The Growth Potential of Thermoelectrics

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Department of Energy
Washington, DC

Thermoelectric Applications Workshop
Del Coronado Hotel
San Diego, California
September 29, 2009

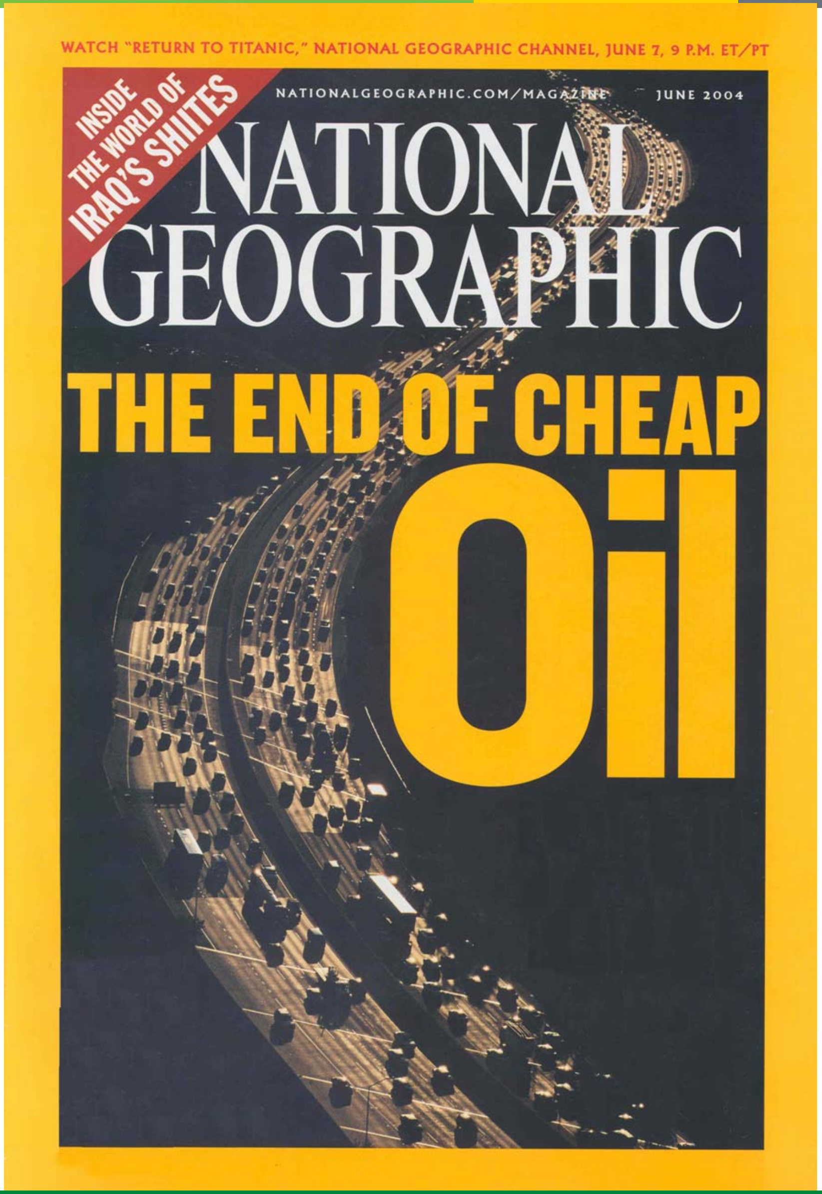
Workshop Overview

- **Thermoelectric Material Efficiency is being Improved**
- **Thermoelectric Technology and Applications are in Accelerated Development World-Wide**
- **Every Major Automotive Vehicle OEM is investigating Thermoelectric Applications**
  - **Thermoelectric Generators will be Commercially Introduced in Autos in a Limited Number as early as 2013**
  - **Thermoelectric Air Conditioner/Heaters (HVAC) Scheduled for Commercial Introduction on or about 2015 in Autos**
  - **Historically Semiconductor Costs Come Down with Large Increased Volume**

