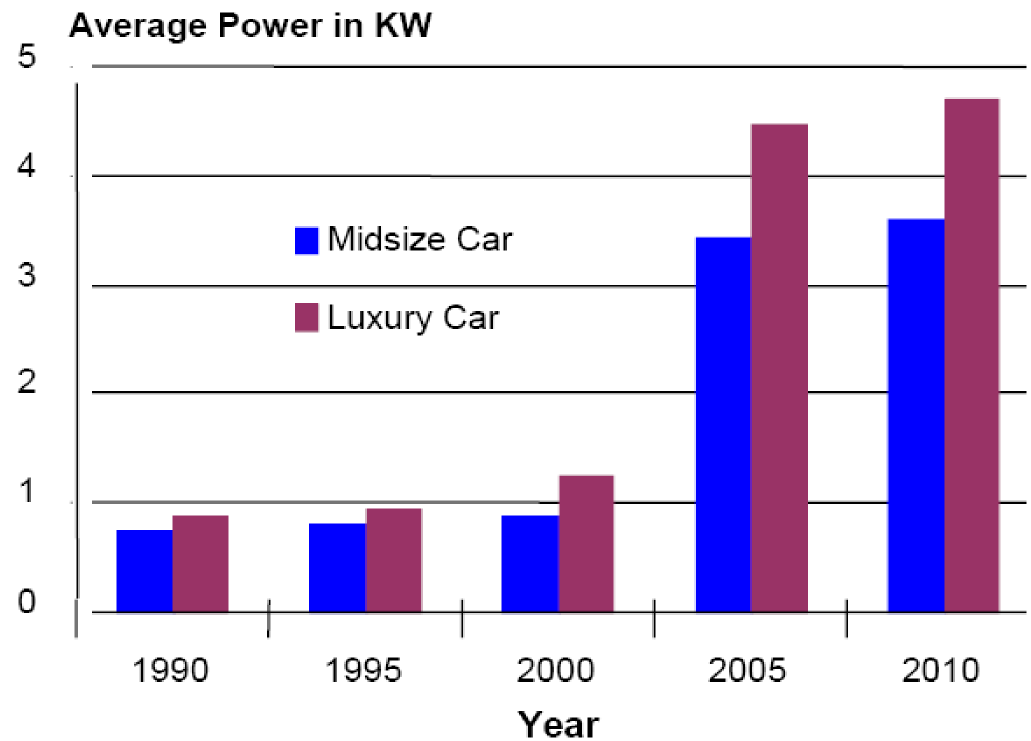
Available Energy in Engine Exhaust



Increasing Electrical Power Requirements for Vehicles

- 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

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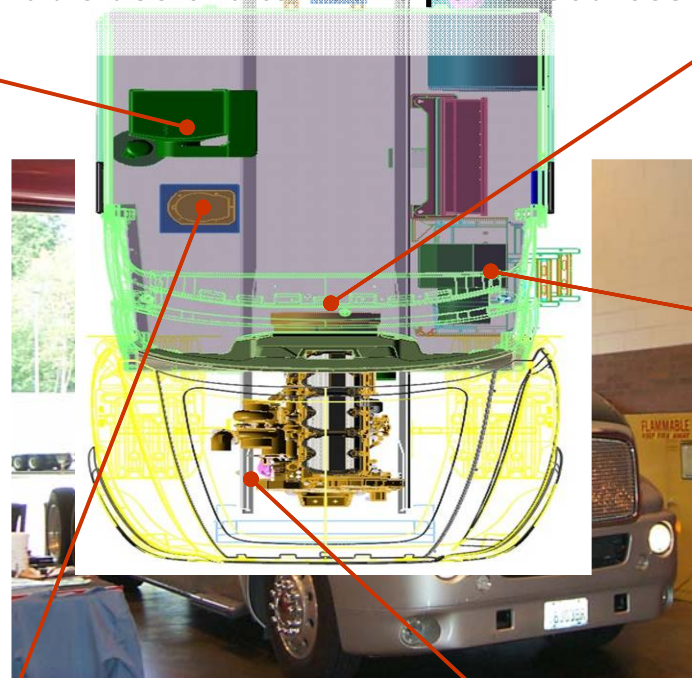
Beltless or More Electric Engine

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

Starter Generator Motor

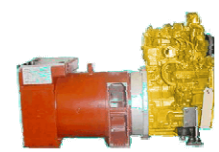
Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

