Thermoelectrics Applications Review

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FreedomCAR and Vehicle Technologies
Energy Efficiency and Renewable Energy
U.S. Department of Energy

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European Thermoelectric Conference
Odessa, Ukraine
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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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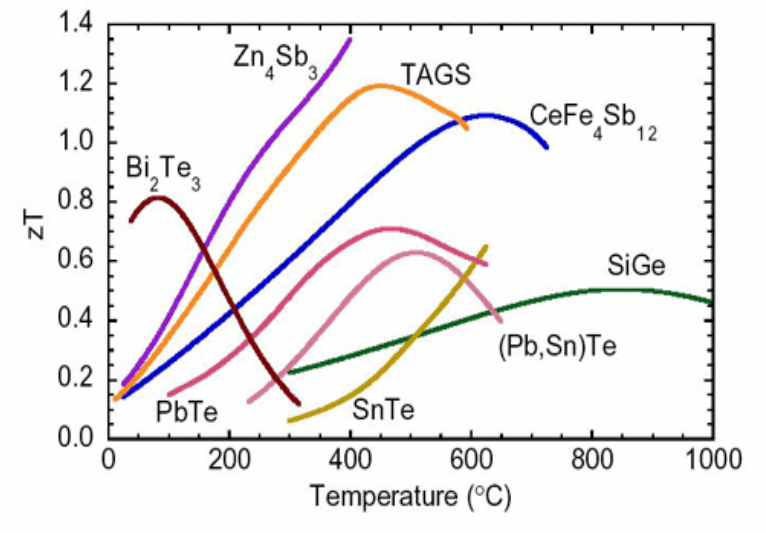
reduce fuel consumption
greenhouse
gases
silent running

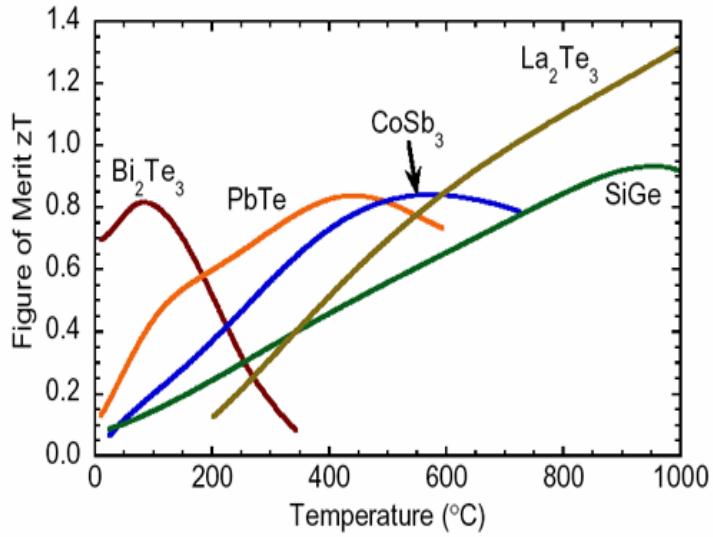
If Not Now, When?

- While This Presentation is Primarily Focused on Automotive Applications of Thermoelectrics it Includes Several Other Significant Applications to Illustrate the Versatility of Thermoelectrics . Success Should Accelerate Fundamental Research in Thermoelectrics as Well as Extend Applications

Current TE Materials



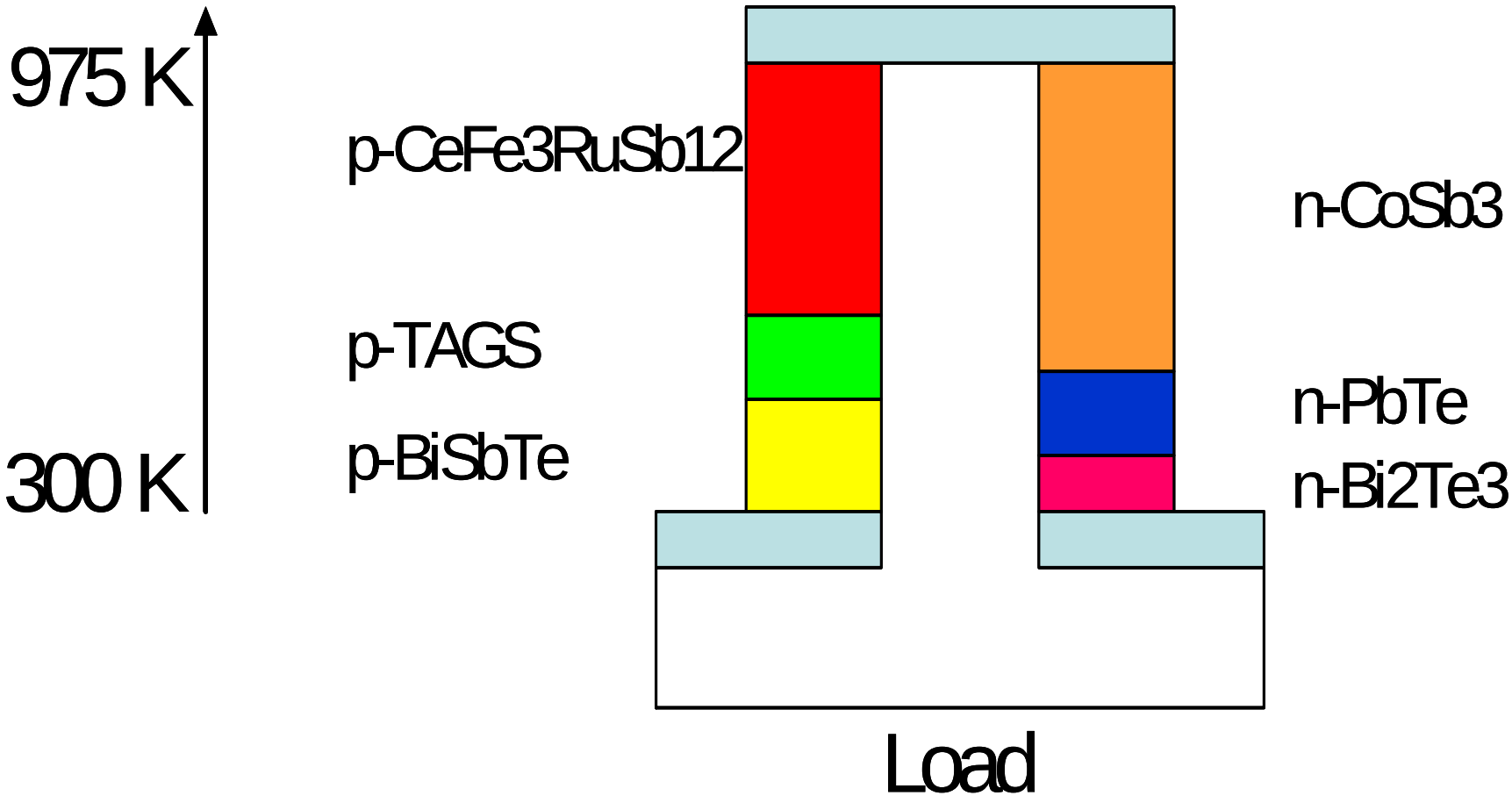
P-type TE material



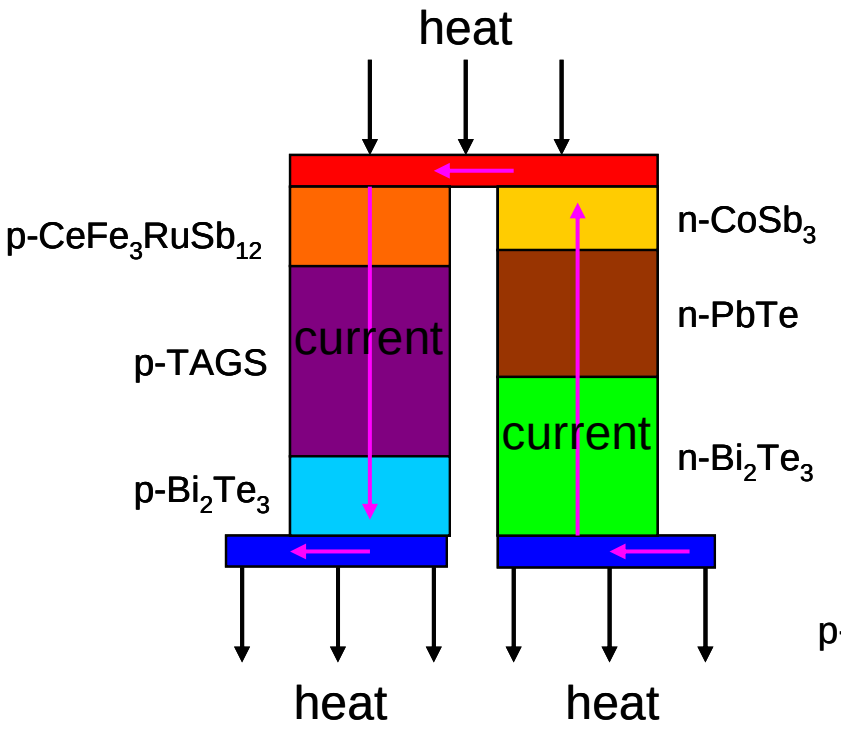
N-type TE material

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

Segmented TE Couple

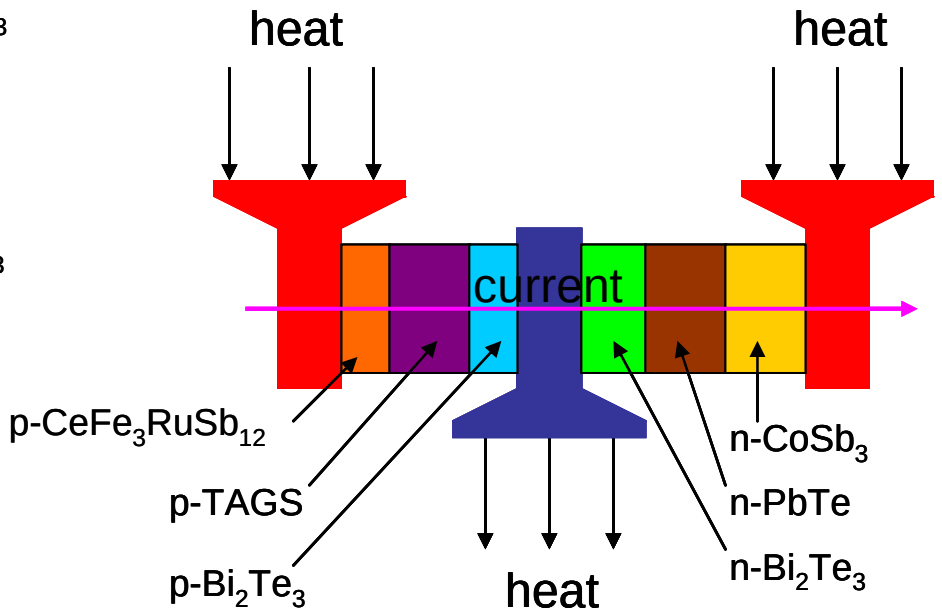


TE Couple Configuration Alternatives with Segmented Elements



- Traditional configuration

- Alternative “Y” configuration



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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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

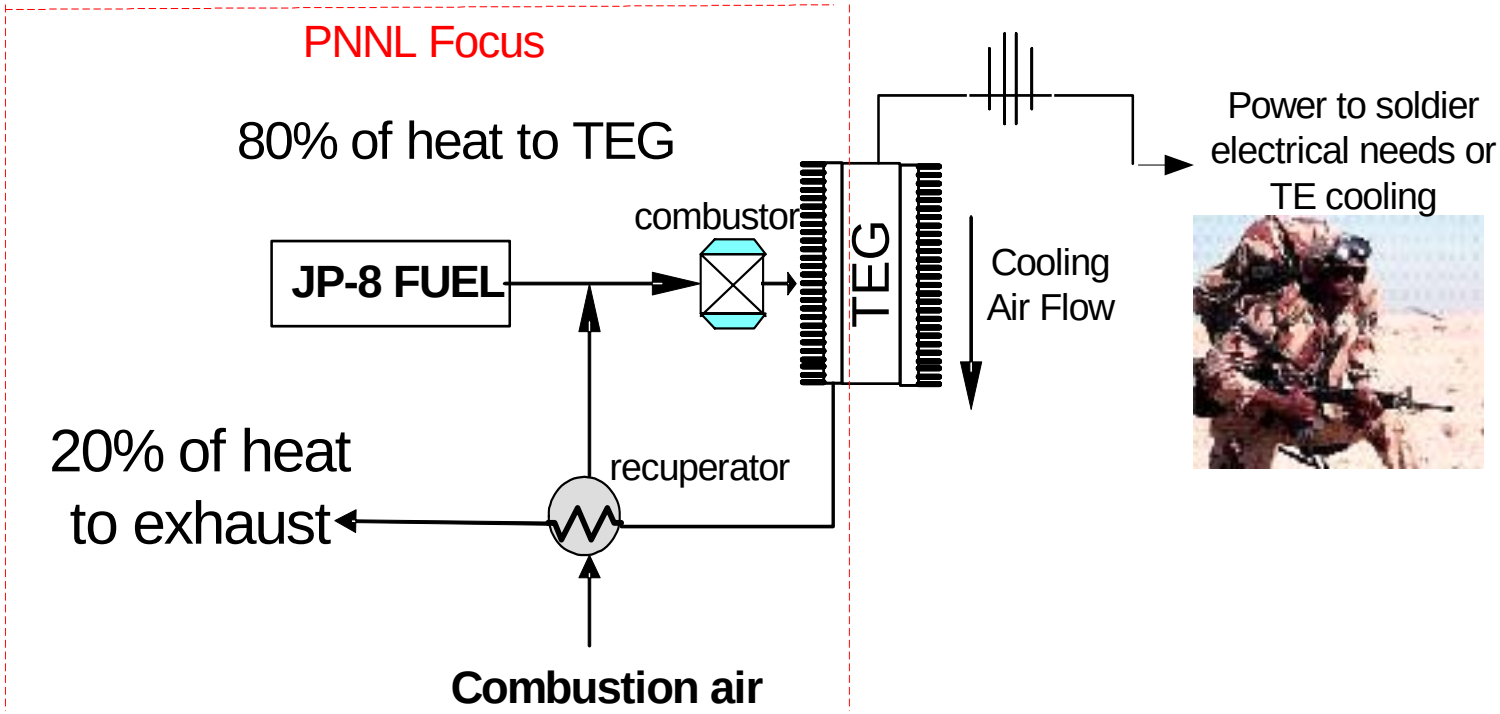
- >30% weight savings over existing systems

Assumptions
12 hour mission @ 110°F ambient temperature

DARPA TTO Program Manager: Ed van Reuth

Man-Portable Power (DARPA/UTRC Program)

- Performed heat-exchanger design optimization for 200 W_e TE-based lightweight power generator
- Developed mass-optimized designs for air recuperator and cold-side TEG heat sink
- Total system mass at 3 kg