Opportunities for Thermoelectrics

Increased Availability and Lower Costs of High Efficiency Thermoelectric Modules Should Stimulate Opportunities for Thermoelectric Direct Conversion of Waste Heat to Electricity for:

- **Industrial Processes,**
- **Stationary Power Plants,**
- **Marine, Rail and Aircraft**
- **Off-Highway Engines,**
- **Geothermal**
- **Wide Range of Military Applications**


WATCH "RETURN TO TITANIC," NATIONAL GEOGRAPHIC CHANNEL, JUNE 7, 9 P.M. ET/PT
INSIDE THE WORLD OF IRAQ'S SHIITES
NATIONALGEOGRAPHIC.COM/MAGAZINE
JUNE 2004
NATIONAL GEOGRAPHIC
THE END OF CHEAP
Oil

Opportunities for Thermoelectrics

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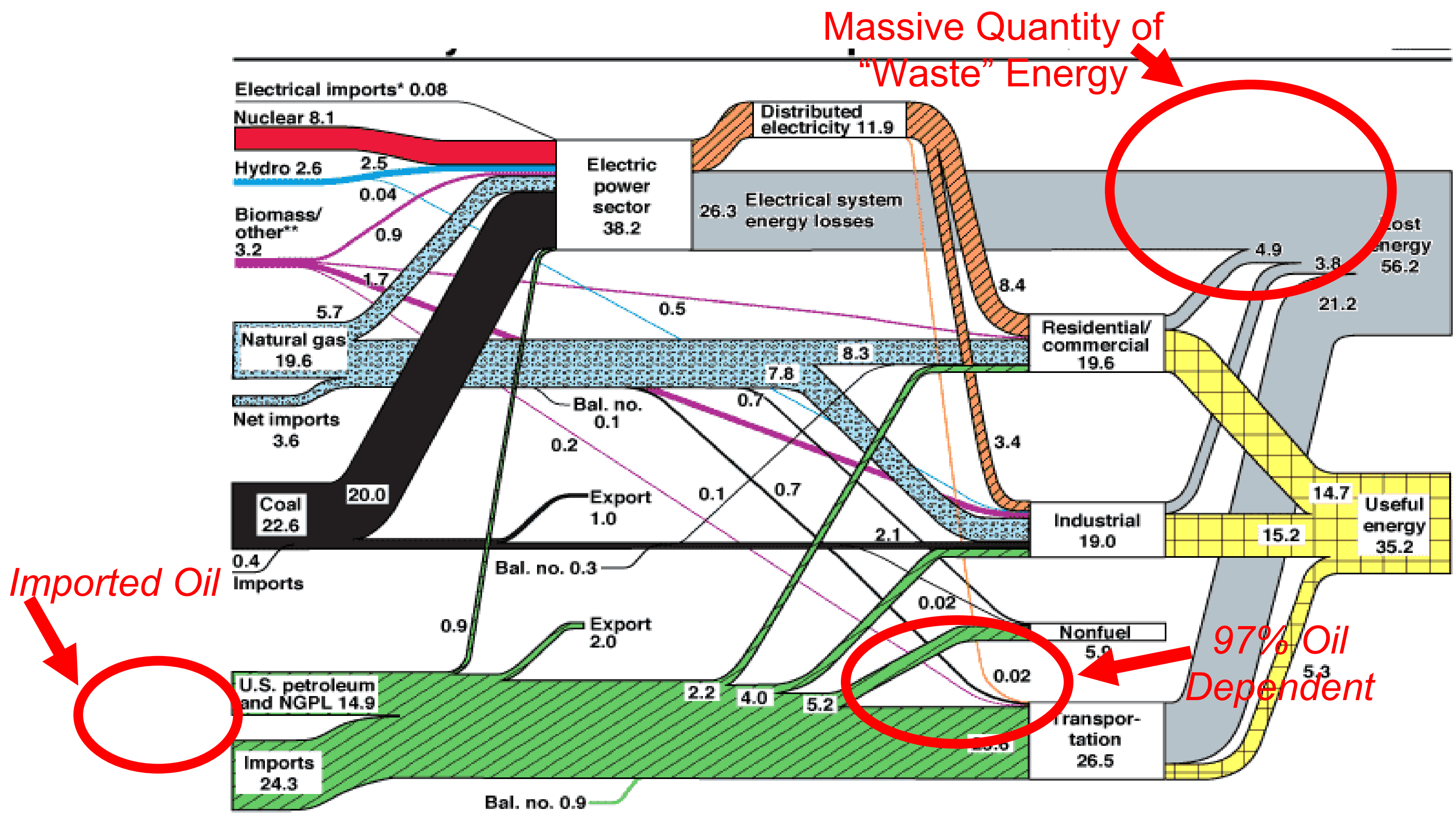
"Waste Heat" Can Be Directly Converted to Electricity