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

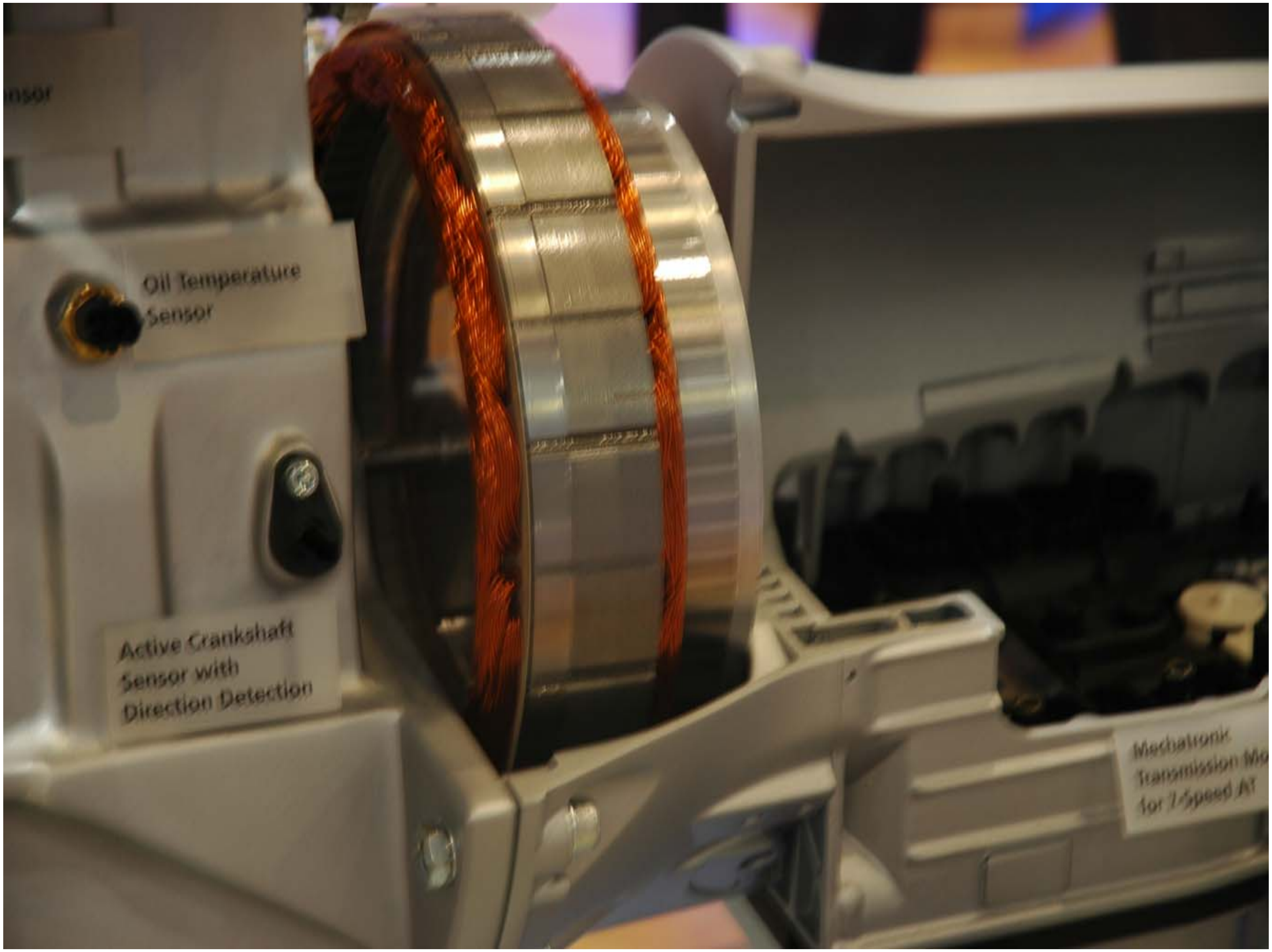
Electric Water Pump

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

Electric Oil Pump

Variable speed
Higher efficiency

Integrated Alternator/Motor/Starter/Damper



Overall Goals and Objectives

- 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

Thermoelectric Generator Teams

- 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

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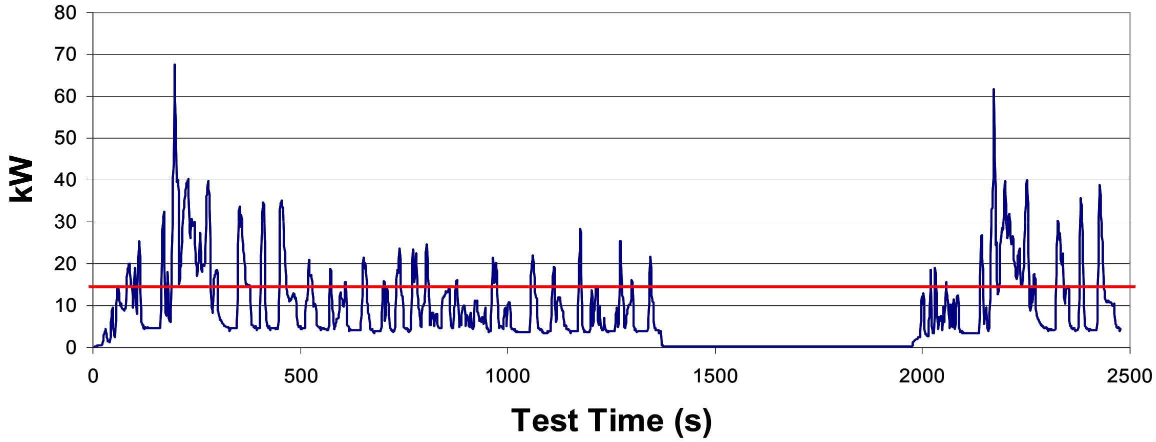
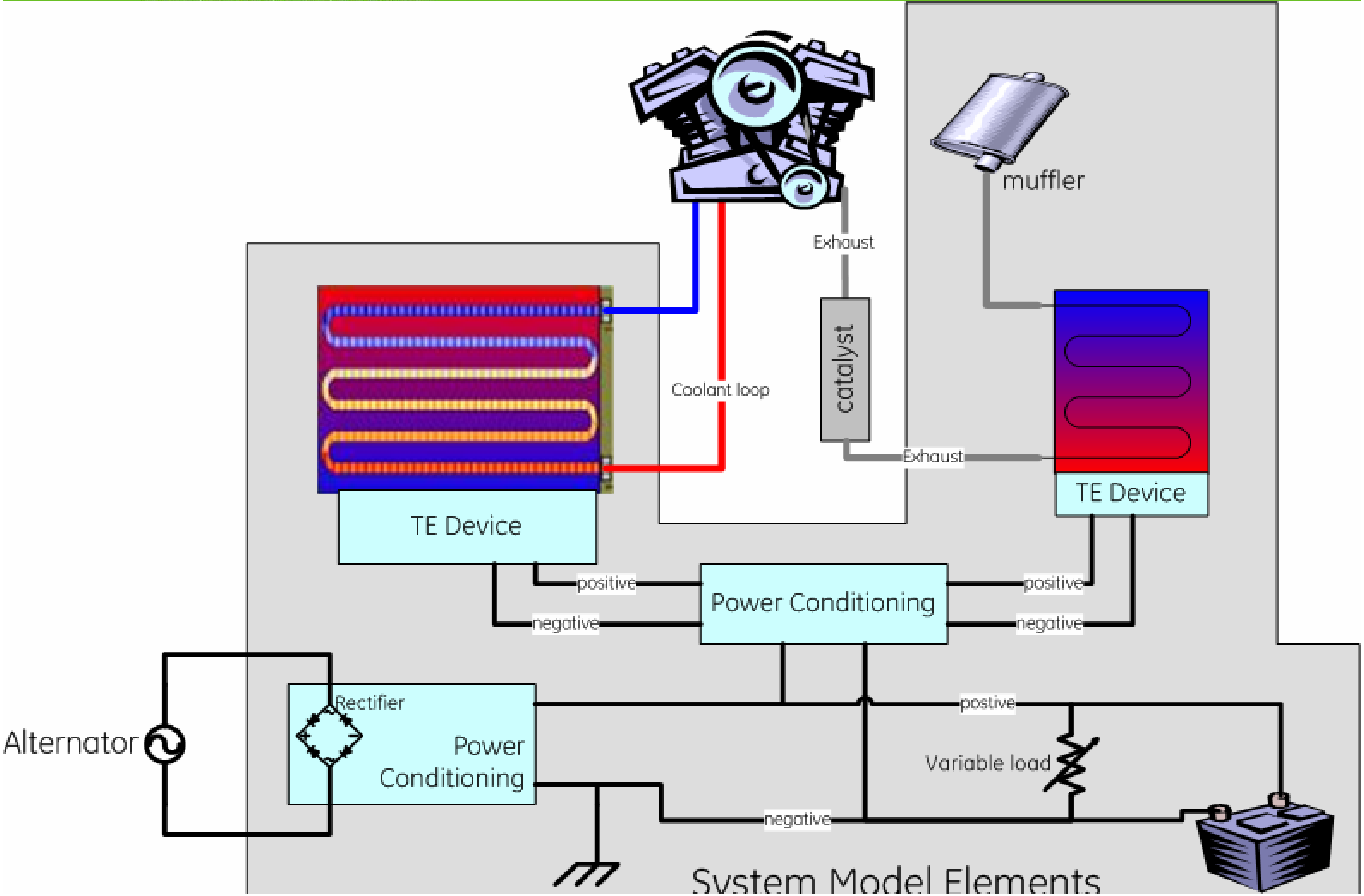
GM Thermoelectric Generator Vehicle Selection – Full Size SUV

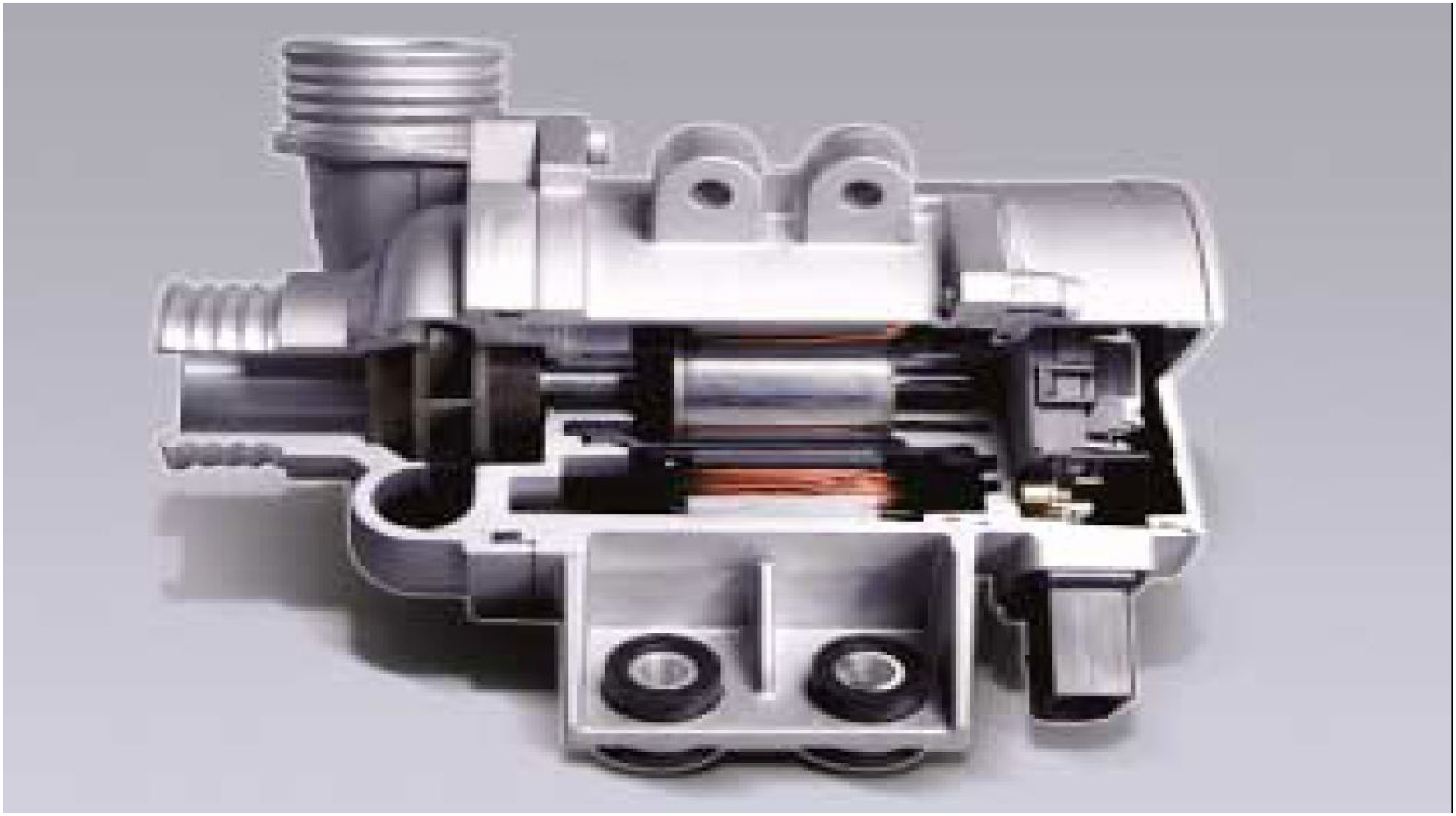
- plenty of space for accommodating TE subsystem
- a lot of waste heat: exhaust and radiator
- current muffler: 610 x 310 x235 (mm)
- available envelope: 840 x 360 x 255 (mm)