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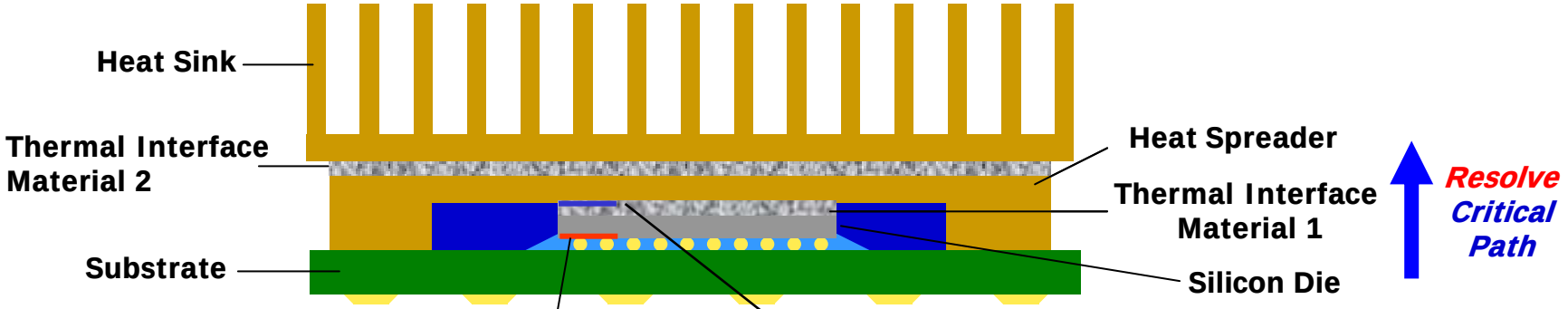
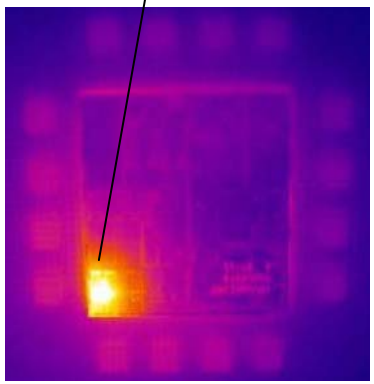
Embedded Semiconductor Cooling Removes Heat From Die to Heat Sink

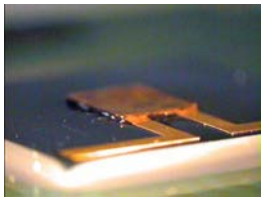


Hotspots effect

- 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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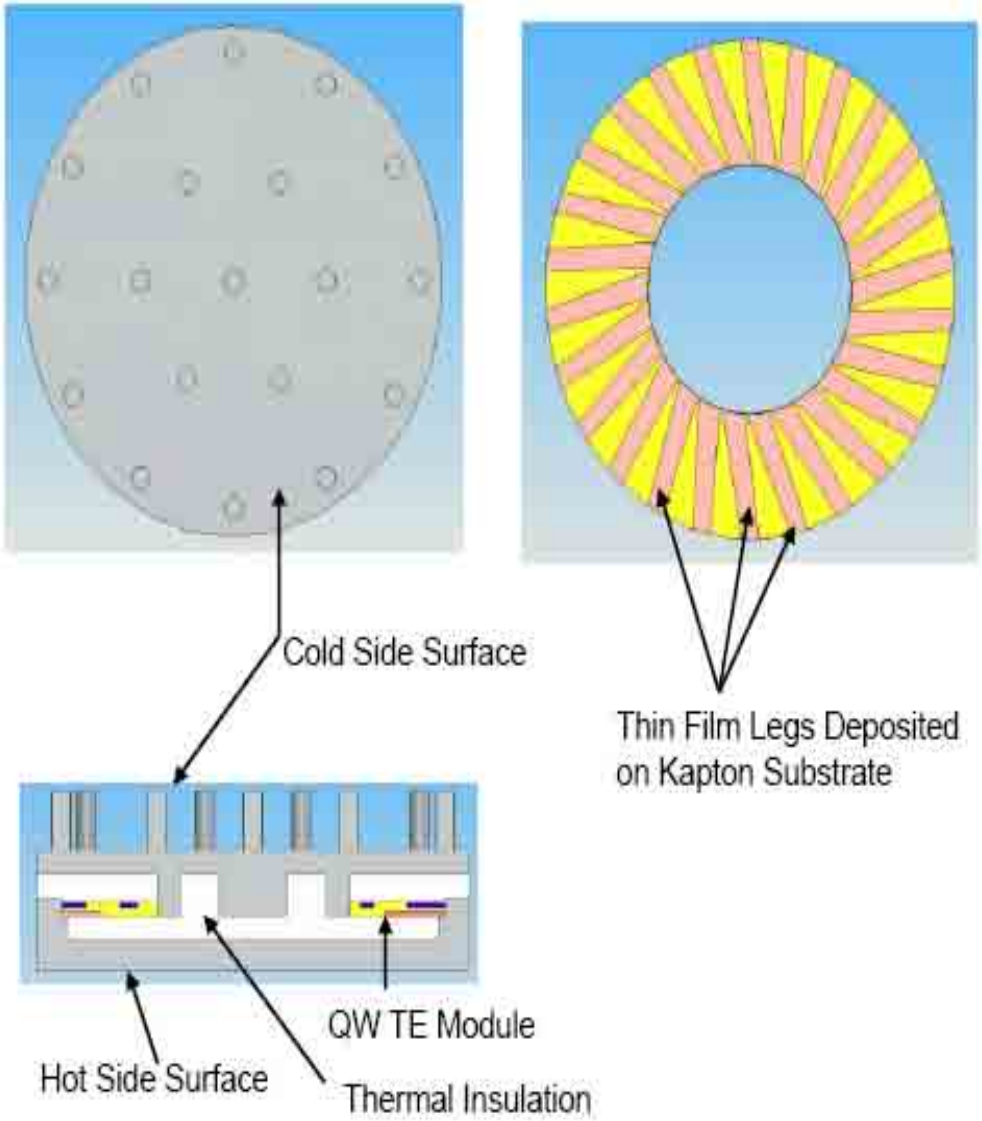
Power-Harvesting QWTE Power Supply for Shipboard Wireless Sensors



Quantum Well TE Module

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.

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USS DOLPHIN AGSS 555 Thermoelectric Air Conditioning Test for Silent Running

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Thermoelectric Fruit Storage

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Thermoelectrics Replacing Gas Compression Refrigeration ?

TODAY

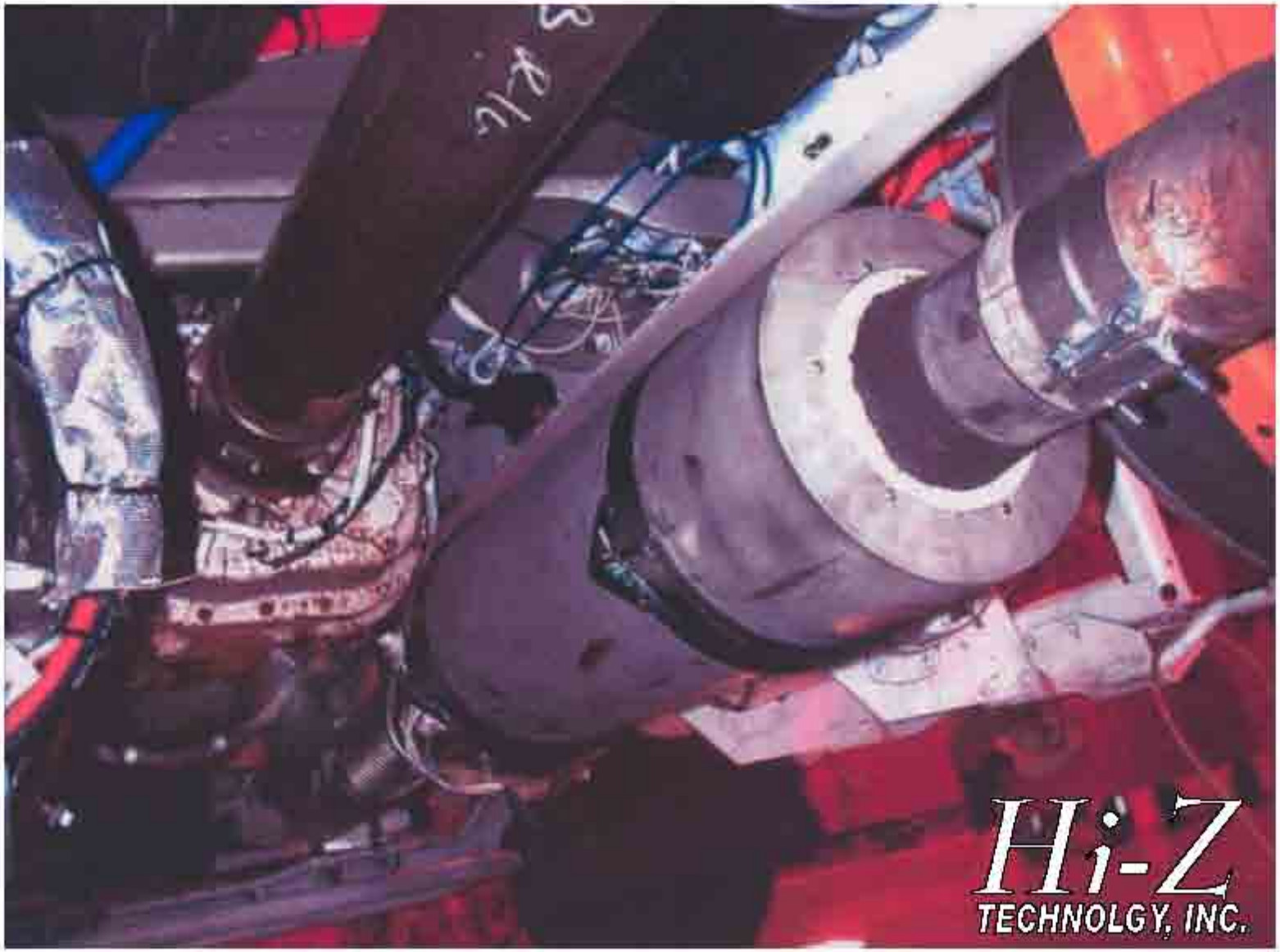
Thermoelectric Hot & Cold Mini Fridge (1.5 ft^3)

FUTURE ?

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

1 kW_e Thermoelectric Generator Installed in Place of Muffler

Potential Location for the Thermoelectric Generator



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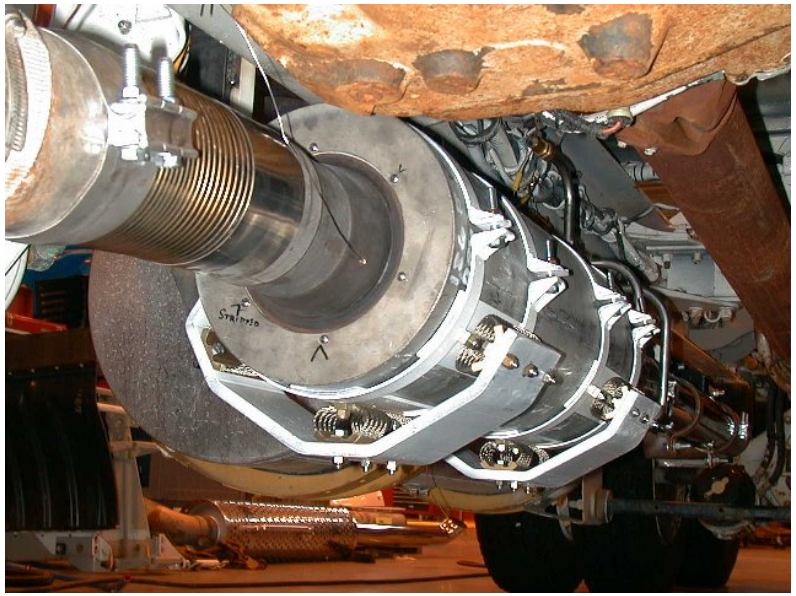
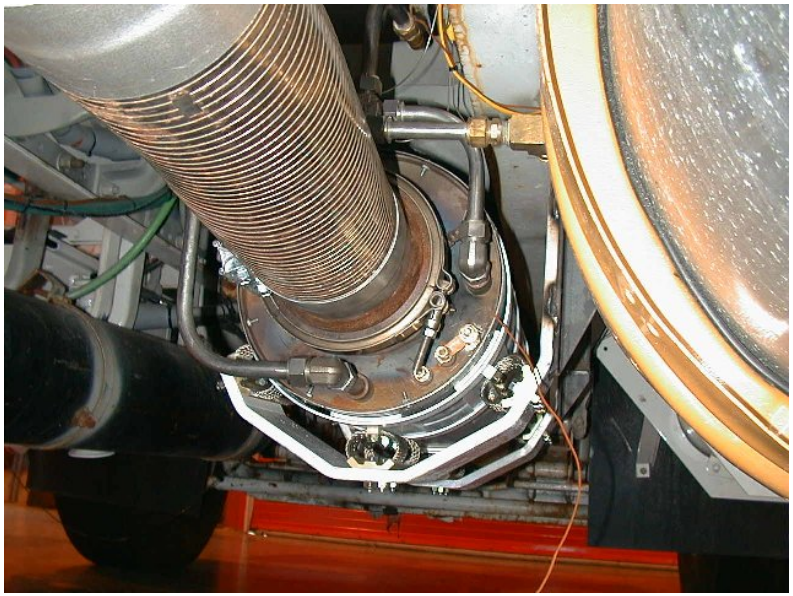
Installed Thermoelectric Generator on Heavy Duty Truck



Front View



Rear View

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

Hi-Z

ORNL Rule of Thumb

- 10 Percent Reduction in vehicle weight can produce a 7 to 8 percent reduction in fuel use (mpg)

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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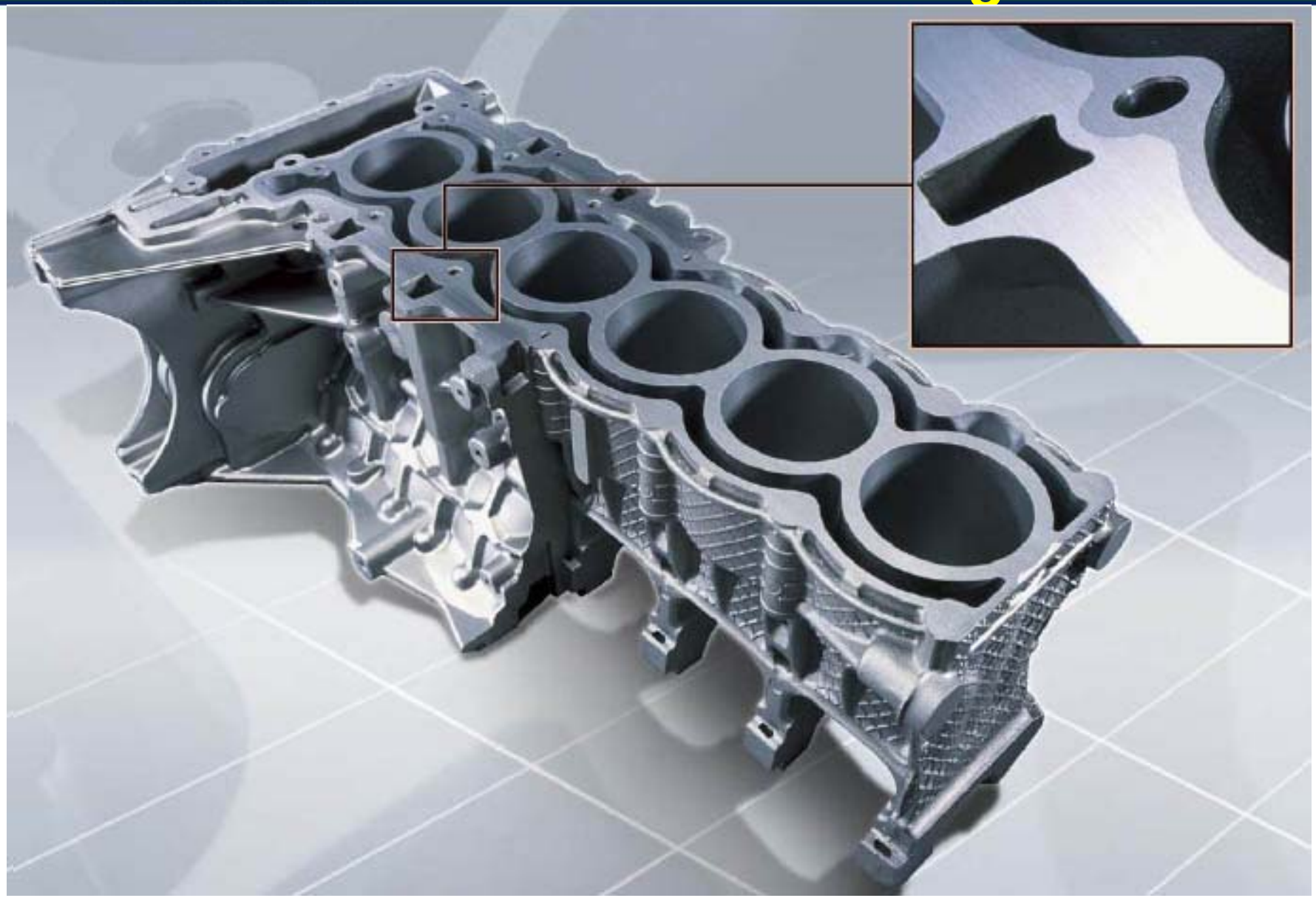
BMW's Magnesium Engine Block 25 % Lighter than Al