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002*.
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

June 2004
Lawrence Livermore National Laboratory
http://eed.llnl.gov/flow

International Perspective

- The World uses 83,700,000 barrels of non-renewable petroleum daily
- When does demand for petroleum exceed supply ?
- Transportation is going more electric
  - Thermoelectrics can have a significant role
    - Also in other waste heat producing technologies

Beltless or More Electric Engine

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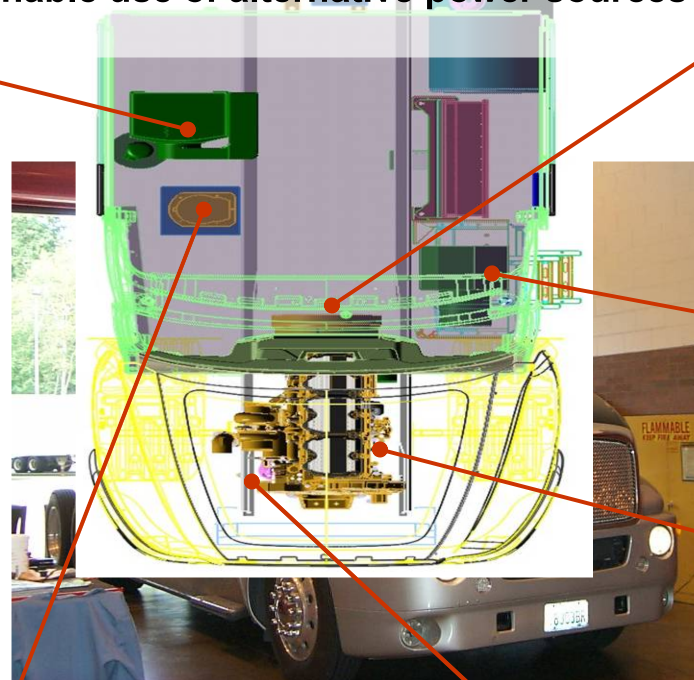
Truck Electrification

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

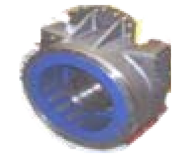
Down Converter

Supplies
12 V Battery from DC Bus

Compressed Air Module

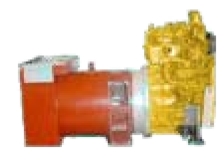
Supplies compressed air for brakes and ride control