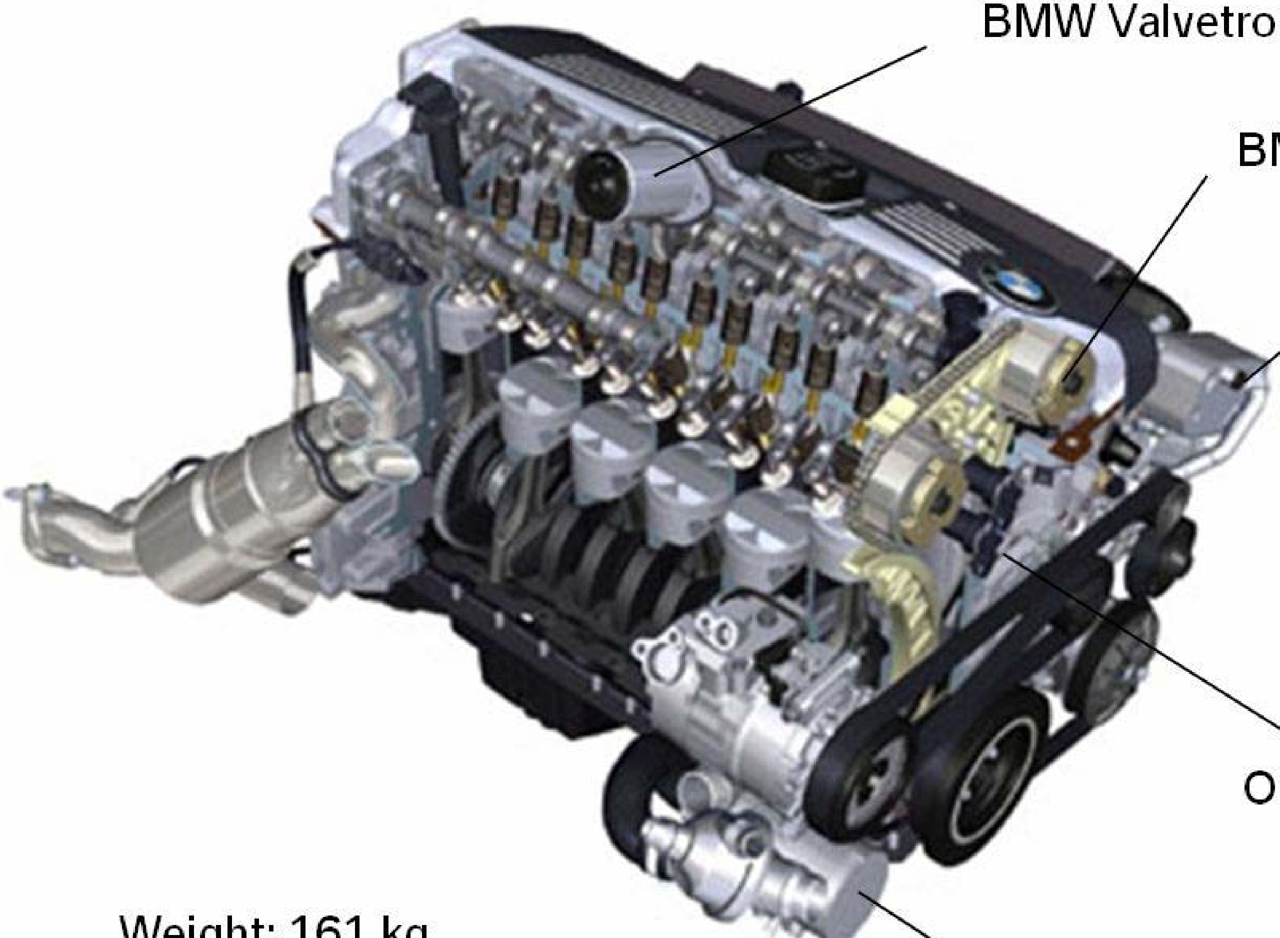
GM's Thermoelectric Generators



BMW's Electric Water Pump Improves Fuel Economy 1.5 to 2.0 %

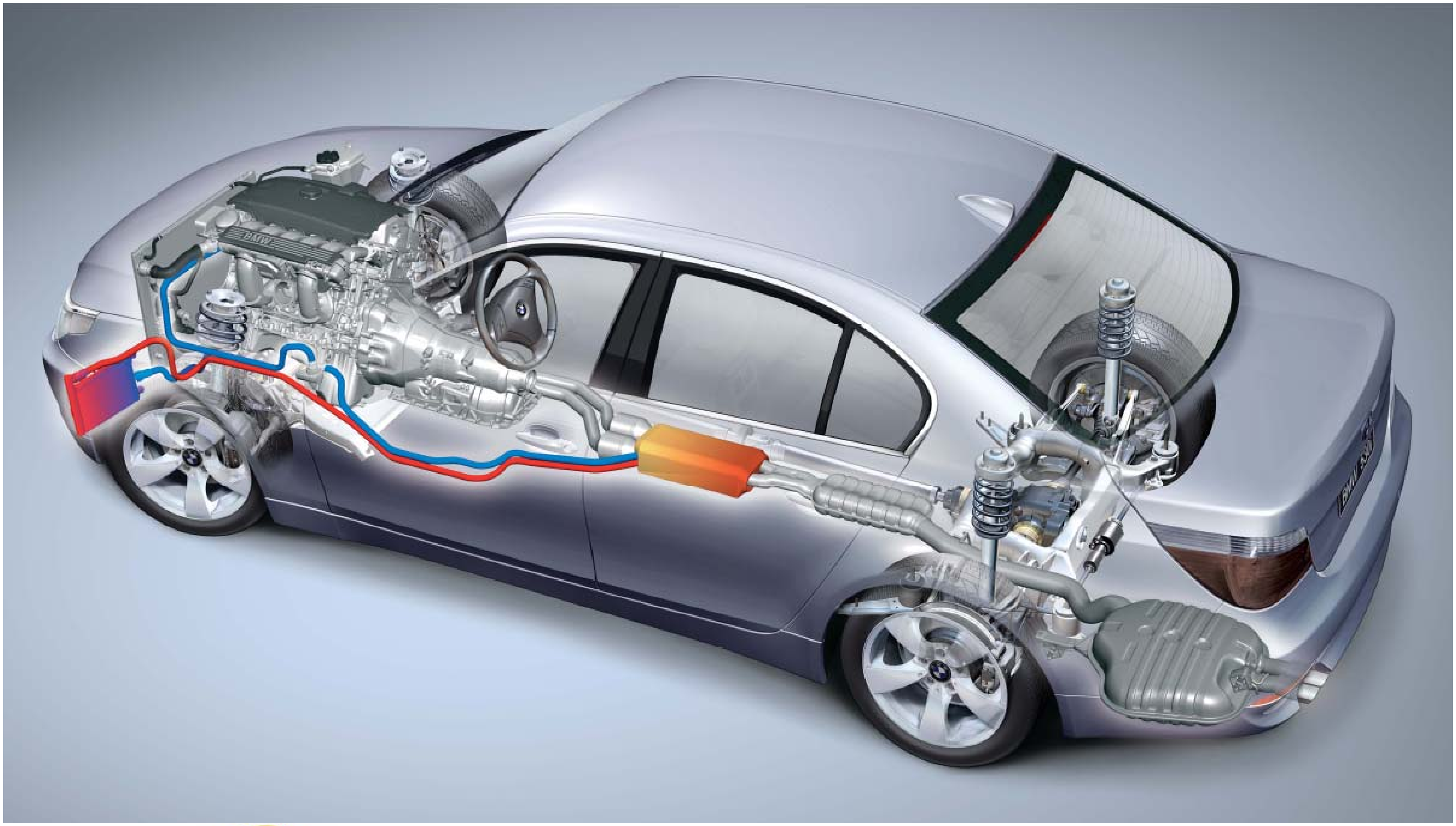


BWM Series 5, 3 L Gasoline Engine with Electric Water pump



Weight: 161 kg
Power: 190 kW
Max engine speed: 7000 rpm

BMW Series 5 , Model Year 2010, 3.0 Liter Gasoline Engine w/ Thermoelectric Generator



FreedomCAR & Fuel Partnership
Visteon®
BSST innovative solutions in temperature control

ORNL Empirical Data

- Rule of Thumb for Cars
- 10 percent Reduction in Vehicle Weight Results in a 5 to 7 Percent Improvement in Fuel economy

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.