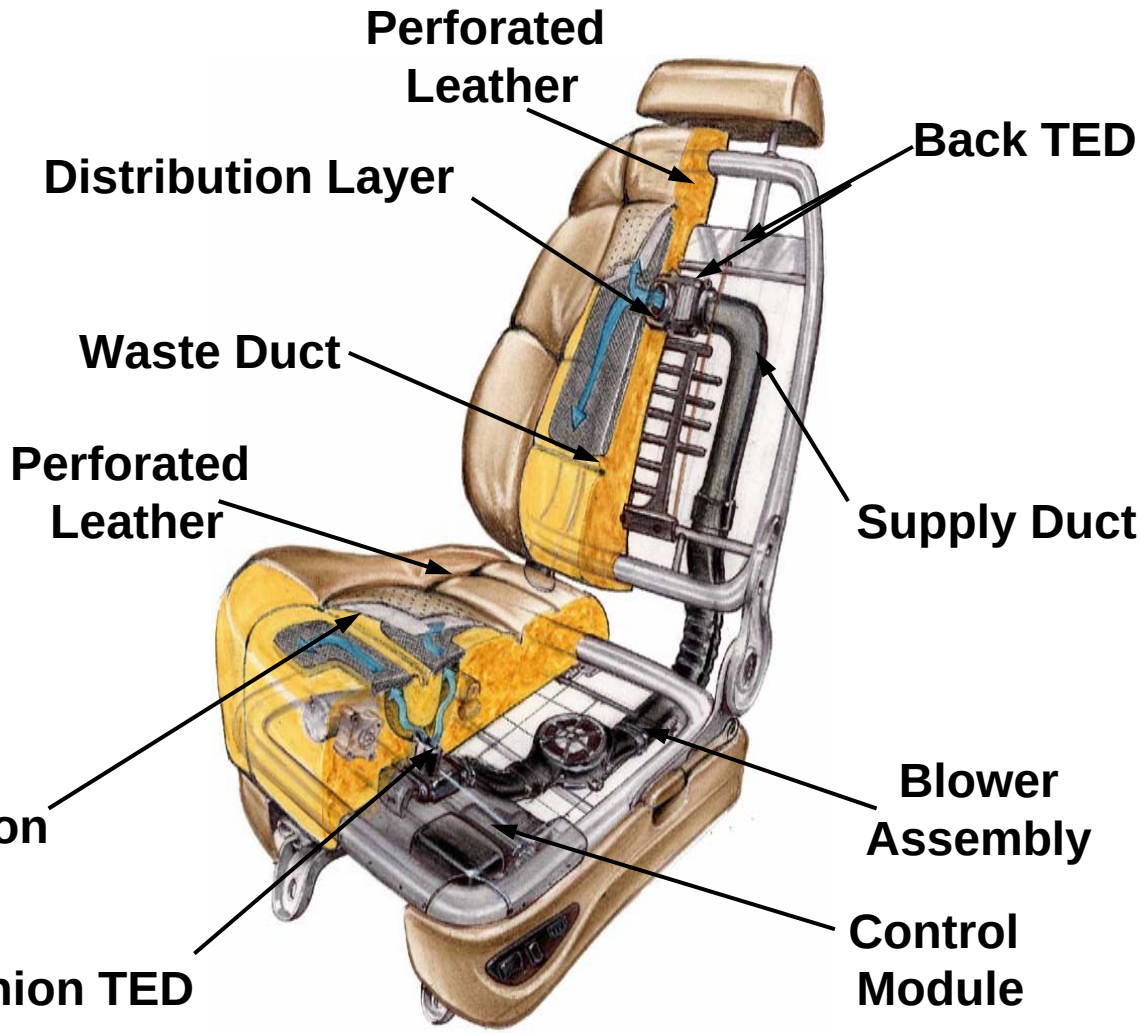


Logical Thermoelectric Market

- Why Thermoelectrics in Vehicles?
  - Roughly 17 Million Cars sold in US Annually
    - US Fleet ~ 220 Million Personal Vehicles
  - Improve Fuel Economy
  - Reduce Regulated Emissions
  - Reduce Greenhouse Gas Emissions

Climate Control Seat™ (CCS) System Vehicle Application

Production CCS Assembly



Class 1 Supplier

- Over 5 Million Thermoelectric Climate Control Seats Supplied to Auto Industry

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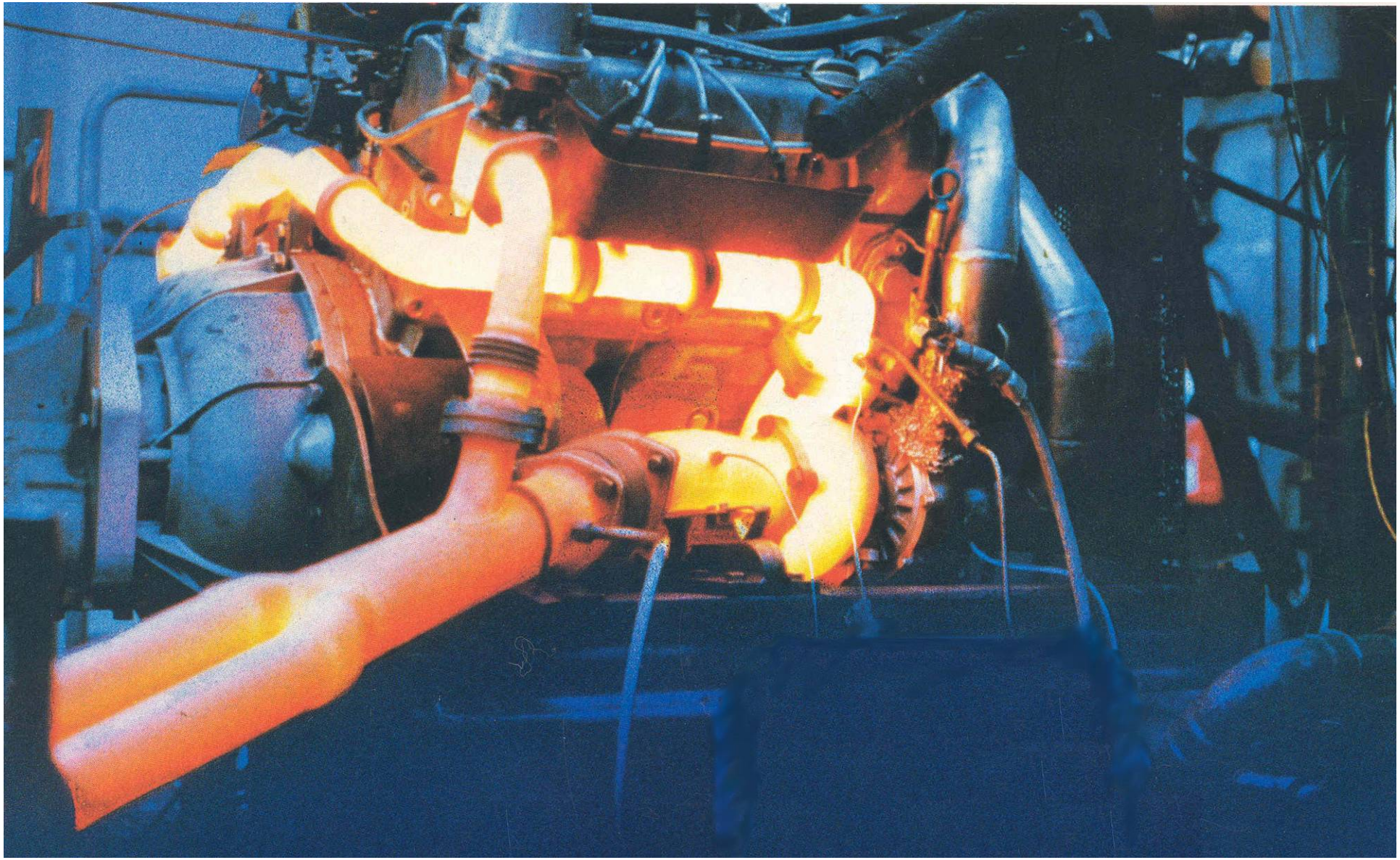
Available Energy in Engine Exhaust



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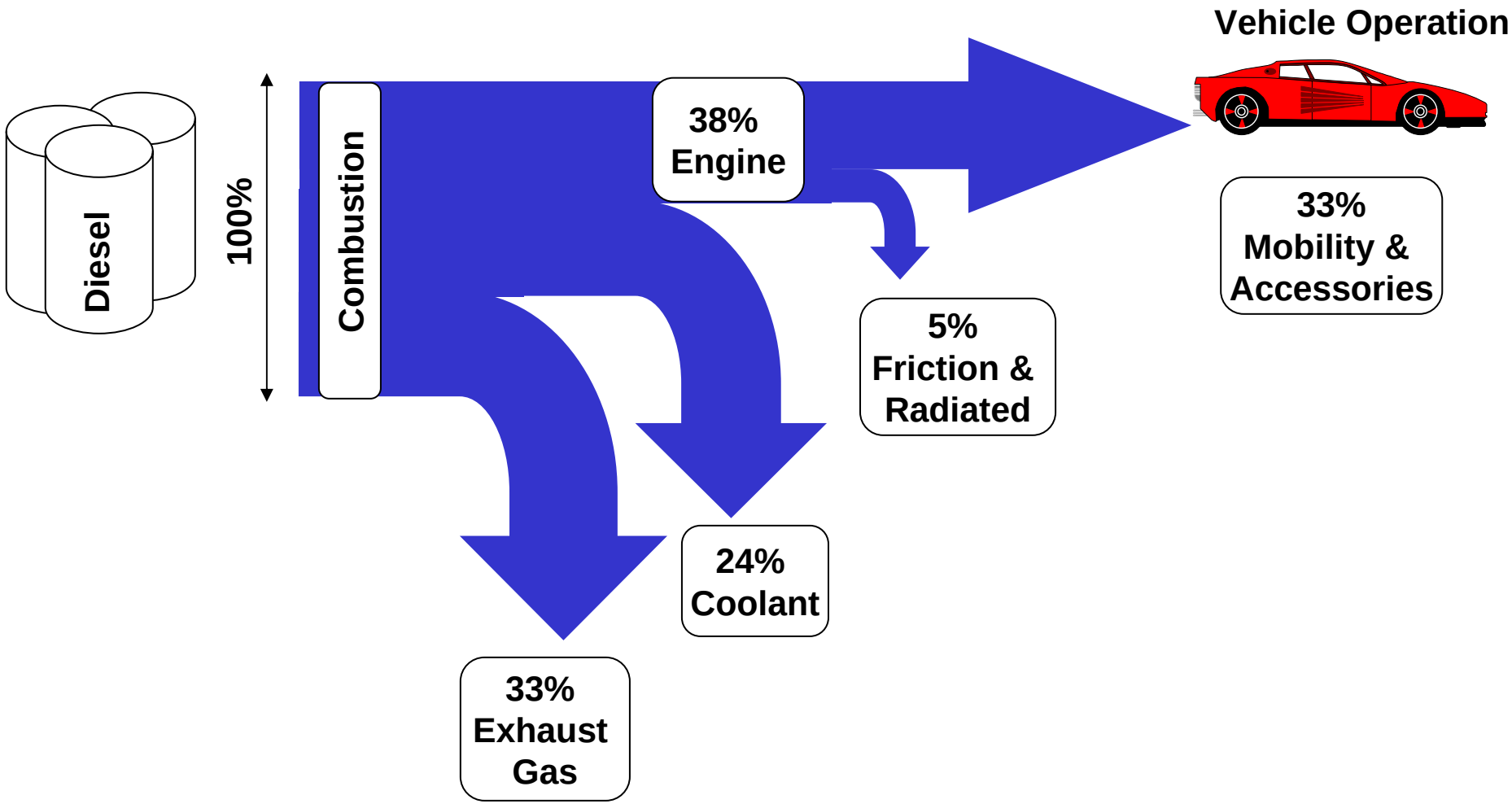
Potential Thermoelectric Heat Sources



Diesel Engine (Light Truck or Passenger Vehicle)

Target

- Recover as much of the 57 percent of fuel energy lost as engine waste heat

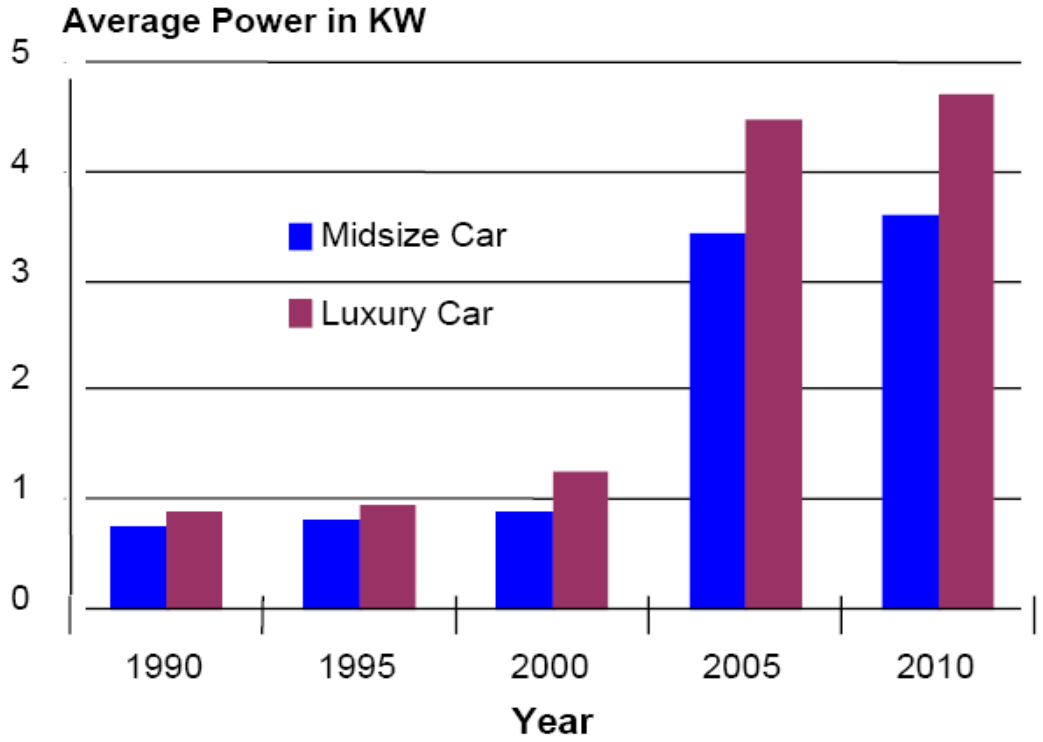
Vehicular Electrical Uses

- Why develop Electrical Power in a Vehicle?
- How Would this Electricity be used?