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

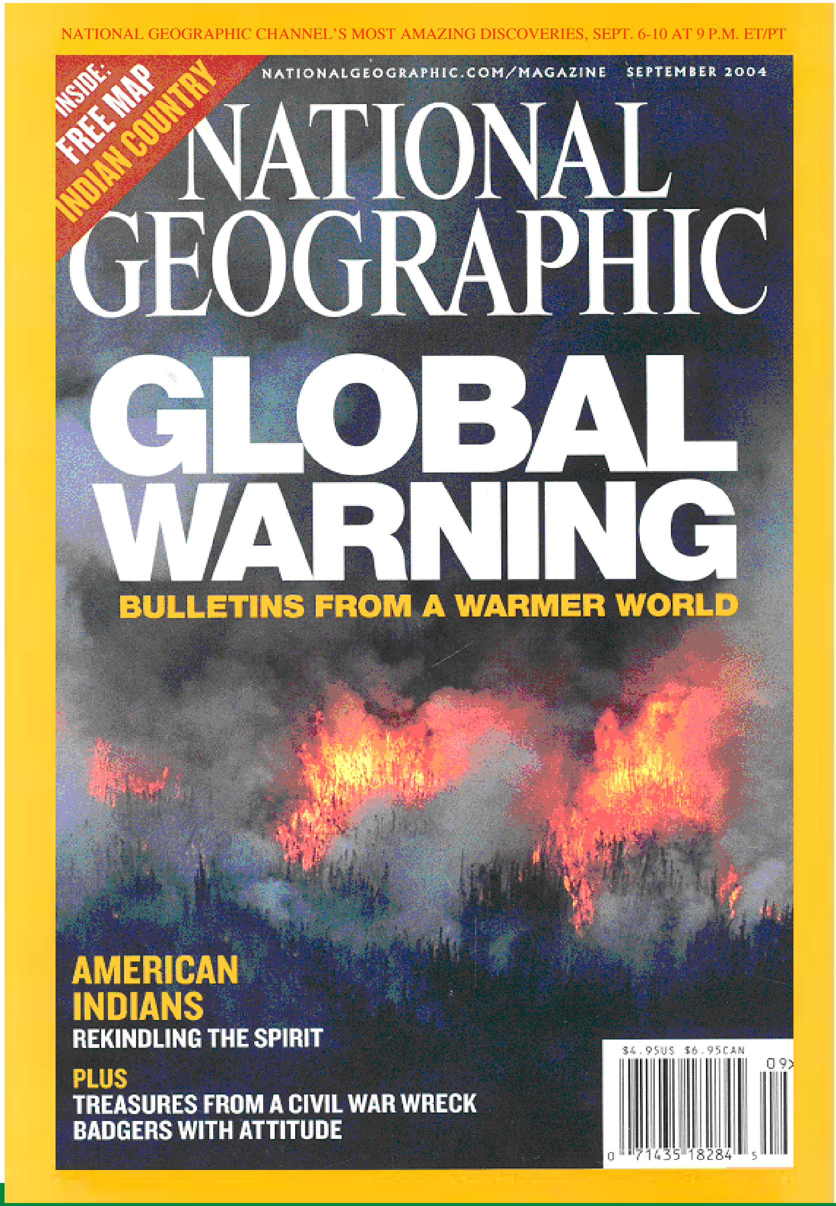
Electric Water Pump

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

Electric Oil Pump

Variable speed
Higher efficiency

Heating Up… Melting Down…



Carbon Balance Through Internal Combustion Engine

Gasoline C_7H_{16}

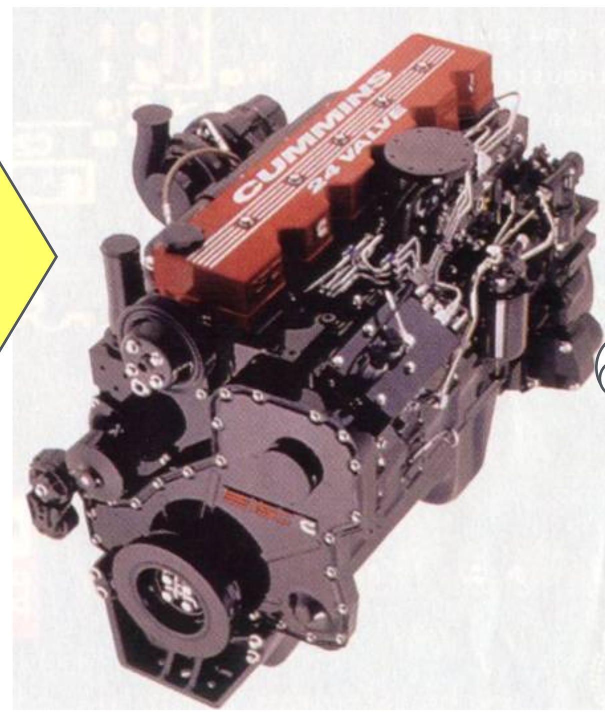
Diesel $C_{18}H_{30}$

Methanol CH_3OH

Ethanol C_2H_5OH

Natural Gas (Primarily Methane, CH_4)