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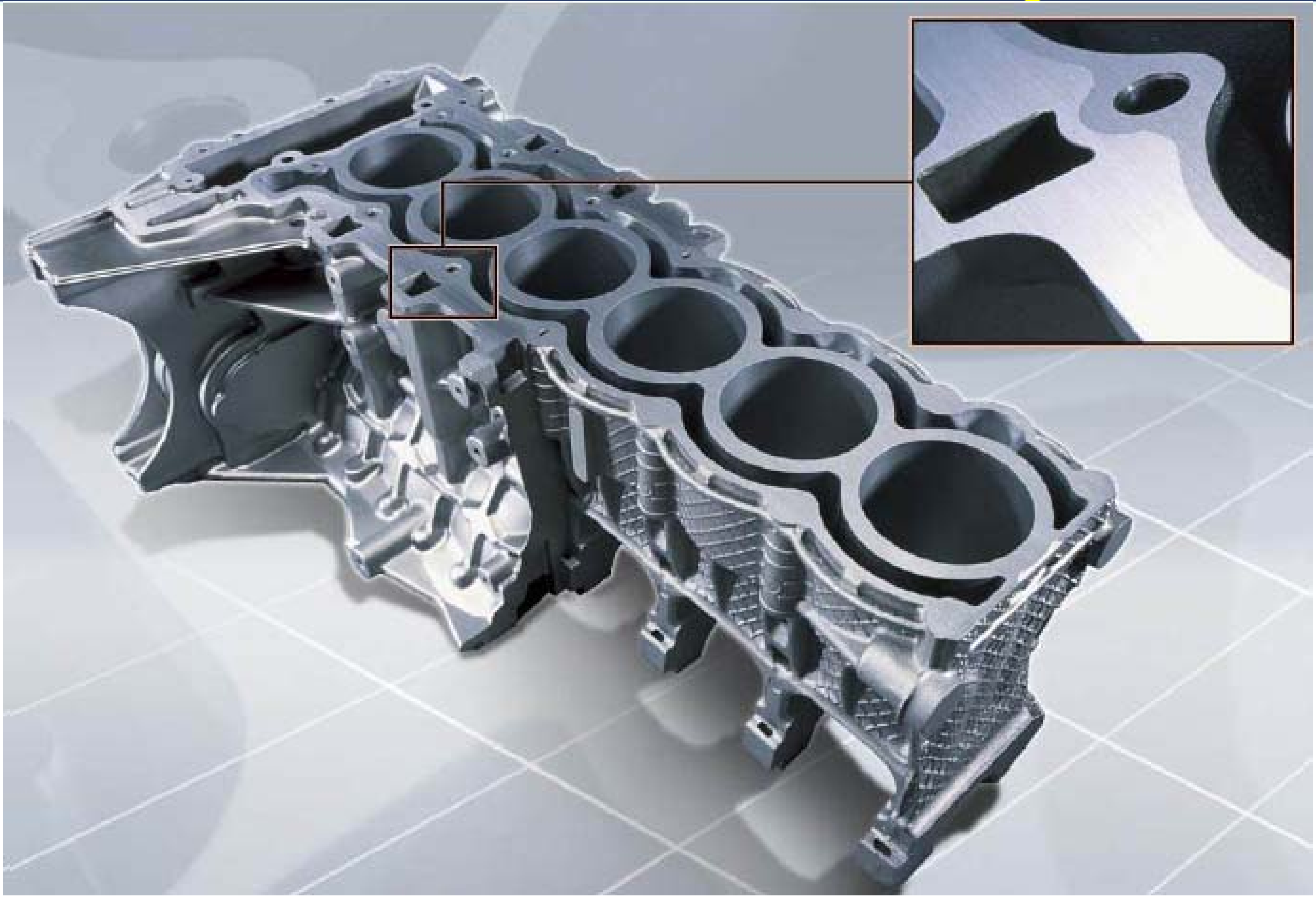
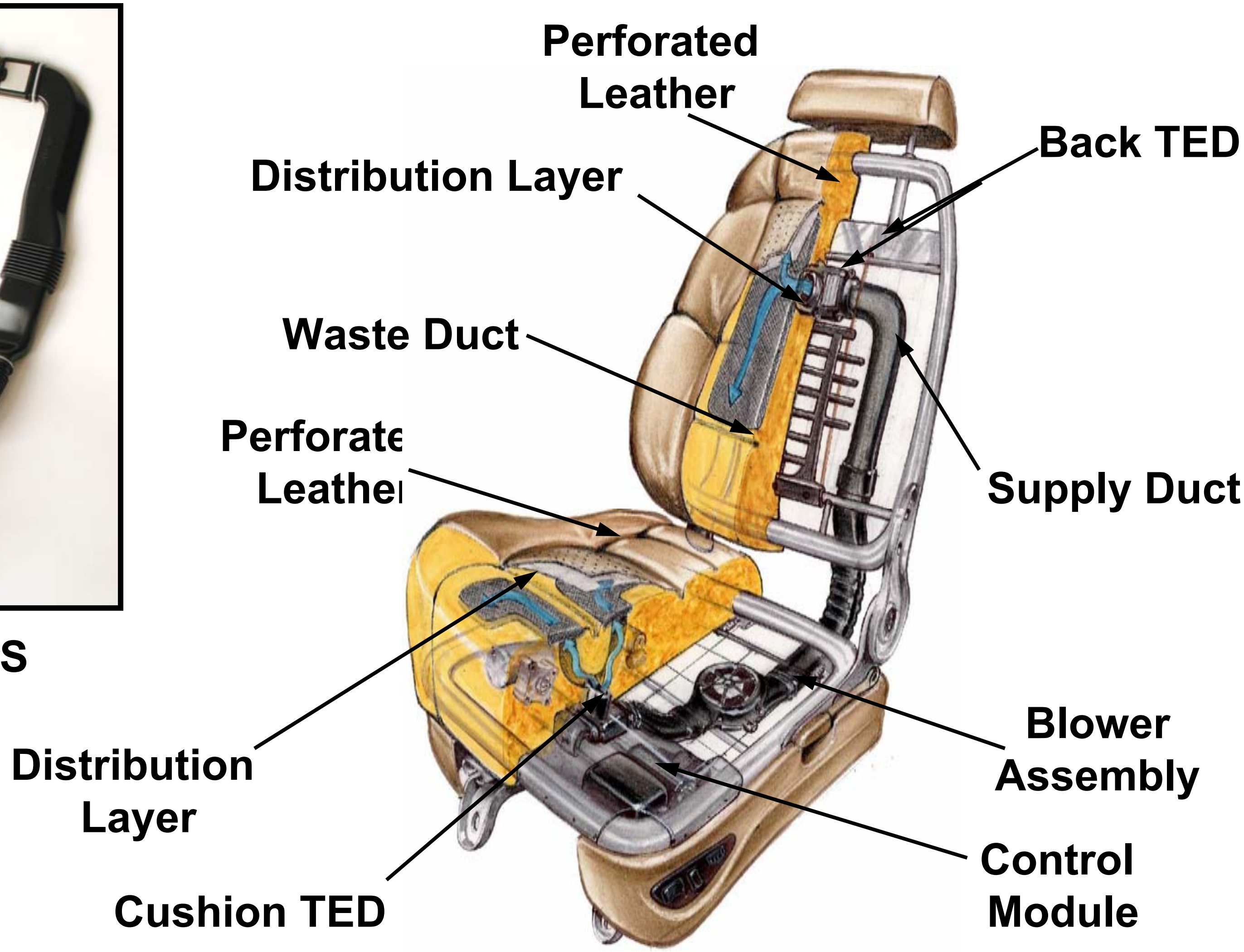
BMW's Magnesium Engine Block



Climate Control Seat™ (CCS) System Vehicle Application

Production CCS Assembly



Thermoelectric Applications by UTRC and BSST

today…

POWER SOURCE

- Batteries

CLIMATE CONTROL

- None

Enabled by Thermoelectrics (TE)

…tomorrow

POWER SOURCE

- Logistic fuel based system

CLIMATE CONTROL

- Thermoelectric based cooling/heating
- On-demand

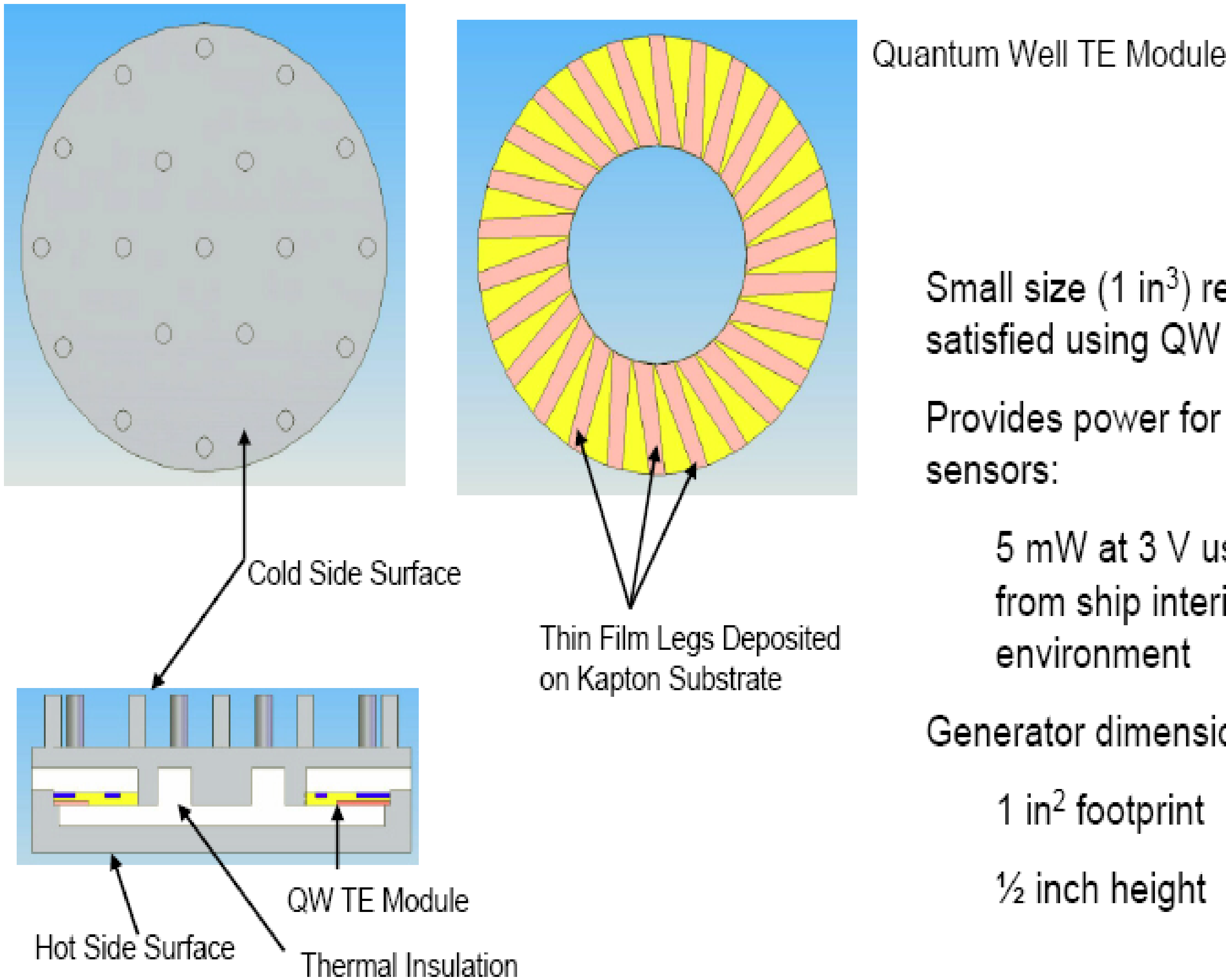
IMPACT

- >30% weight savings over existing systems

Assumptions
12 hour mission @ 110°F ambient temperature

DARPA TTO Program Manager: Ed van Reuth

Power-Harvesting QWTE Power Supply for Shipboard Wireless Sensors



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

Generator dimensions:

- 1 in^2 footprint
- ½ inch height

Hi-Z TECHNOLOGY, INC.