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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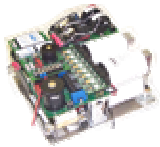
Beltless or More Electric Engine

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

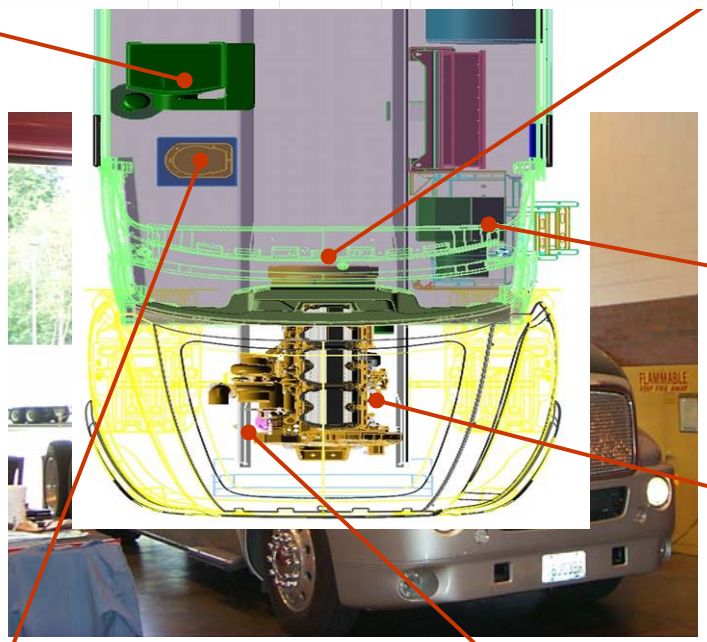


Shore Power and Inverter

Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input Supplies 120 Vac outlets from battery or generator power

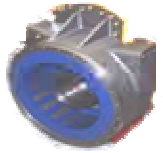
Down Converter

Supplies 12 V Battery from DC Bus



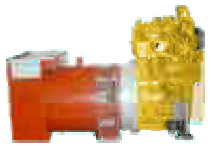
Compressed Air Module

Supplies compressed air for brakes and ride control



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 Water Pump

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

Electric Oil Pump

Variable speed
Higher efficiency

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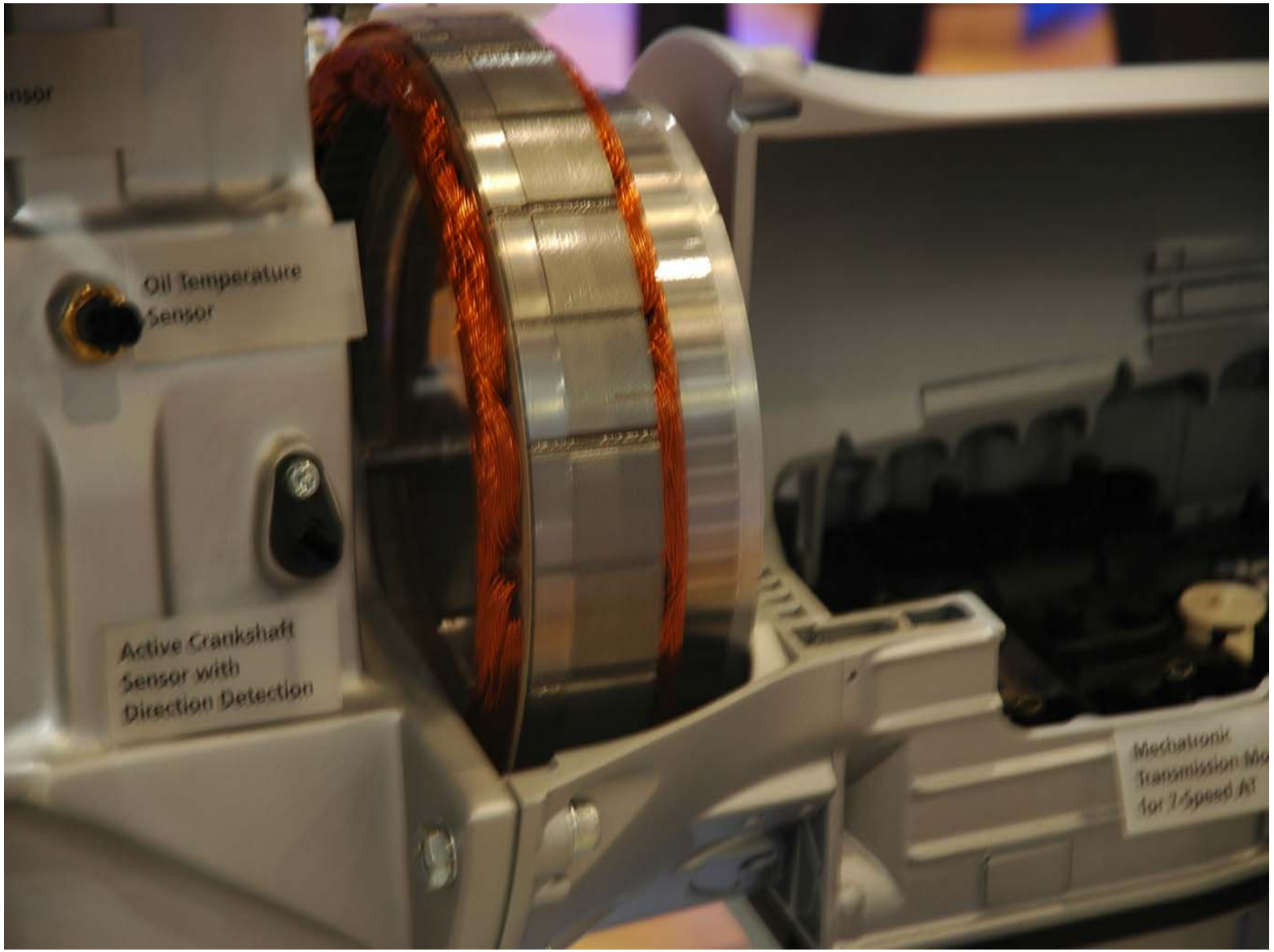
Integrated Alternator/Motor/Starter/Damper



Overall DOE/NETL Program Goals and Objectives

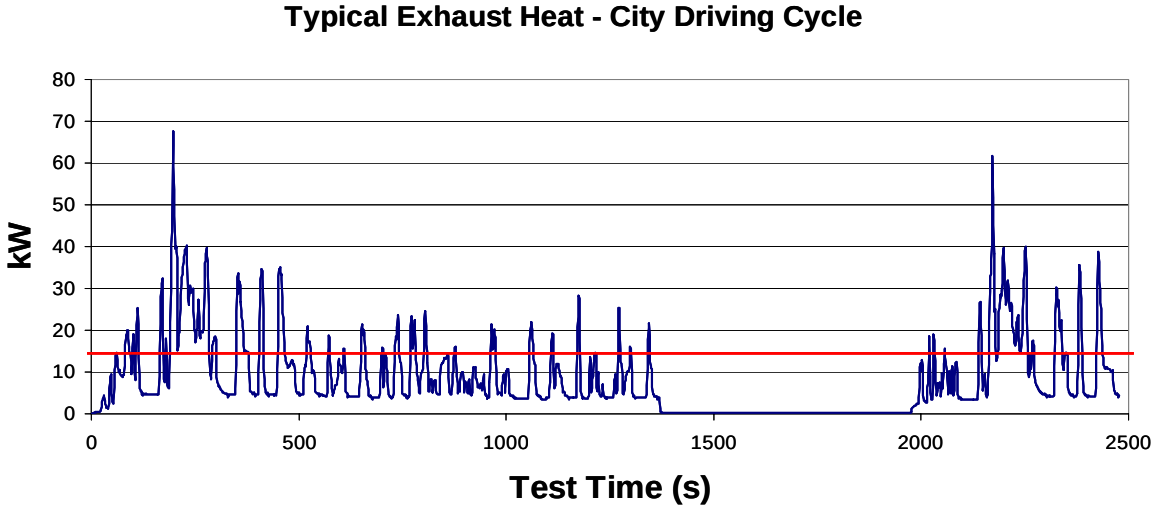
- Develop and integrate a Thermoelectric Generator into a vehicle's electrical system to convert the engine waste heat directly to electricity
- The Goal is to improve fuel economy by a nominal 10 percent
- The Timeline is to introduce in production personal vehicles in the 2011 to 2014

Thermoelectric Generator Teams

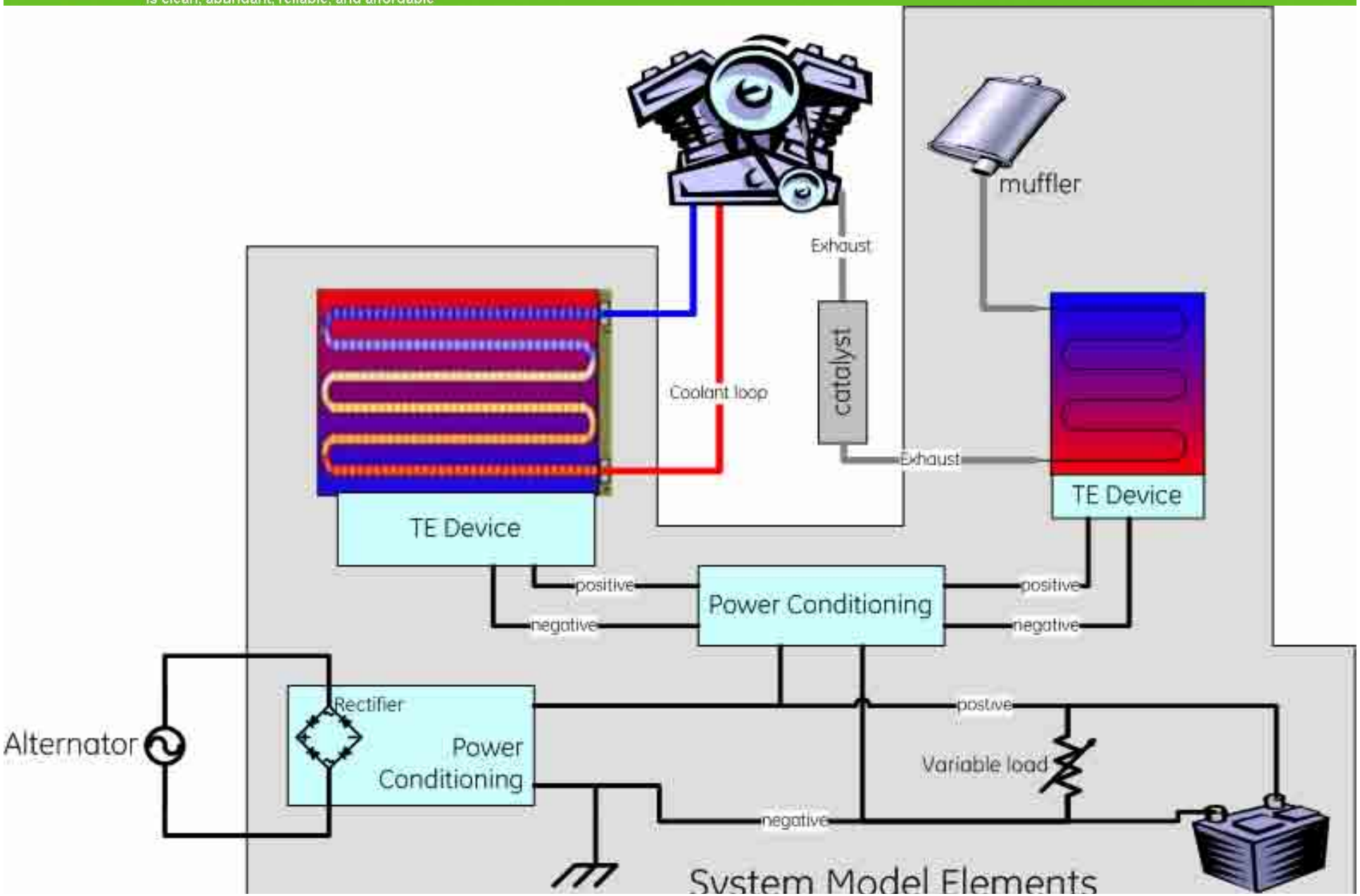
- BSST with BMW, Visteon, Marlow Industries, Virginia Tech, Purdue, U of California-Santa Cruz
- GM with GE, U of Michigan, U of South Florida, ORNL, RTI
- Michigan State with Cummins Engine Company, Tellurex, NASA-JPL, Iowa State

GM Thermoelectric Generator Vehicle Selection – Full Size SUV

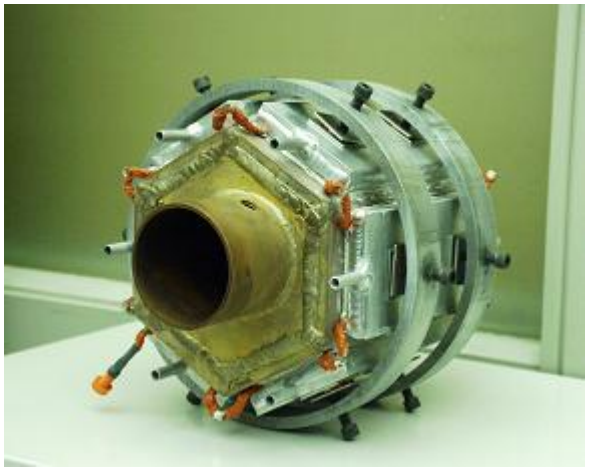
- plenty of space for accommodating TE subsystem
- a lot of waste heat: exhaust and radiator
- current muffler: 610 x 310 x235 (mm)
- available envelope: 840 x 360 x 255 (mm)

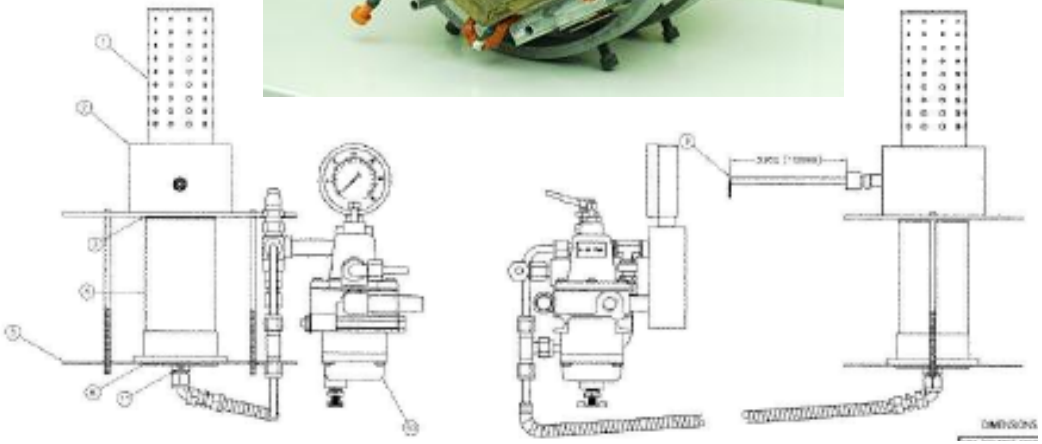


GM's Thermoelectric Generators



GM's Conceptual TE Generators – Gen I and GEN II





- Gen I delivered 110W at the exhaust of a 4-cylinder car
- Expected peak output for GEN II ~ 12 volts, 24 A, and 290 W (water cooled)
- Work with GE to validate subsystem model, characterize parasitic losses and interface resistances

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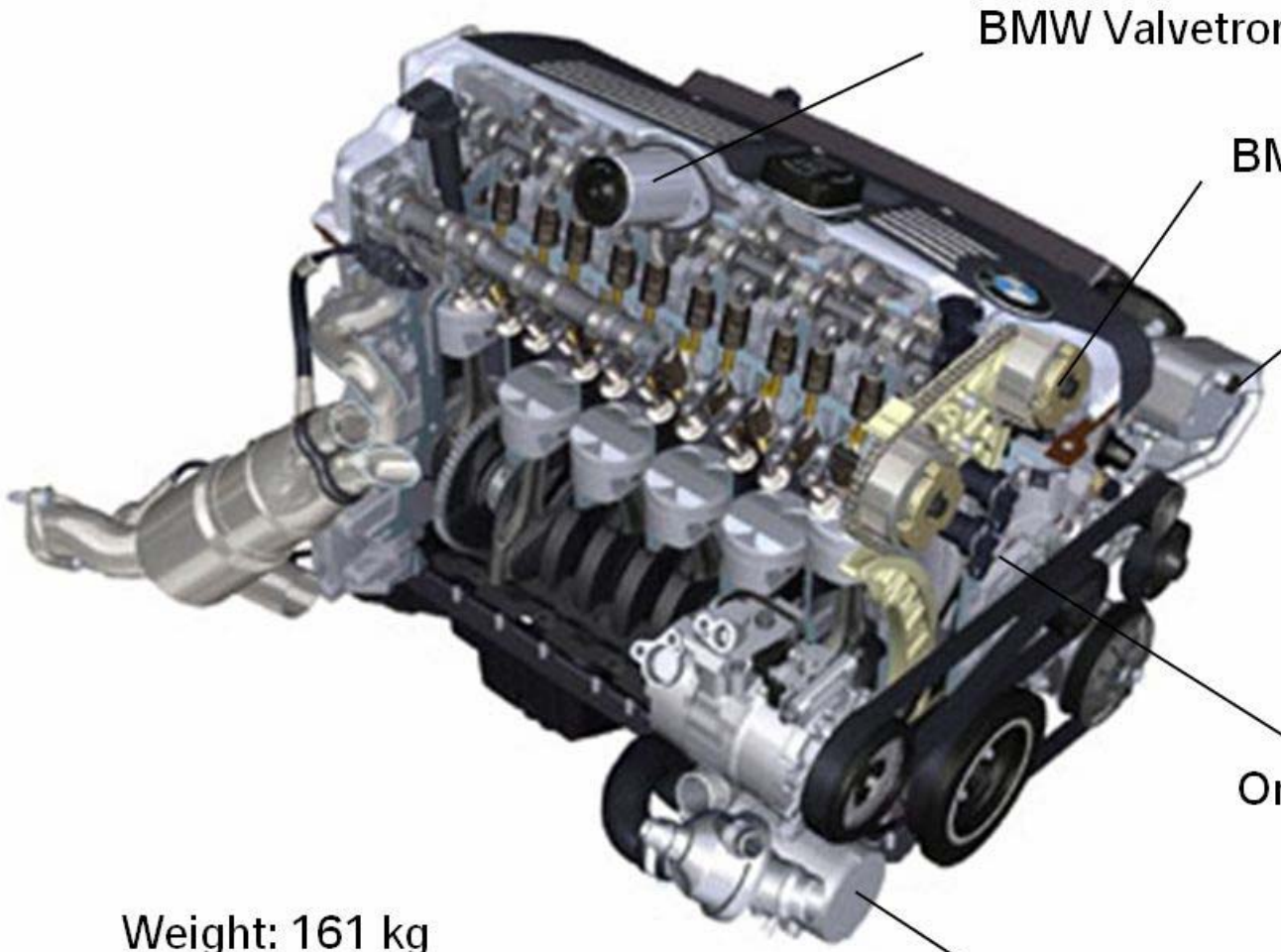
BMW's Electric Water Pump Improves Fuel Economy 1.5 to 2.0 %

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



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

Vehicle / Engine Selection

Selected platform - BMW 530i

Selected engine - Inline 6 cylinder, 3.0 l displacement

- The selected vehicle is The state-of-the-art BMW sedan with a 3 liter displacement engine (BMW 530i, MY 2006, automatic transmission).
- The engine is the newest generation of highly efficient, in-line, 6-cylinder engines with characteristics representative of engines in the 2010 to 2015 timeframe

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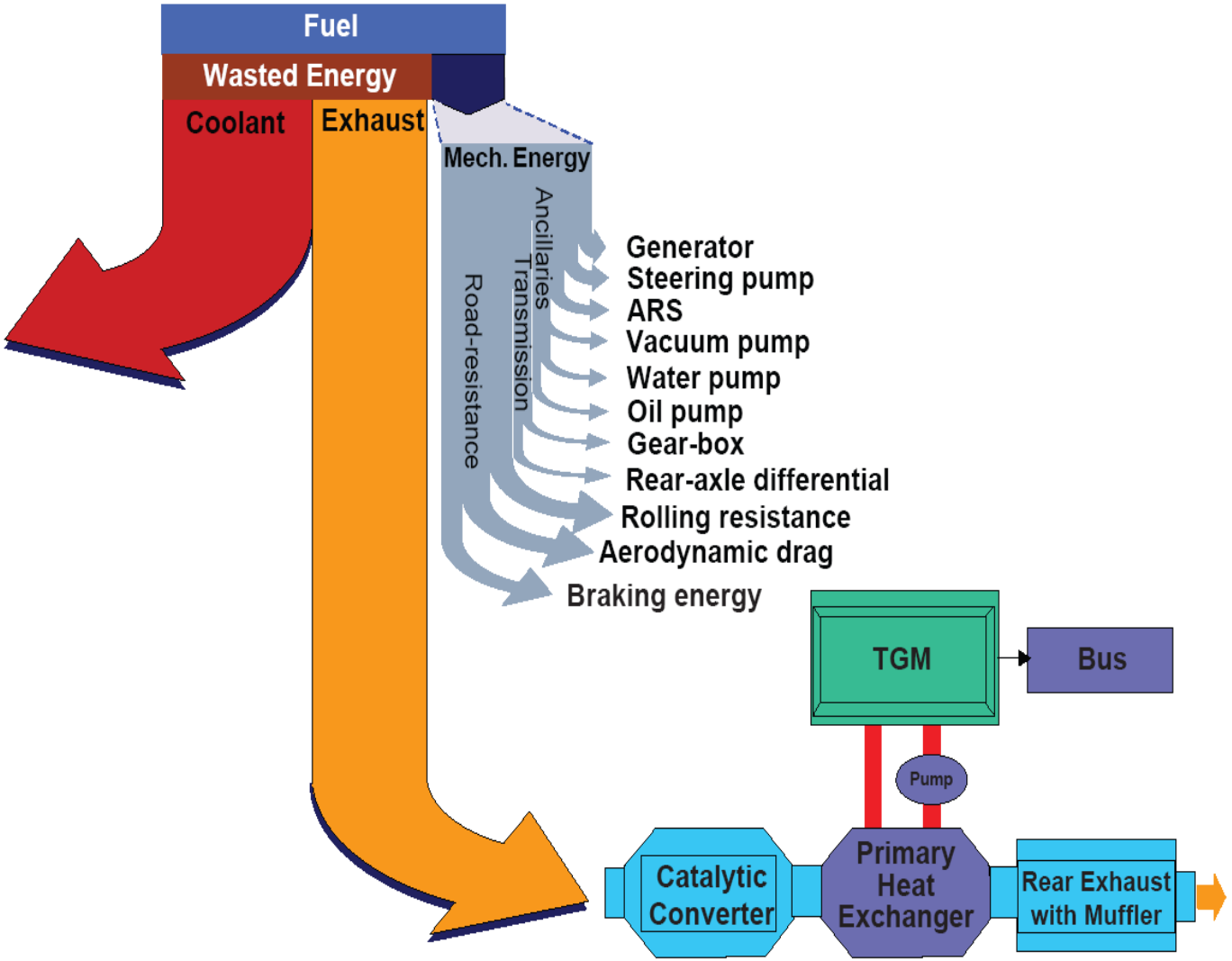
BSST - VISTEON - BMW BLOCK DIAGRAM THERMOELECTRIC GENERATOR



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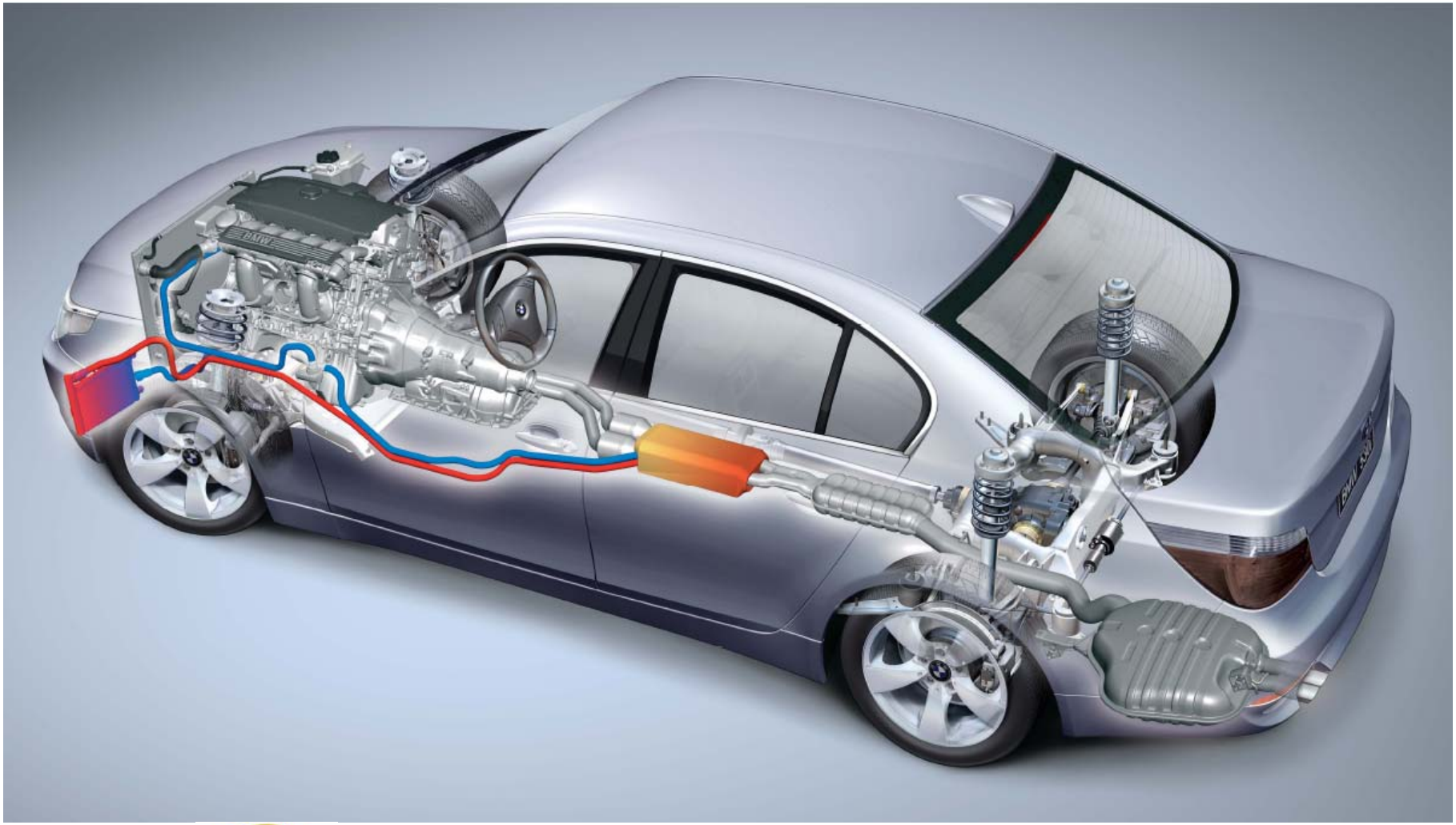
BMW Series 5 , Model Year 2010, 3.0 Liter Gasoline Engine w/ Thermoelectric Generator



FreedomCAR & Fuel Partnership

Visteon

BSST innovative solutions in temperature control

BMW

MINI

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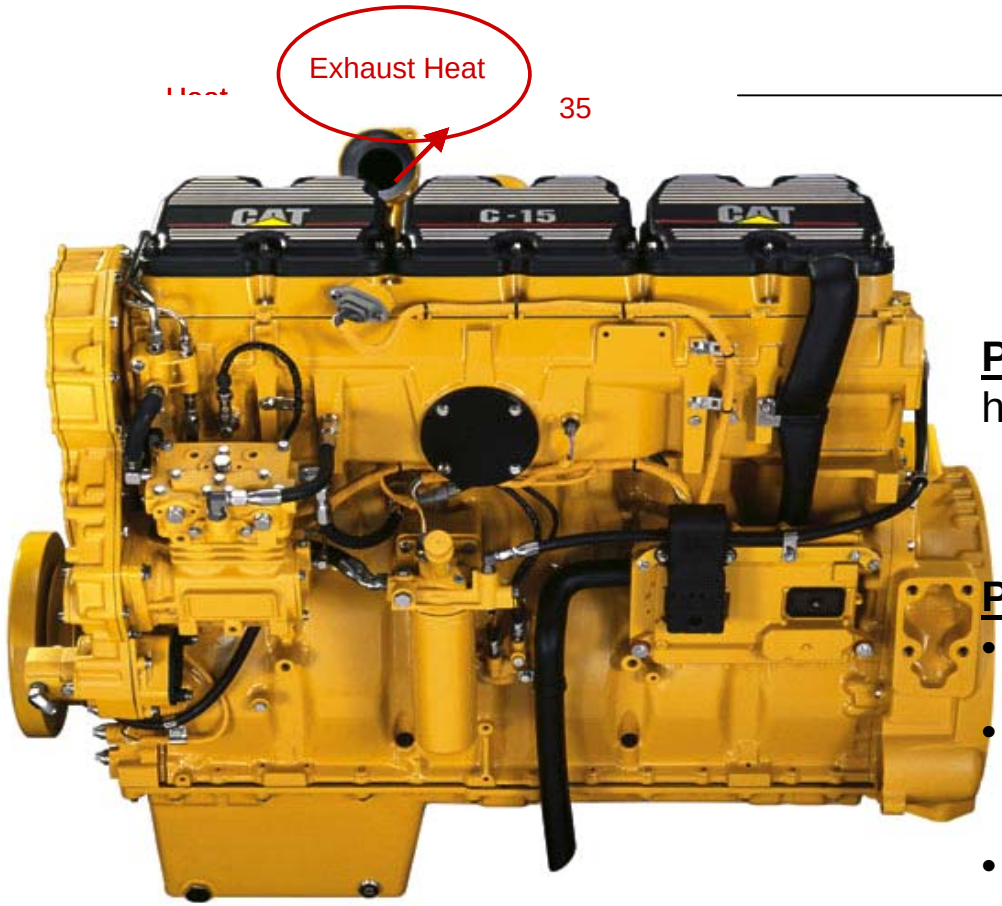
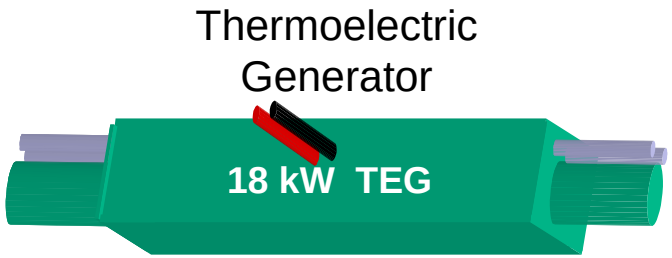
DOE/NETL Thermoelectric Generator Program for Heavy Duty Trucks





Project Objective: Improve fuel efficiency of heavy-duty, on-highway trucks by 10%

Phase I Results:

- 18 kW TE generator designed
- Full system projects 8 – 8.5% improvement in fuel economy
- critical customers demand, to buy, 2 – 9% improvement in fuel economy