Thermoelectric Wristwatch

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)
- 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)

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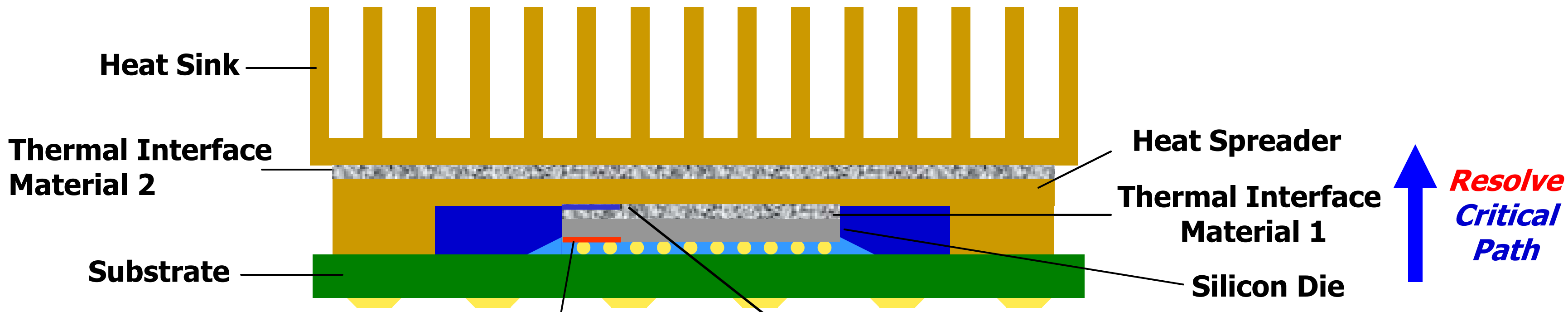
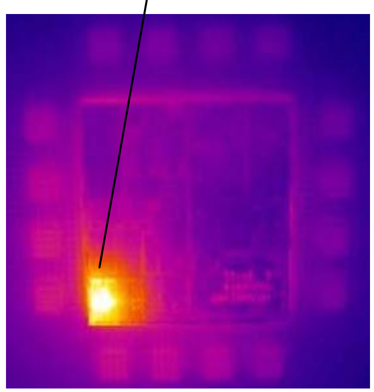
Embedded Semiconductor Cooling Removes Heat From Die to Heat Sink

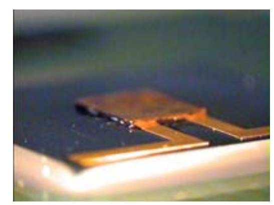


Hotspots effect

- Reliability
- Performance
- Package cost



Nextreme's solution



100 μm thickness

Embedded Thermoelectric in IC

- Active micro-cooling of hotspot
- Reduces total power cooled
- Simplifies package

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USS DOLPHIN AGSS 555 Thermoelectric Air Conditioning Test for Silent Running

Thermoelectric Fruit Storage

Thermoelectrics Replacing Gas Compression Refrigeration ?

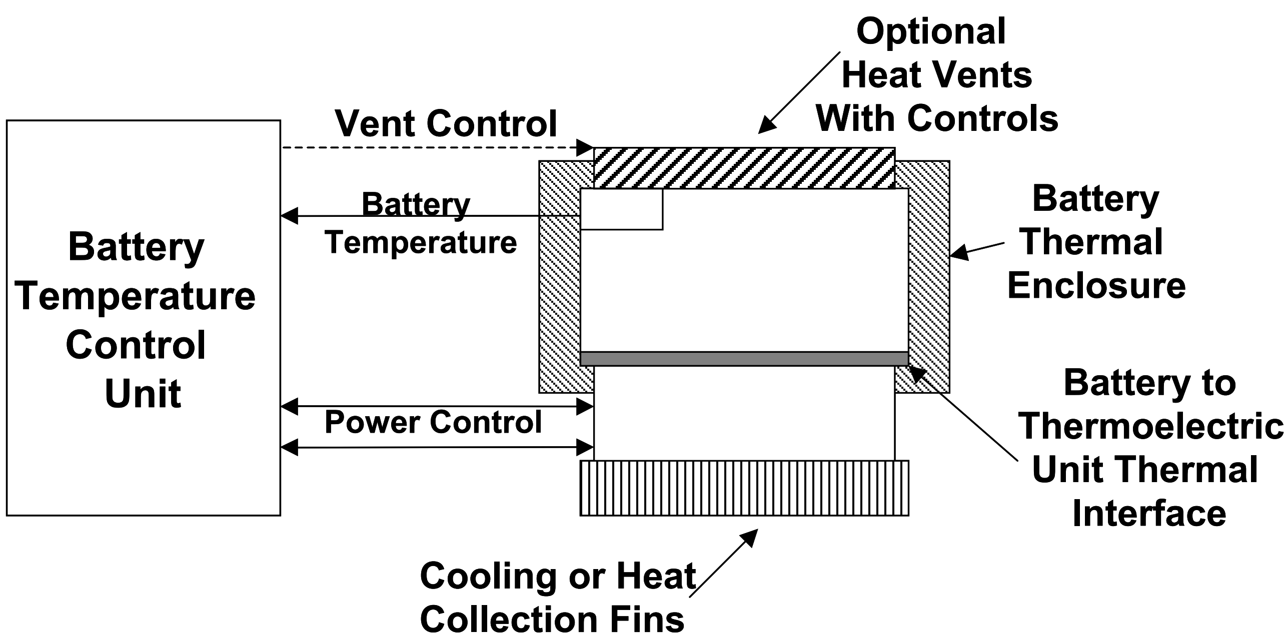
TODAY

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

FUTURE ?

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

A Battery Temperature Control System



significant warranty cost savings, improved battery reliability and quality, and improved battery efficiency and performance; and enables more flexible packaging

Greenhouse Gas (GHG) Initiative

- 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

Automotive Greenhouse Gases from Operating Air Conditioning

- 138 Million Metric Tons per Year of CO_2 equivalent Released from Personal Vehicles in the US as a Result ofUsing Air Conditioning

- Additional significant amounts CO_2e released due to accidents and end of life vehicle salvage releasing R134-a

Solid State Thermoelectric Cooler and Heater Development

- **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

Background

- 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 CO_2
  - The European Union is prohibiting use of R134-a in cars for
    - New models in 2011
    - All new cars in 2017

*Source: Greenhouse Gases and Global Warming Potential Values, from Inventory of U.S. Greenhouse Emissions and Sinks: 1990 – 2000, U.S. Environmental Protection Agency, April 2002.

Integrated Automotive Thermoelectric Generator Powering Thermoelectric Cooling/Heating Unit

- **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**

By 2020 TE Generator Powering TE Cooler/Heater in US Auto Fleet

- **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**
- **(.90) (281x10^6cars & Lt Trucks)* (62 gals A/C/car year) (1/365) = 43 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**

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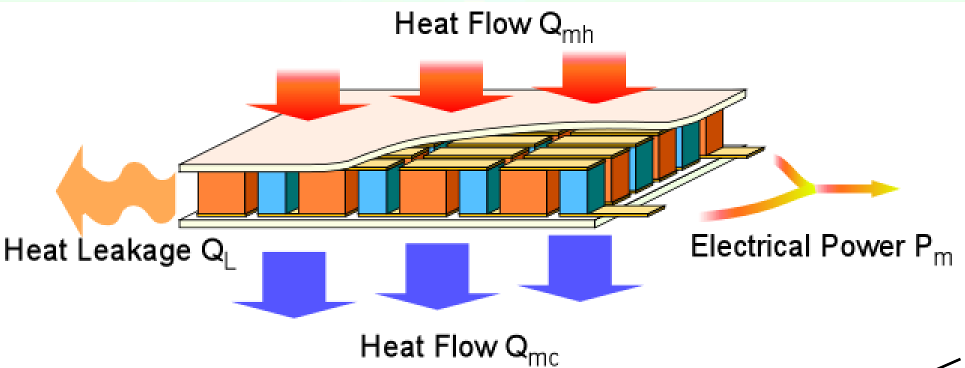
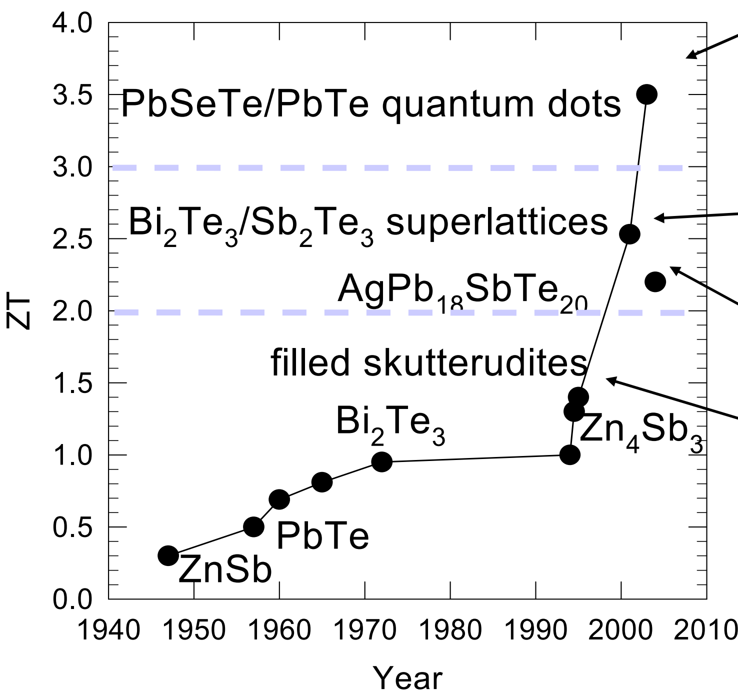
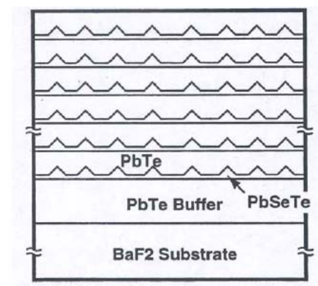
Recent Advances in Efficiency of Thermoelectric Materials

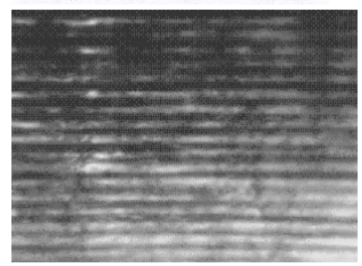


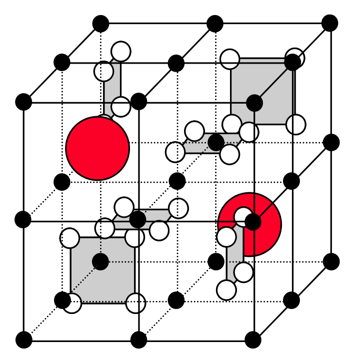
Efficiency:

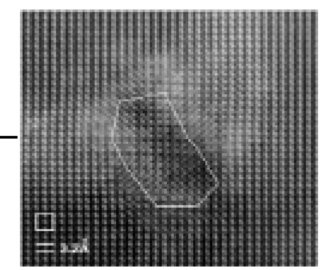
$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}}$$





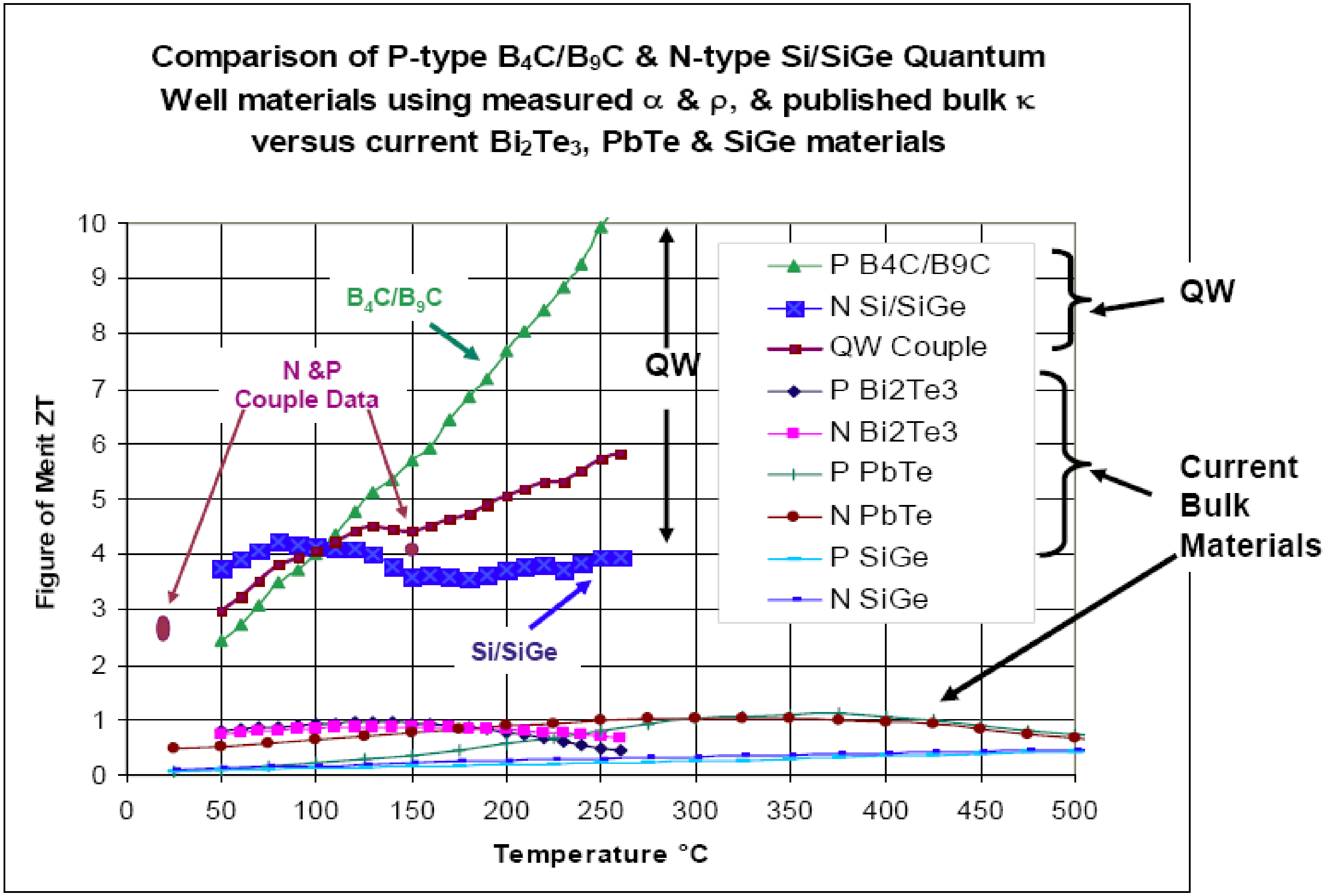






» Many recent thermoelectric material advances are nano-based

Advanced Thermoelectric Figures of Merit



Data: QW & Bi_2Te_3 Hi-Z; PbTe & SiGe JPL Properties Manual

Thermoelectric Nanoscale Materials Emerging in Labs

- 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

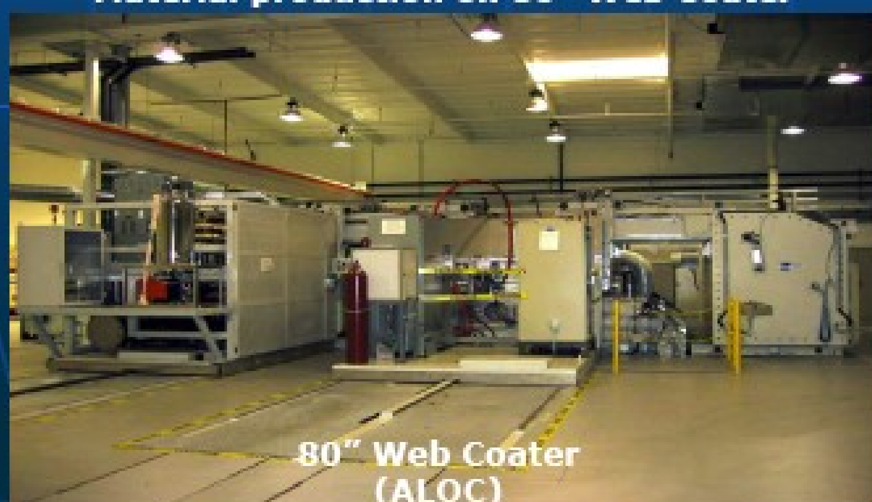
This would be a > 300 % Improvement in Efficiency !