DOE NETL Program Managers: John Fairbanks / Aaron Yocum

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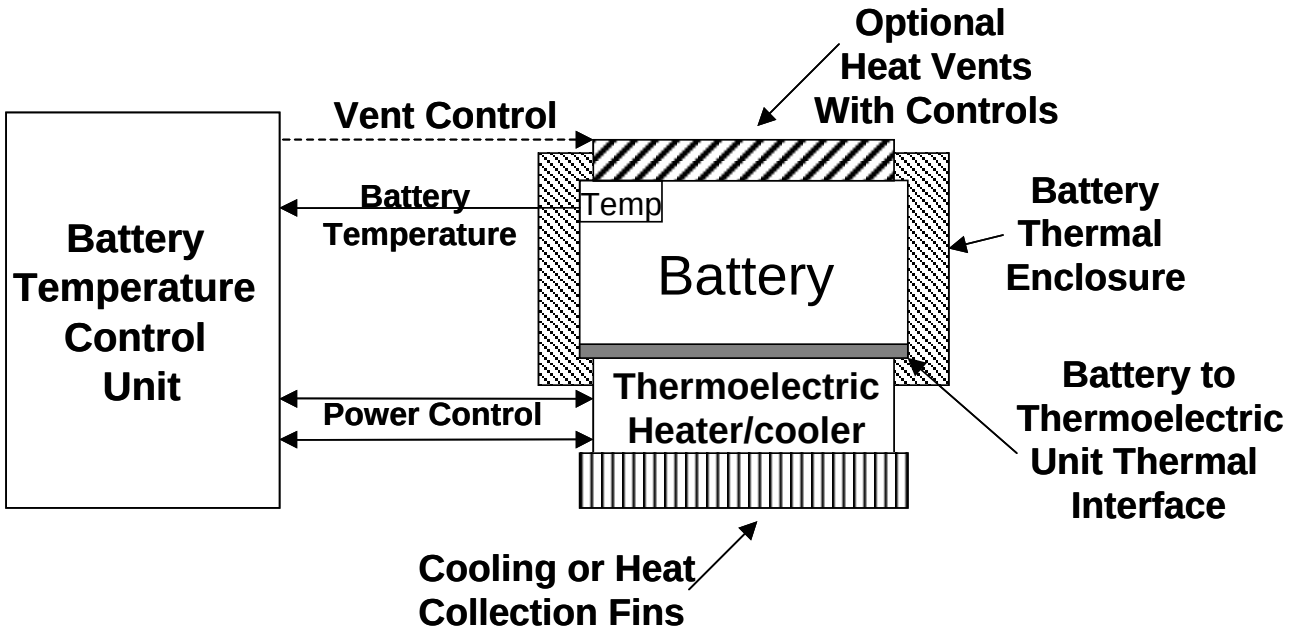
Fuel savings comparison for energy recovery in diesel powered vehicles

	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

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

Barriers/Challenges

- Costs
- Leakproof heat transfer fluid connections
- Vehicle operational vibration stress and strain
- Optimize heat transfer to thermoelectric modules
- Maintain viable electrical contacts
- Dedicated radiator for Thermoelectric Generator
- System weight
- Acceptance of revolutionary technology

Follow On Vehicular Thermoelectrics

- **Thermoelectric Cooler/Heater (HVAC)**
- **Integrate Thermoelectric Generator with Thermoelectric Cooler/Heater**
- **2nd Generation Thermoelectric Generators (20 % Efficient) and Cooler/Heaters (COP >2)**
- **Thermoelectric Generator (30 % efficient) Replacing Automotive SI Gasoline Engine**

CO_2 Produced by Burning One Gallon of Gasoline

- 1 gallon of gasoline weighs 6.3 lbs.
  - Carbon atomic weight is 12
  - Oxygen atomic weight is 16
  - CO_2 atomic weight is 12 + (2x16) = 44
  - CO_2 per lb. Carbon = 44/12 = 3.7
- Gasoline is ~ 87% Carbon (and 13% Hydrogen)
  - Carbon in gasoline is (0.87x6.3) = 5.5 lbs.
- CO_2 produced from burning one gallon of gasoline
  - (3.7 lb. CO_2 /lb. C)x(5.5 lb. C/gallon gasoline) = 20.4 lb. CO_2/ 1 gallon gasoline combusted

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

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.

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 of Using Air Conditioning

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

Integrated 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**
- **First Generation Thermoelectric Generators being developed in the DOE/NETL Program Could supply this DC Power**

Advantages of Distributed Thermoelectric Cooling/Heating

- Delivers climate control directly to occupants
  - uses < 1/4 the power consumed by centralized system
- Improves occupant comfort by fast response and individual control
- Improves reliability since no moving parts or refrigerant gas
- Lowers cost, weight and complexity
  - Compatible with electrification of vehicle powertrains and subsystems

Replacing R134-a Compressed Gas System with Thermoelectric HVAC

- **3.1 Million Metric tons CO_2e Leak/year from 198 million personal vehicles in the U.S.**
- **Disbursed Thermoelectric HVAC requires 1/4 the energy of Compressed Refrigerant Gas (46.5 gallons saved per vehicle per year)**
- **(46.5gals)(8.9 kg CO_2/gal) = 414 kg CO_2/vehicle.**
- **(414kg CO_2) (198 M vehicles) = 8.2 M Metric tons**
- **(3.1) + (8.2) = 11.3 Million Metric Tons CO_2e Saved**

Integrated Thermoelectric Generator Powering Thermoelectric Cooling/Heating Unit

- Would save 12.3 Billion gallons of fuel/year when installed in US personal vehicle fleet
- Or (12.3 x 10^9 gals) (8.9 kg CO_2e/gal) = 110 million metric tons of CO_2e + Leakage

(142 kg CO2e/yr vehicle) (198 M Vehicles) =

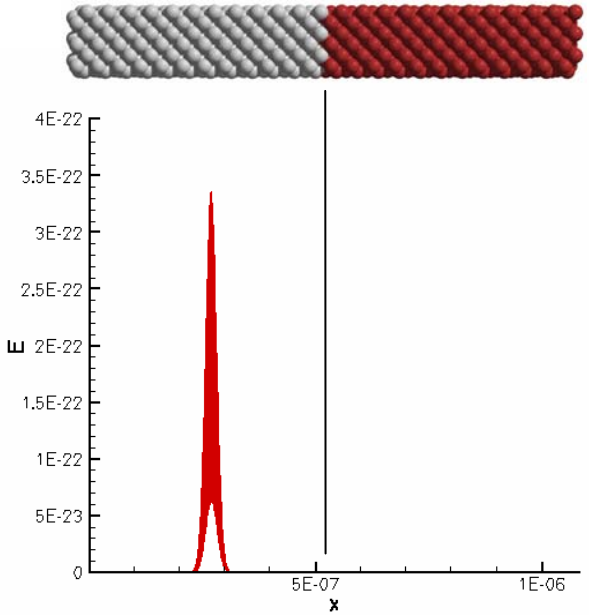
28.1 million metric tons of CO_2e

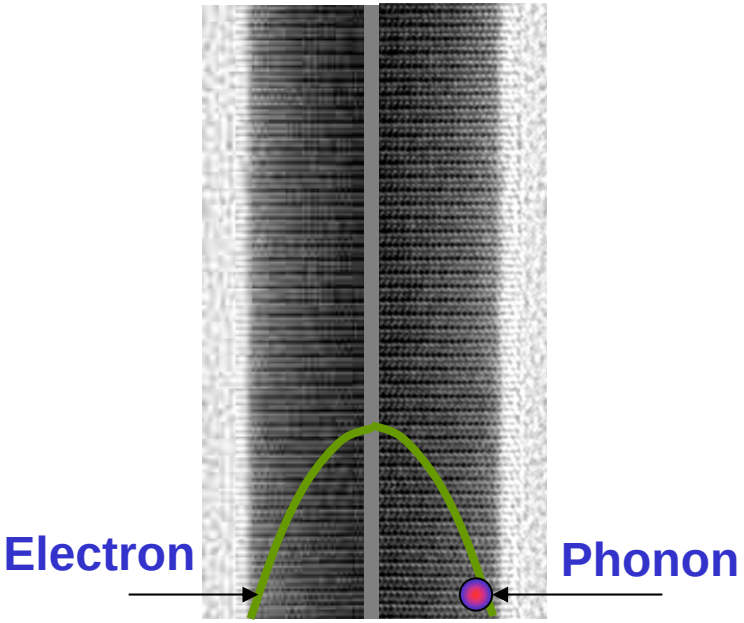
Total 138 million metric tons of CO_2e/year when 90 percent of U.S. personal vehicle fleet has TEG powering TE HVAC.

Nanoscale Effects for Thermoelectrics

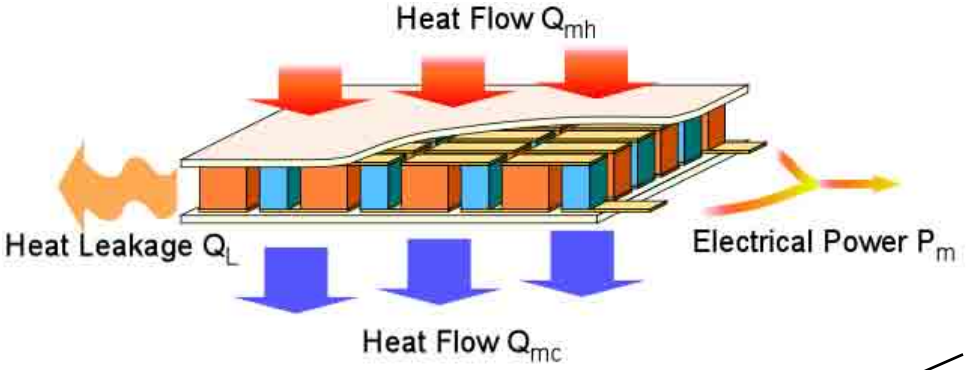
Interfaces that Scatter Phonons but not Electrons

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



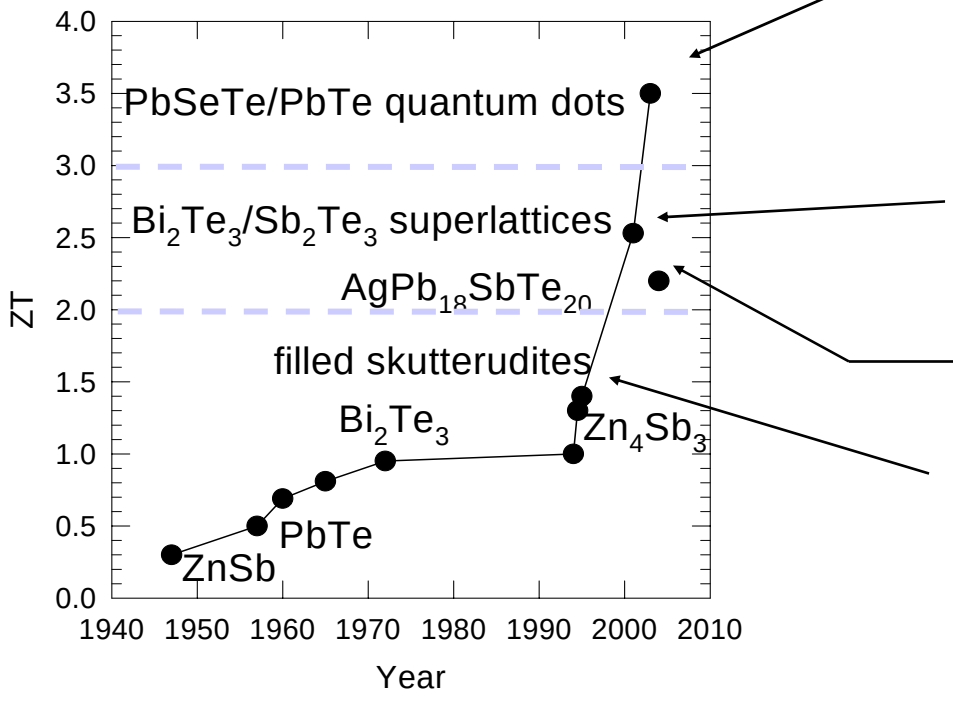


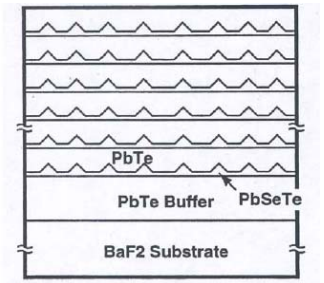
Recent Advances in Efficiency of Thermoelectric Materials

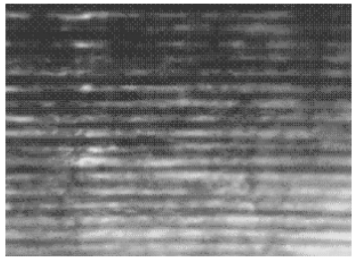


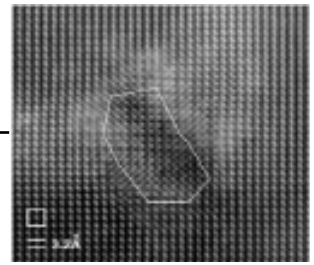
Efficiency:

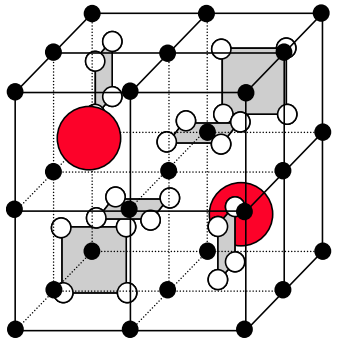
$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}}$$











» Many recent thermoelectric material advances are nano-based

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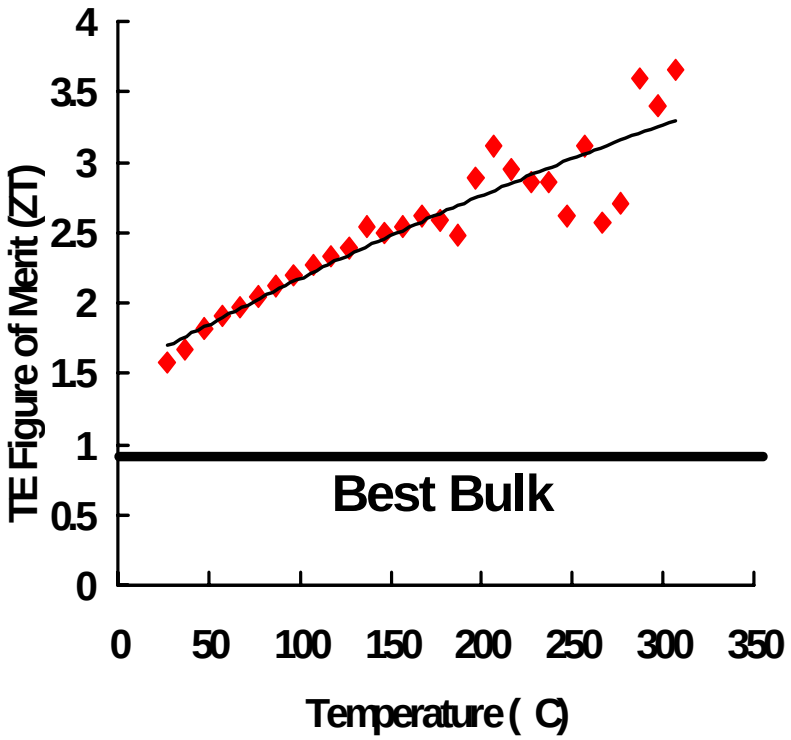
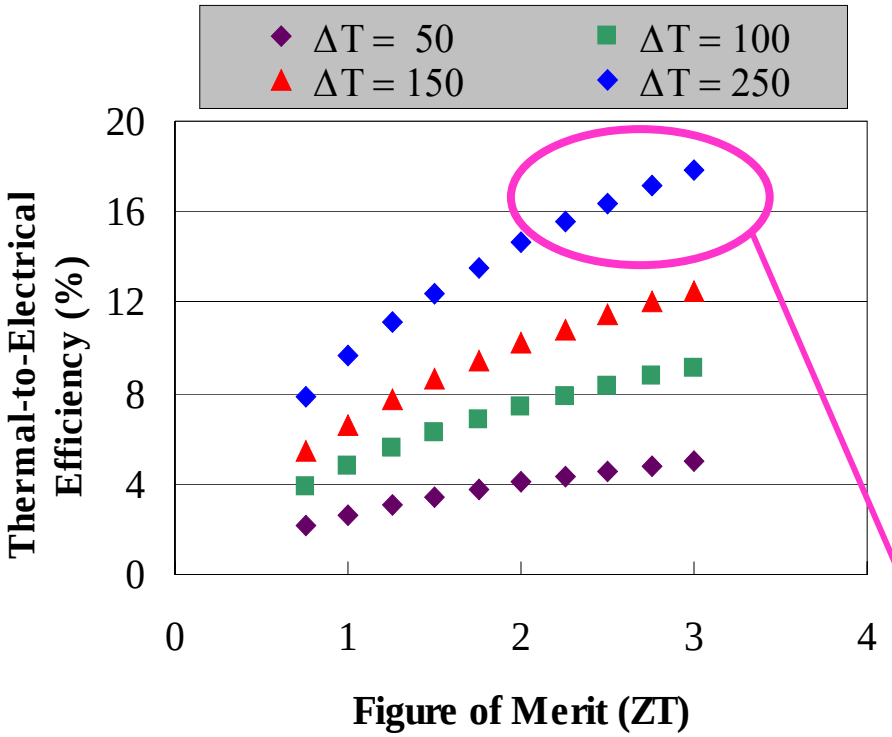
N-type QDSL TE Performance



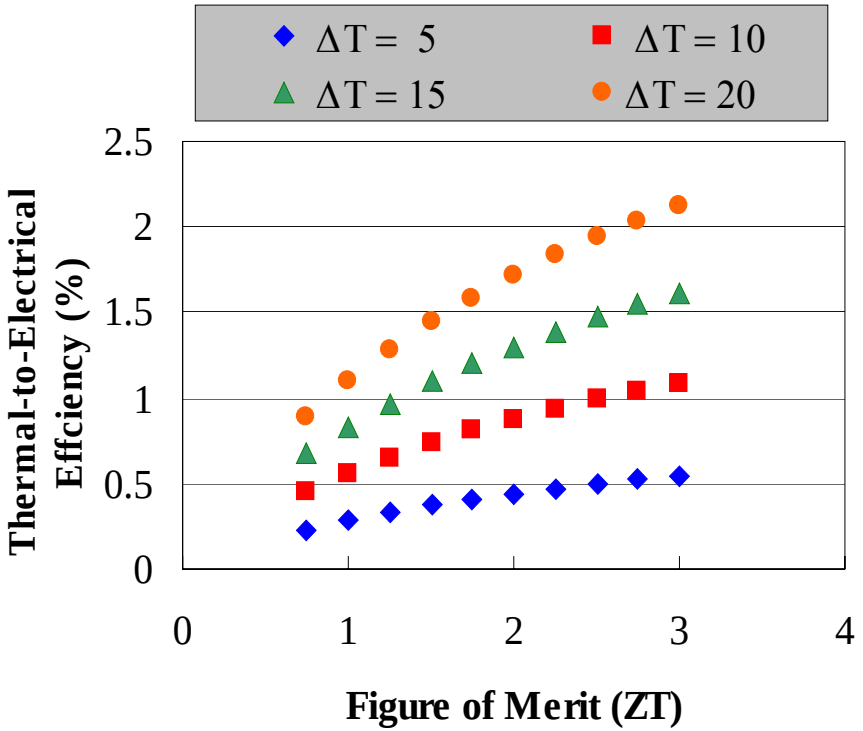
•ref. TC Harman et al , Science 297 (2002) p 2229

Impact of ZT on Efficiency

Medium-Grade Heat Sources



Low-Grade Heat Sources



Exciting for many applications

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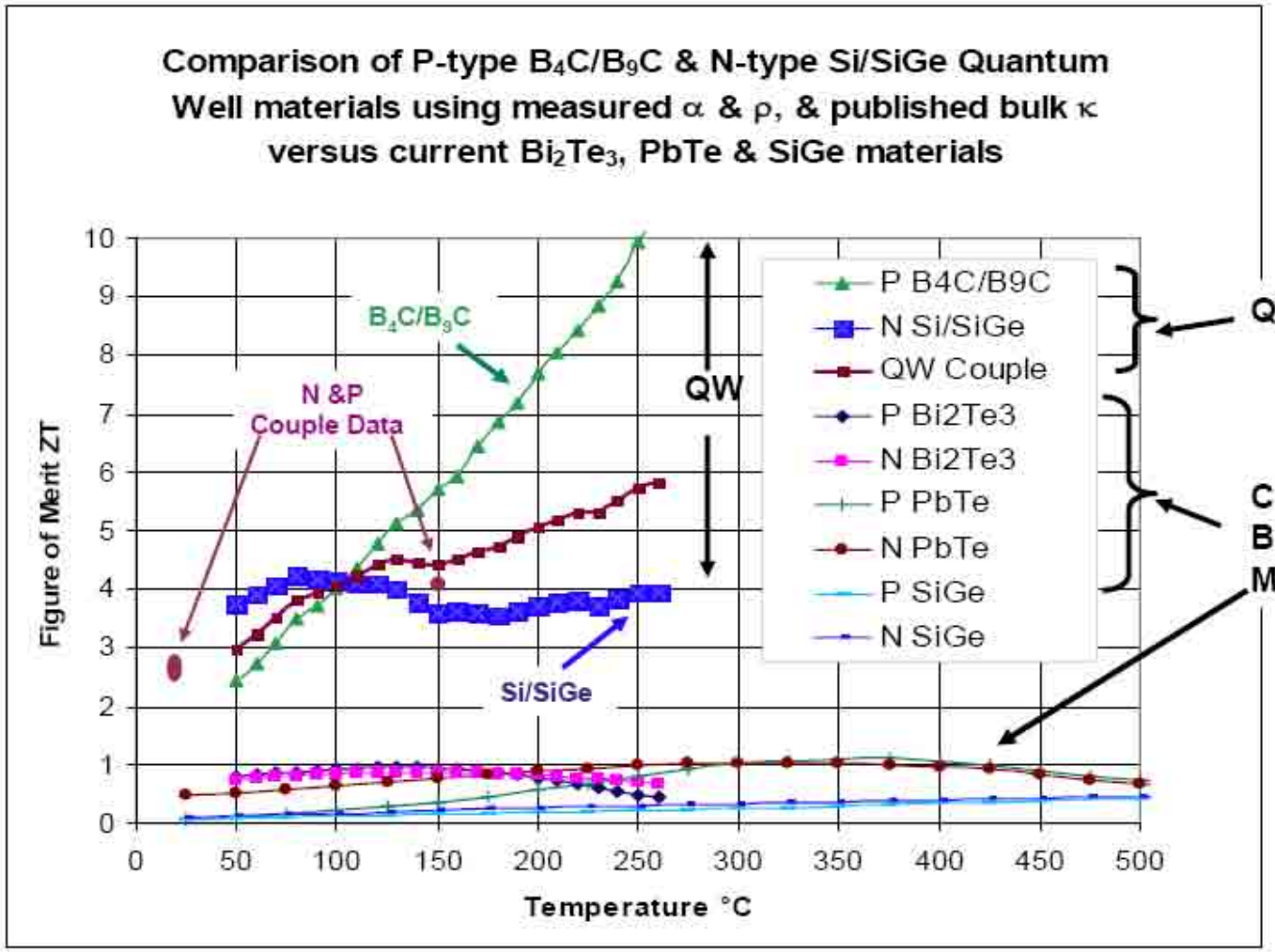
Advanced Thermoelectric Figures of Merit



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

Hi-Z TECHNOLOGY, INC.

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 scheduled at
      - » NASA - JPL
      - » Oak Ridge National Lab

This would be a > 300 % Improvement in Efficiency !

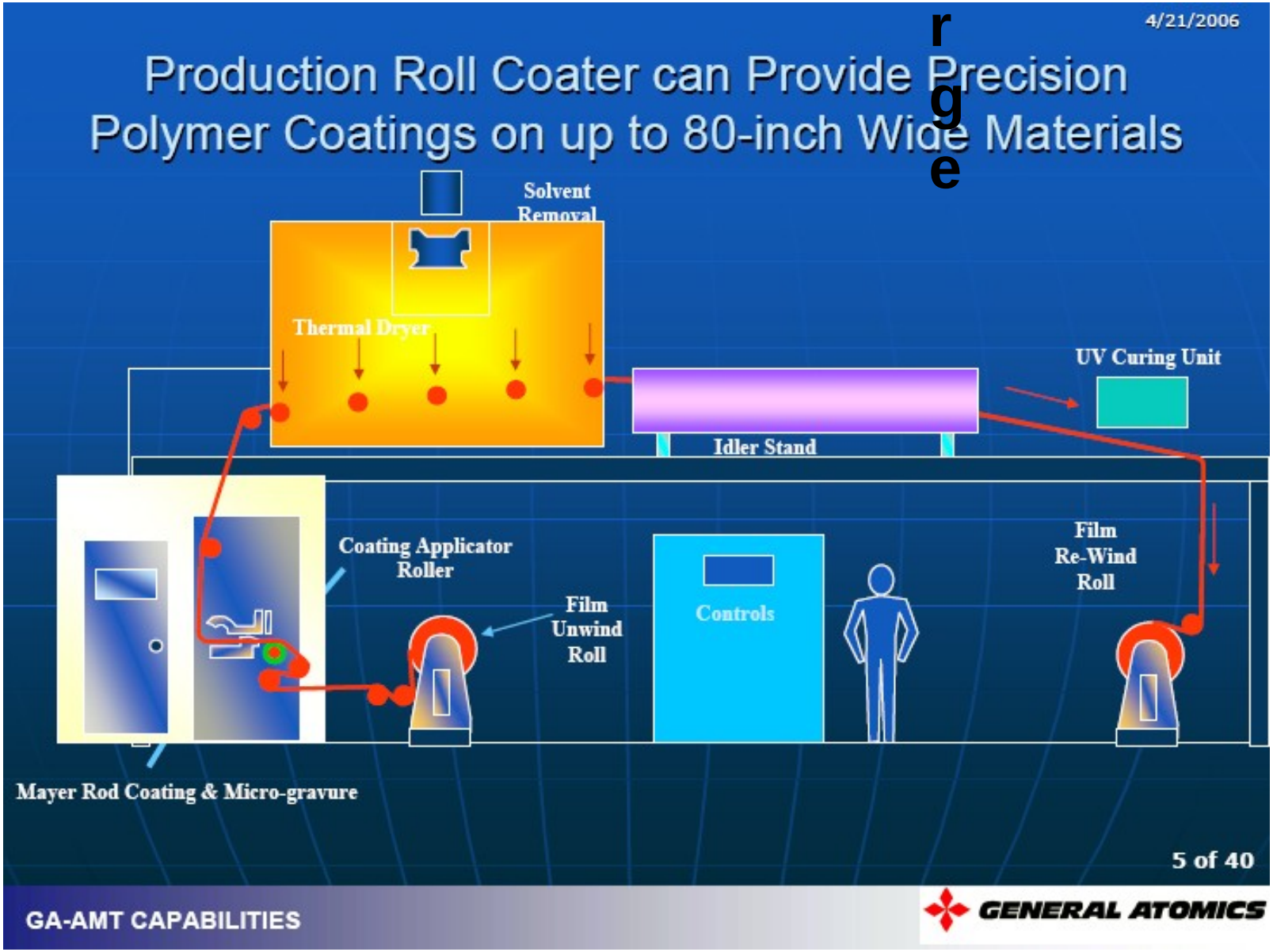
General Atomics Sputtering Capabilities

New coatings developed on R&D coater

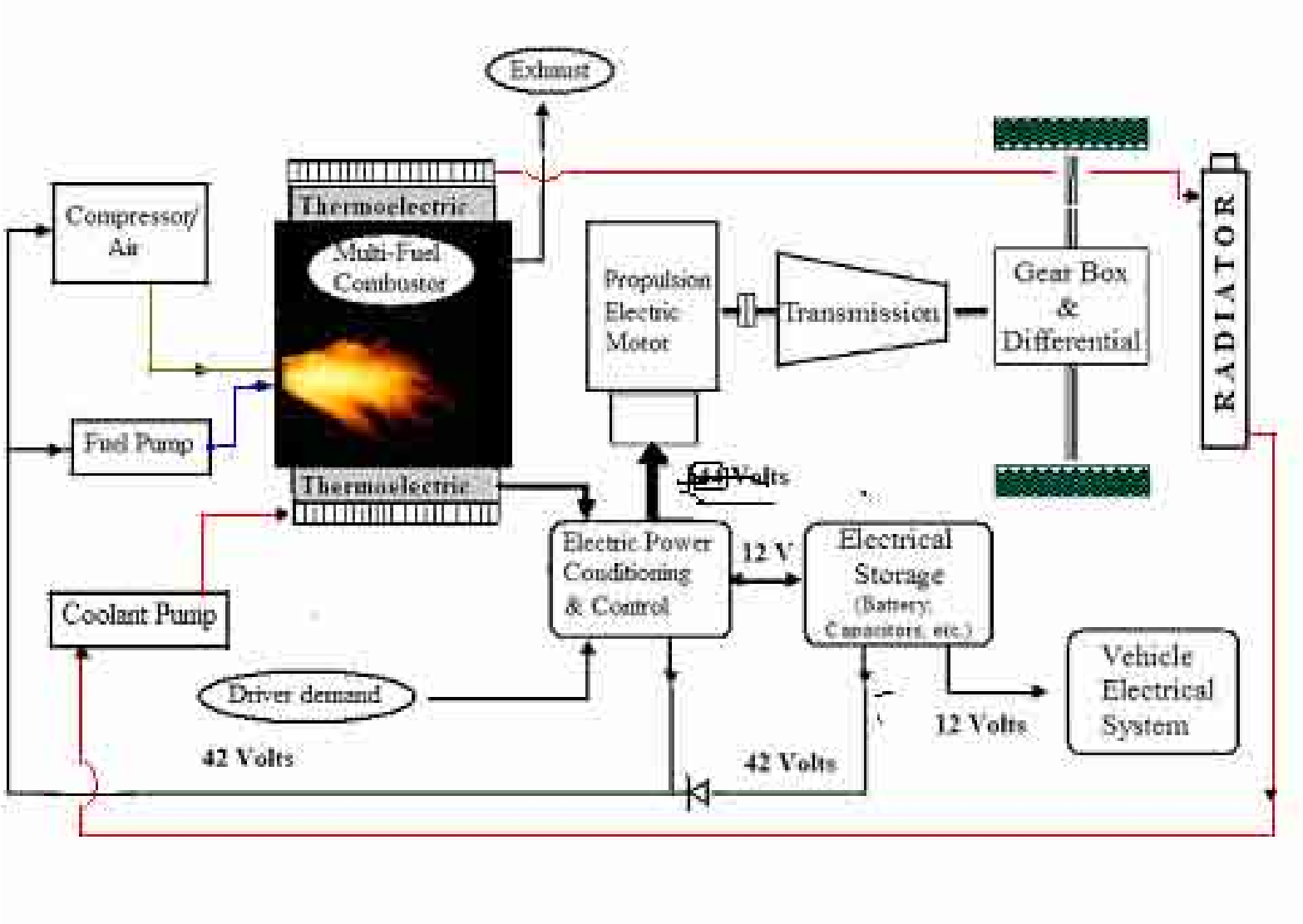
New products developed on R&D Web Coaters