General Atomics Sputtering Capabilities

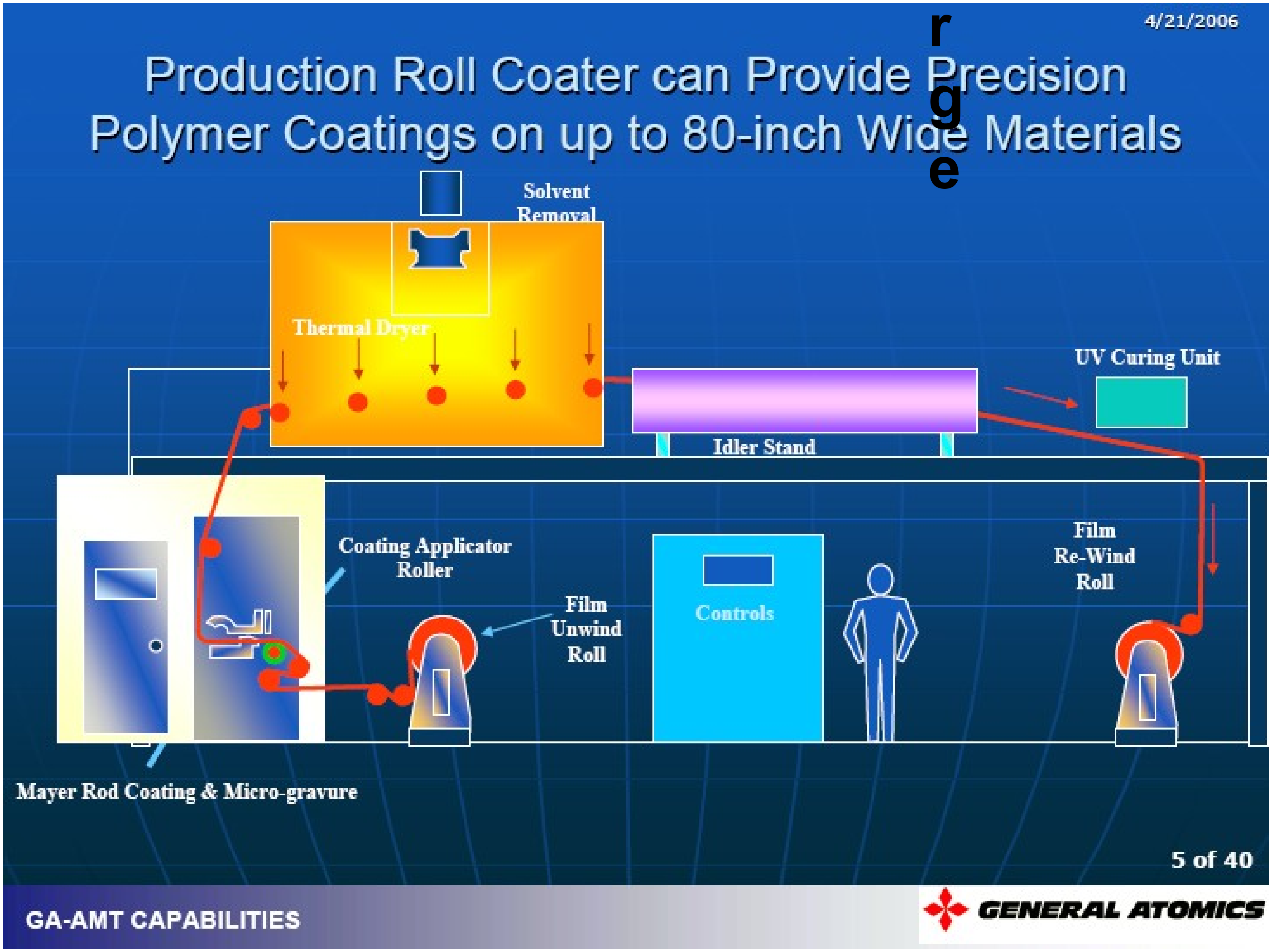
New coatings developed on R&D coater

New products developed on R&D Web Coaters

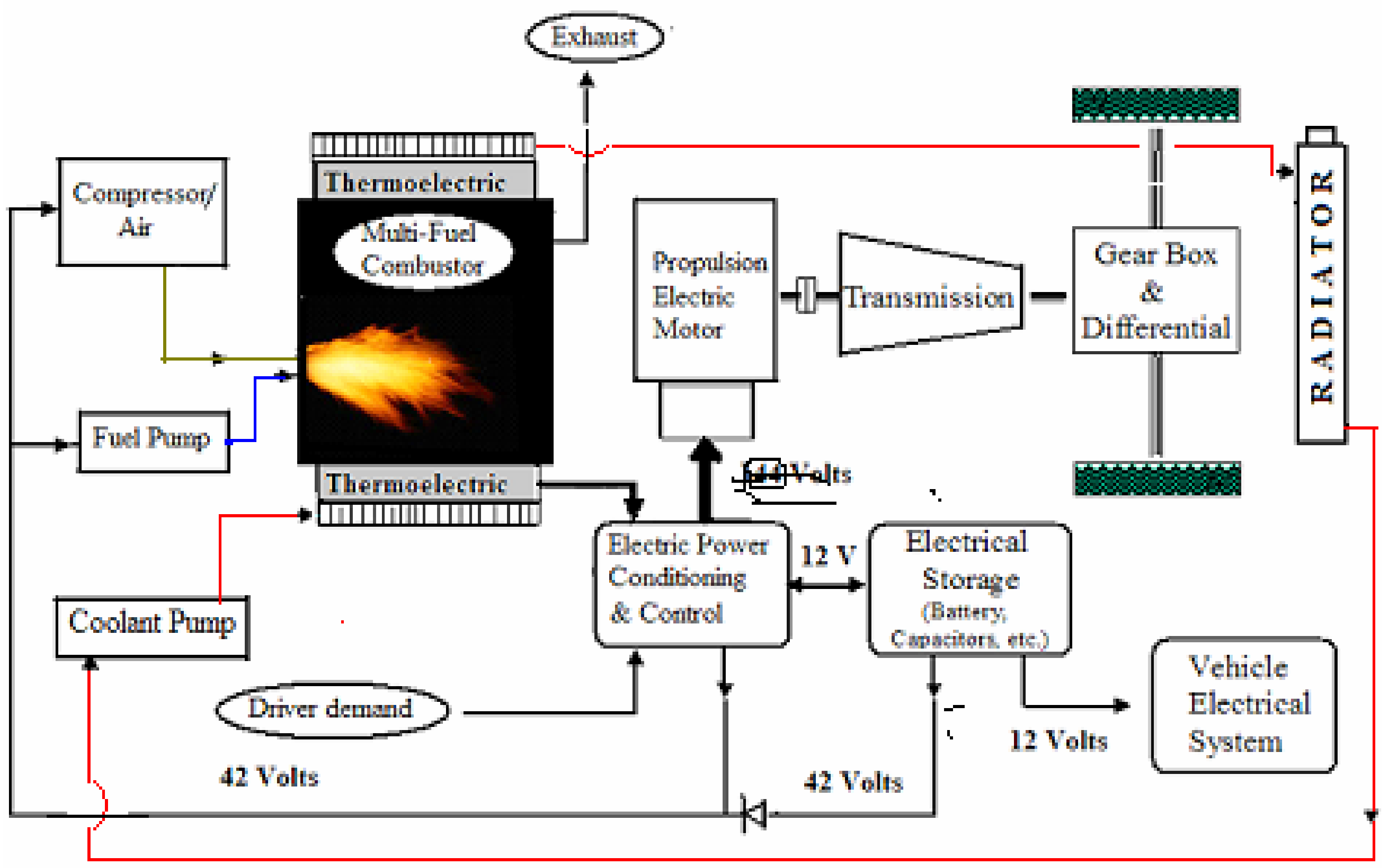
Material production on 80" Web Coater



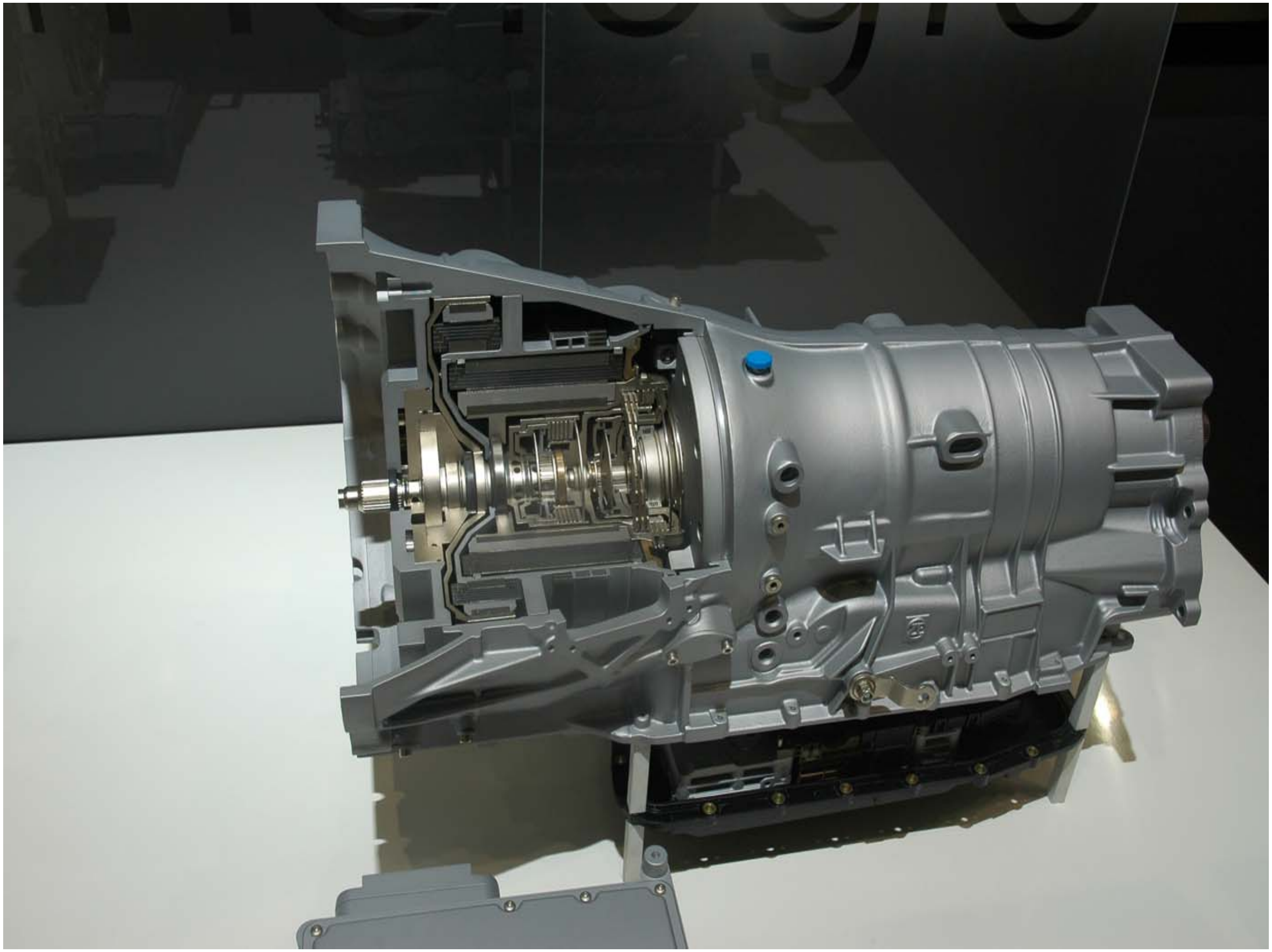
Large Scale Sputter Coating System



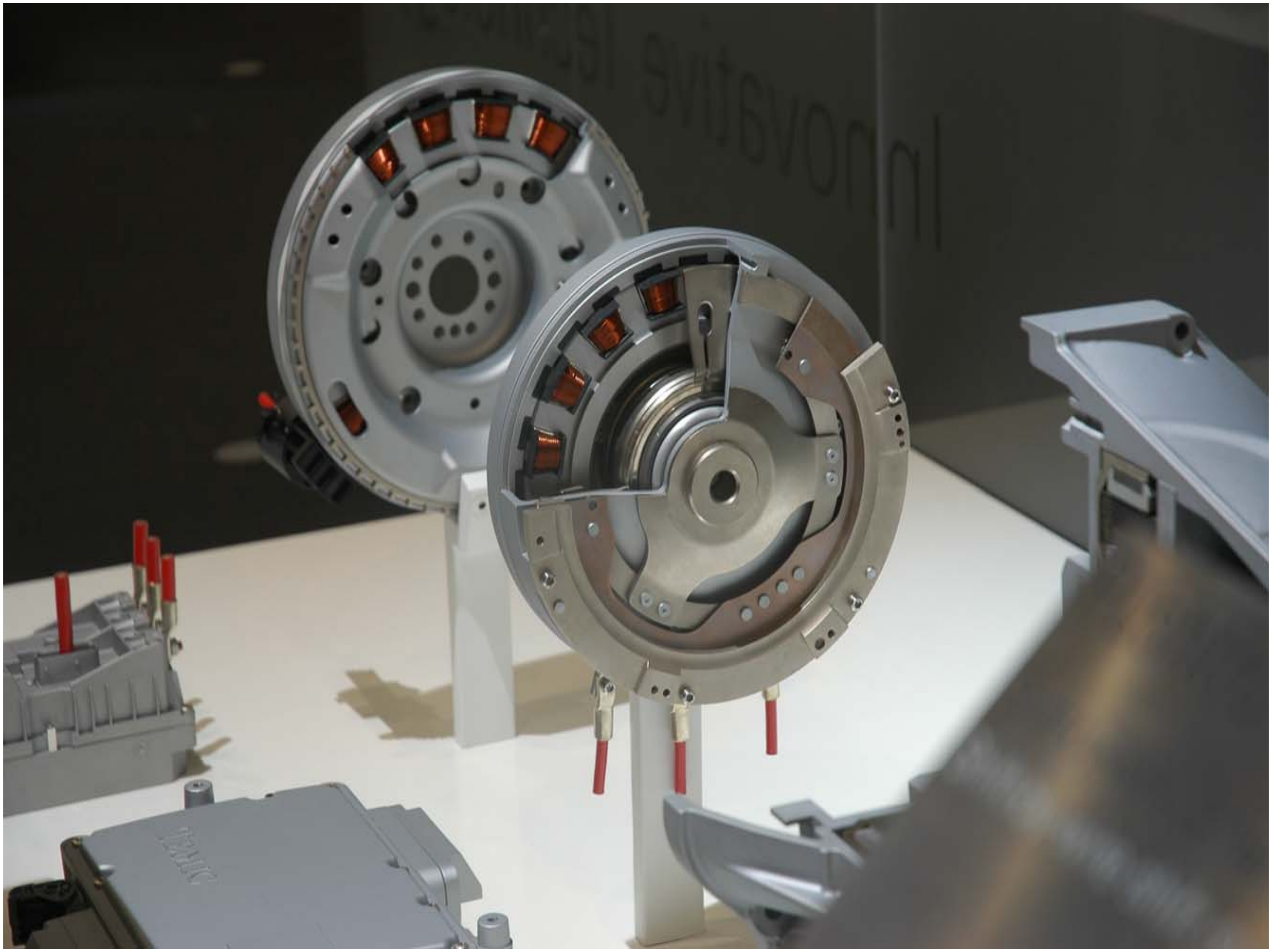
Solid State Thermoelectric Hybrid Vehicular Electric Powertrain



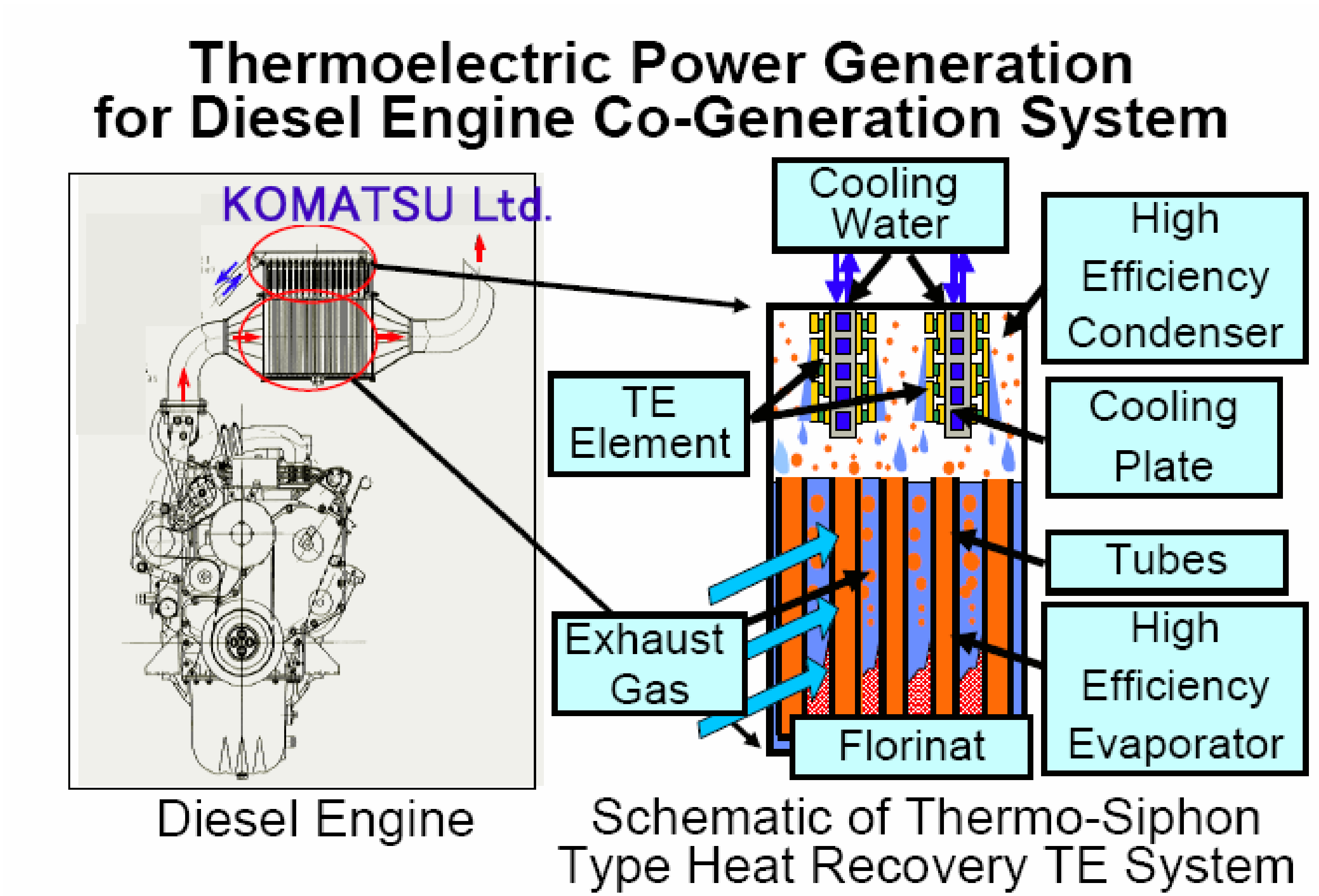
Transmission
Electrical to Mechanical



Electric Motor Drive Wheels "Drive by Wire"



Japanese Vehicular Thermoelectric Generator Program



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

VEHICLE THERMOELECTRIC APPLICATIONS TIMELINE

- **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

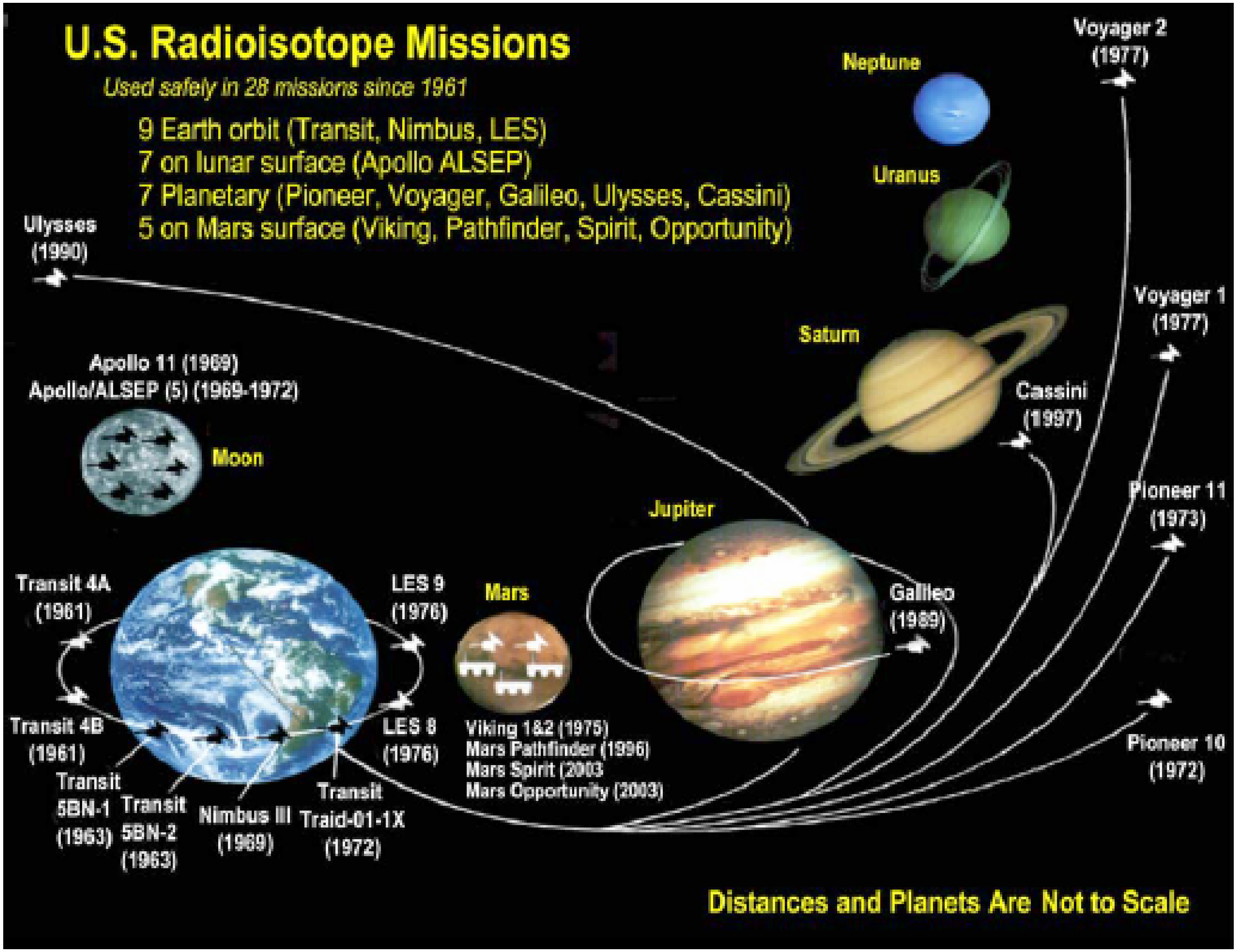
Very Long Term (~2060)

Radioisotope Thermoelectric Generator/Battery Powertrain

Expensive but Long Life – 30 years

Change vehicle body every 5-8 years

Spacecraft Using Radioisotope Thermoelectric Generators



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 CO_2
  - (109.5 g/year) (1,300) =142.4 kg CO_2equivalent per year
- Increase in CO_2 from fuel used for Vehicle A/C
  - (62 gals/yr) (8.9 kg CO_2/gal) = 552 kg CO_2/yr
  - (552 kg CO_2/yr)+(142.4 kg CO_2e/yr) =
  - 694 kg/yr CO_2/vehicle
- Total CO_2 emitted from a personal vehicle's engine/year
  - (696 gal/yr) (8.9 kg/yr) = 6,194 kg CO_2/yr
- Thus ~11 % of total CO_2 emitted from personal vehicles comes from using Air Conditioning

  (2.2×10^8 vehicles) (.9) (6.94×10^2 kg/yr CO_2e/vehicle) =

  13.8×10^{10} kg/yr CO_2 or 138 Million Metric Tons/yr CO_2e

*Source: Greenhouse Gases and Global Warming Potential Values, from Inventory of U.S. Greenhouse Emissions and Sinks: 1990 – 2000, U.S. Environmental Protection Agency, April 2002.