Material production on 80" Web Coater

Large Scale Sputter Coating System



Solid State Thermoelectric Hybrid Vehicular Electric Powertrain



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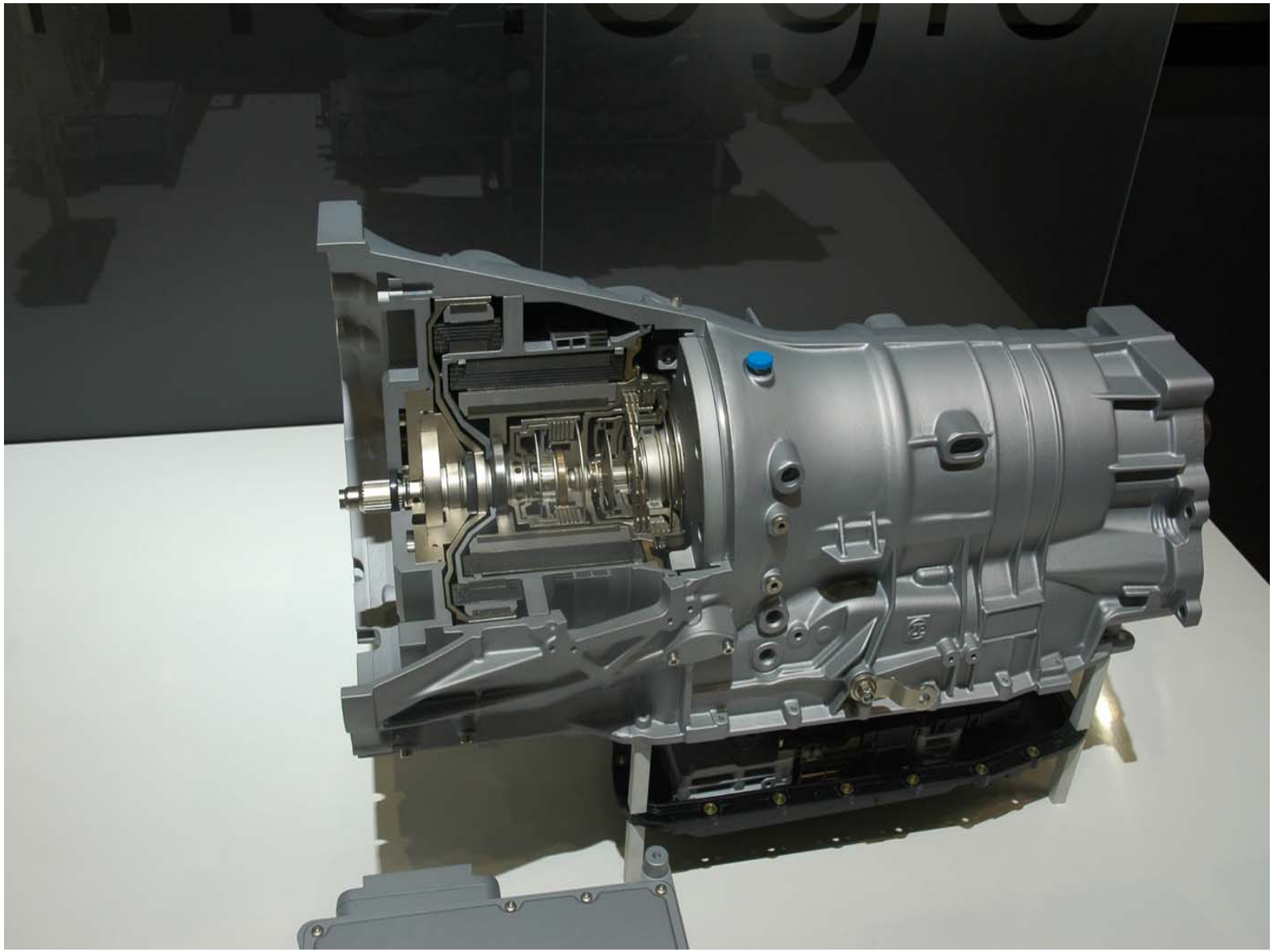
Transmission Electrical to Mechanical



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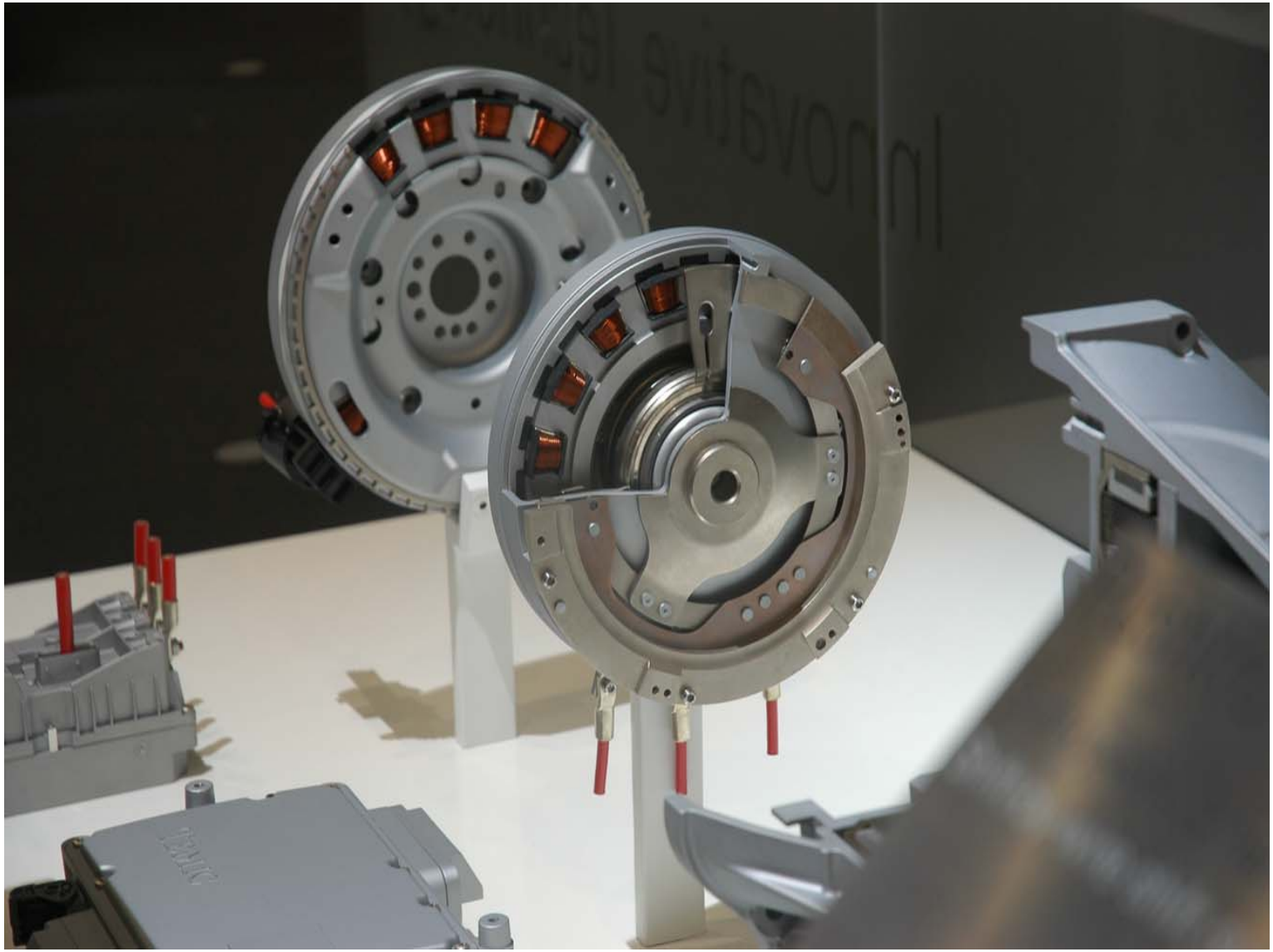
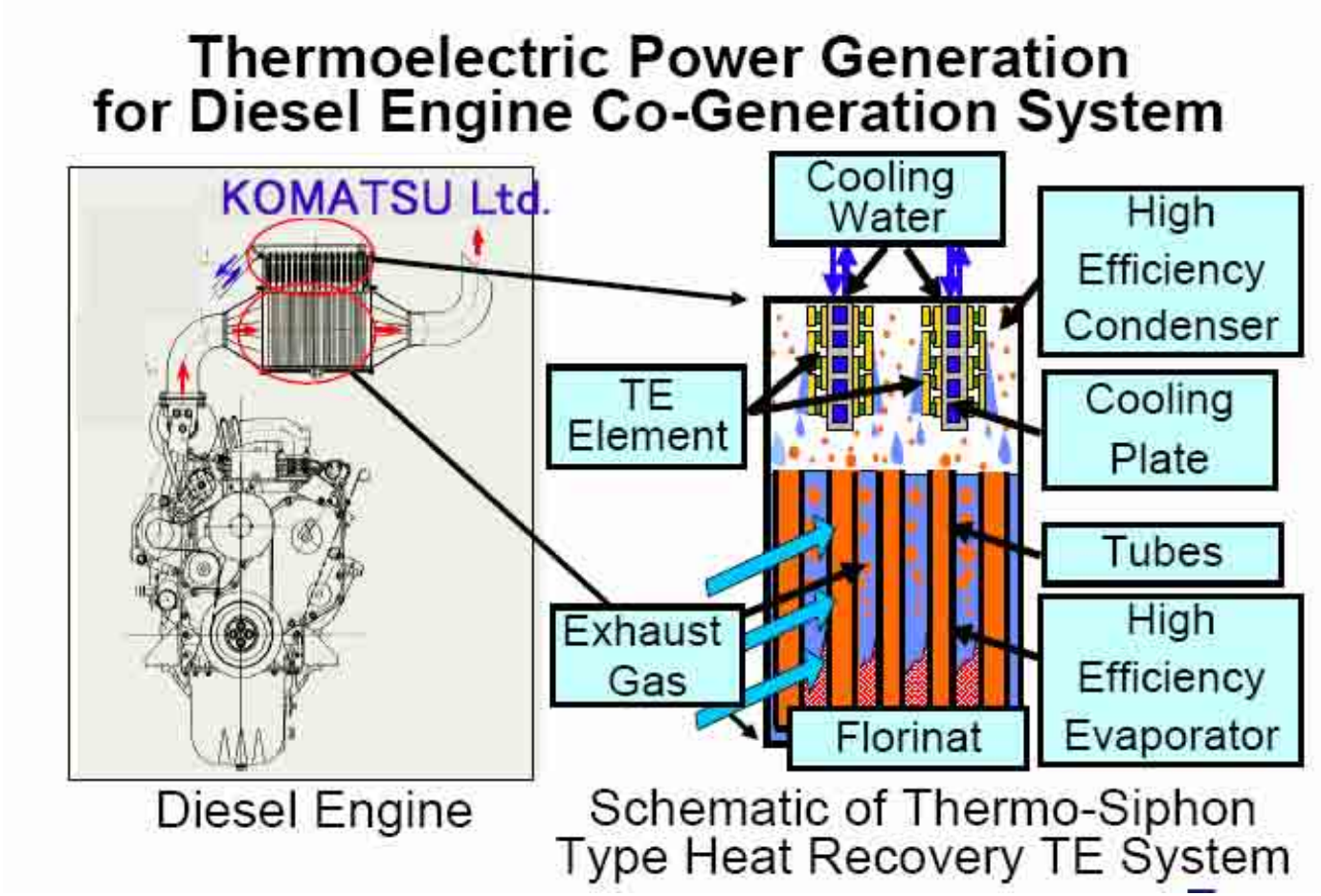
Electric Motor Drive Wheels "Drive by Wire"



Japanese Vehicular Thermoelectric Generator Program



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

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VEHICLE THERMOELECTRIC APPLICATIONS TIMELINE

- Current Vehicular Applications of Thermoelectrics
  - Climate Control Seats
  - Drink Cooler/Heater
  - 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 (2017 +)

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

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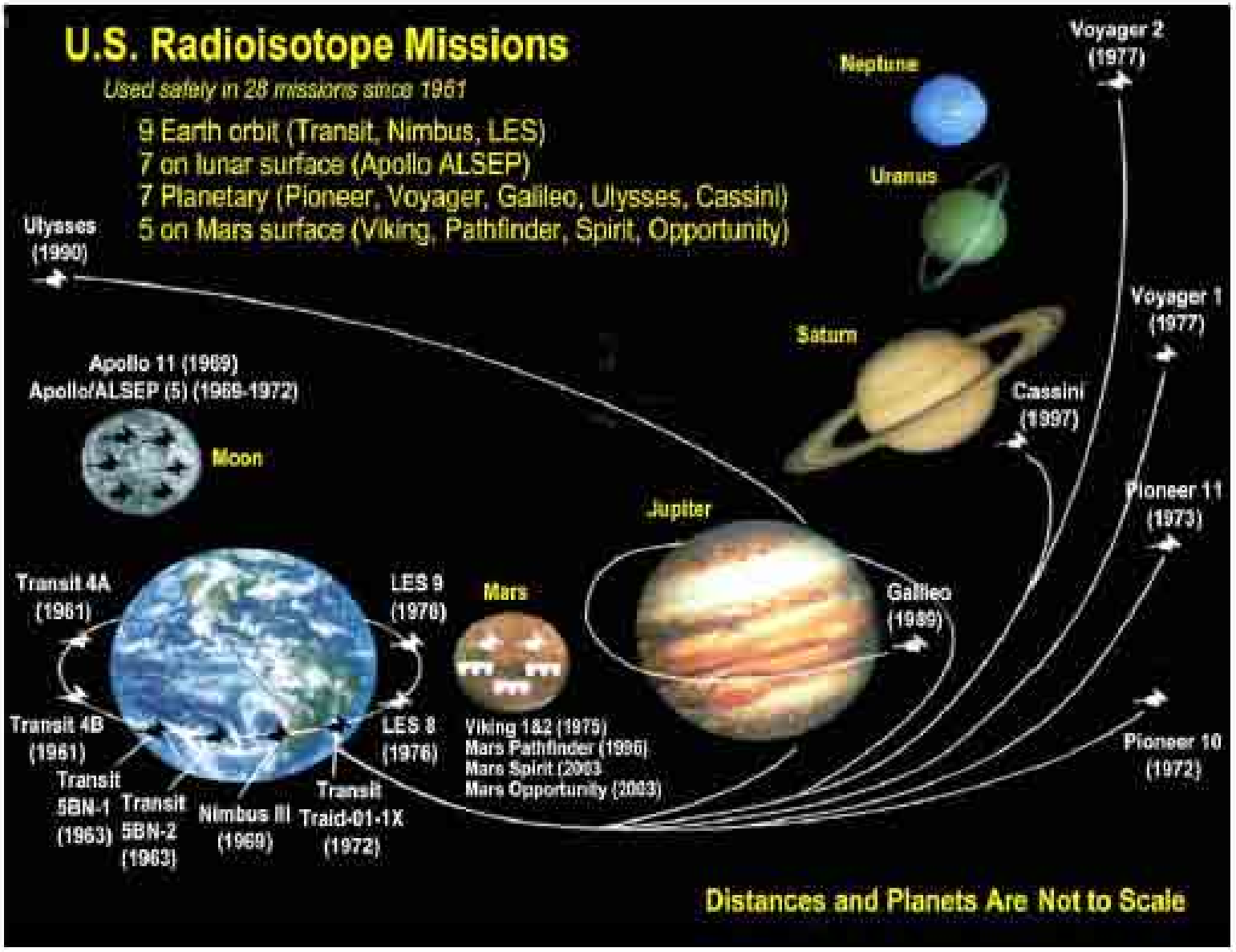
Spacecraft Using Radioisotope Thermoelectric Generators



Making It Happen Thermoelectric-wise

- 1st Generation Vehicular Thermoelectric Generators and HVAC systems will pioneer solid state power applications
- Nanoscale thermoelectric materials have emerged in Labs that are > 300 % more efficient than those in 1st generation devices
- Scaling up nanoscale thermoelectrics is difficult and expensive
- Successful introduction of 1st generation thermoelectric devices should enhance investment by commercial, government and venture capitalists in commercially viable scale-up as well as expanding fundamental work