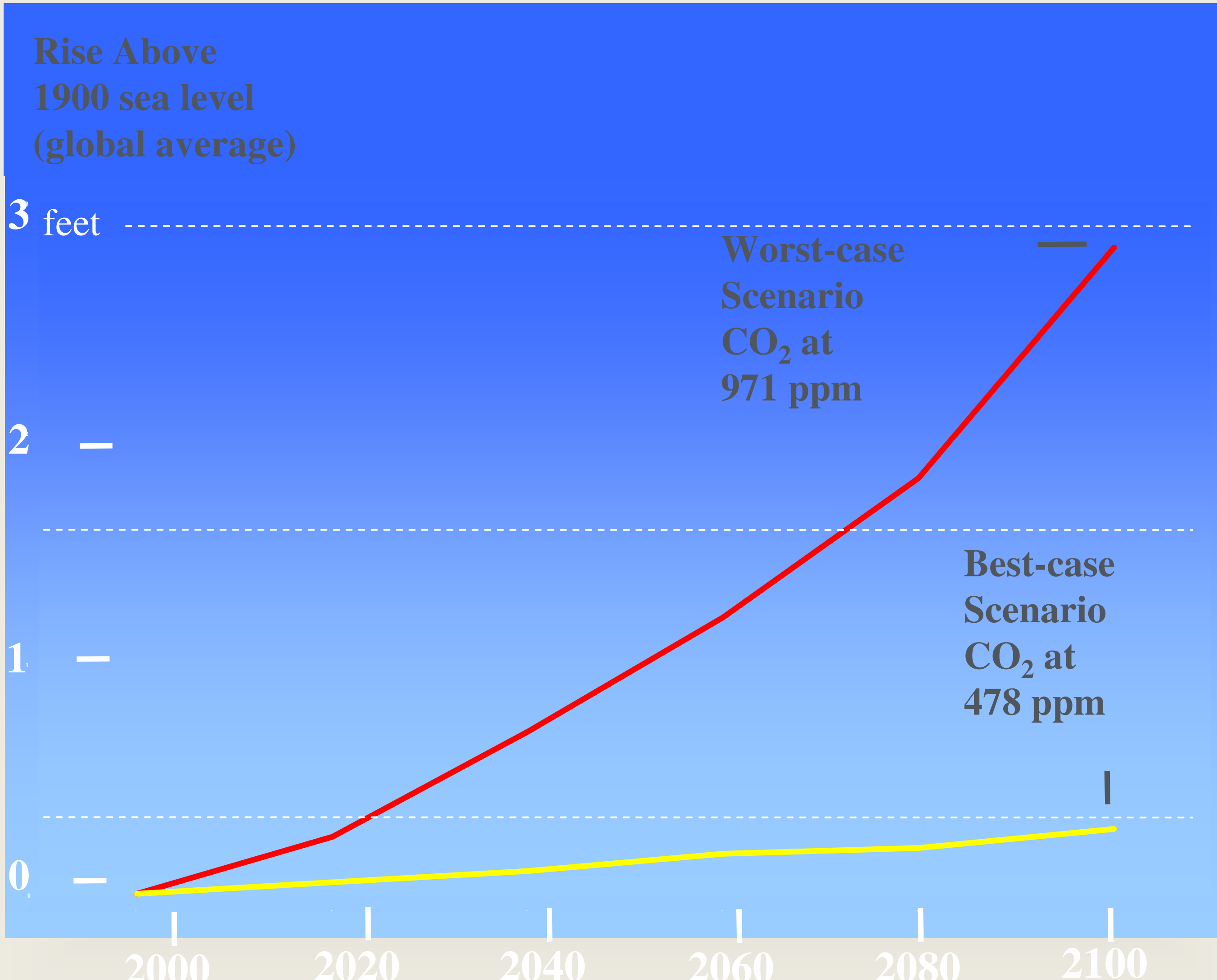
Propane C_3H_8



Carbon

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

Sea Level Rising

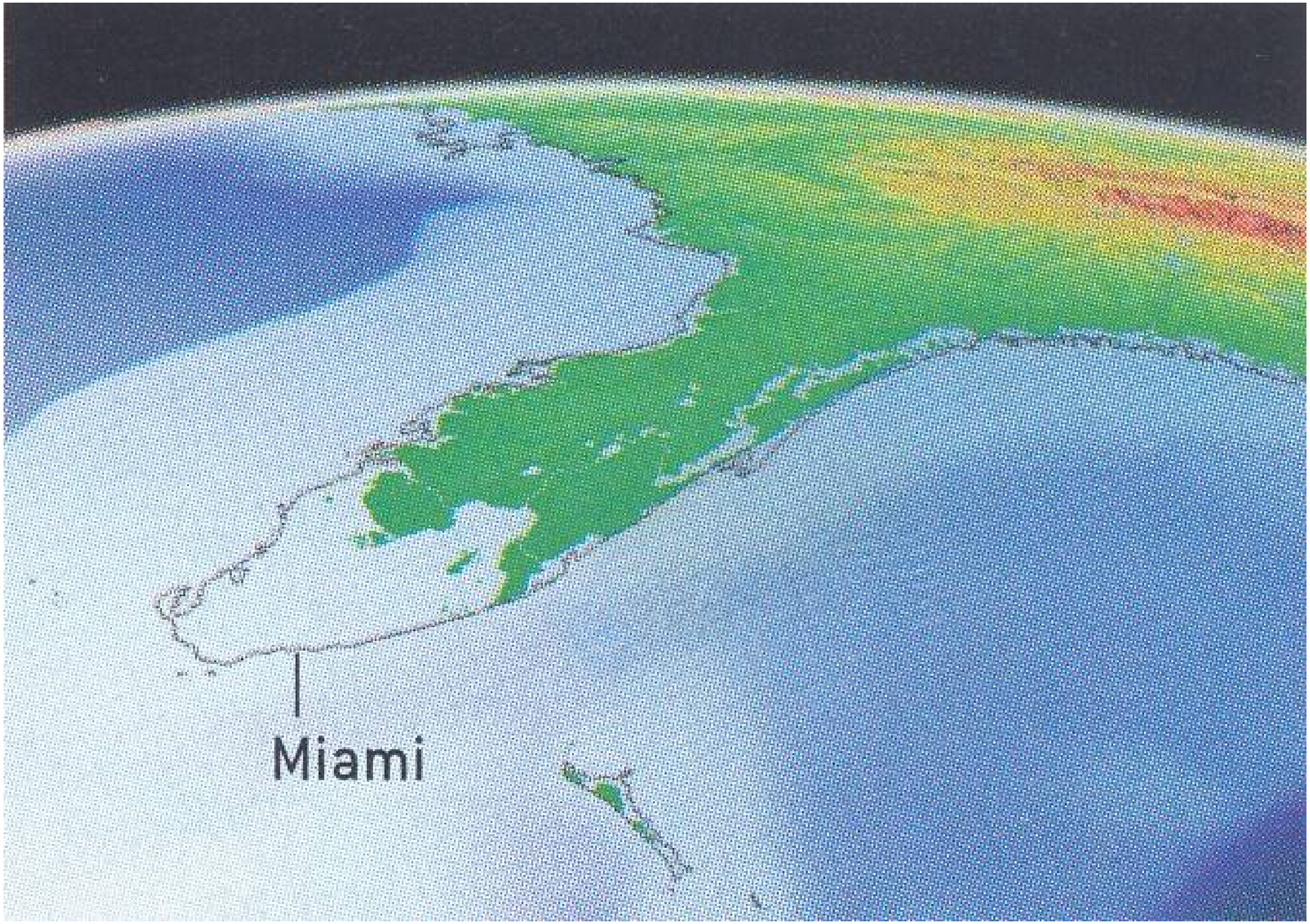


In Bangladesh, at just over 3 feet of rise, 70 million people could be displaced.

75 percent of coastal Louisiana wetlands would be destroyed at just over 1.5 feet.

Many low-Lying South Sea islands are at further risk of flooding at about 4 inches.

Source: National Geographic, September 2004



Worst Case Scenario

Available Energy in Auto Engine Exhaust

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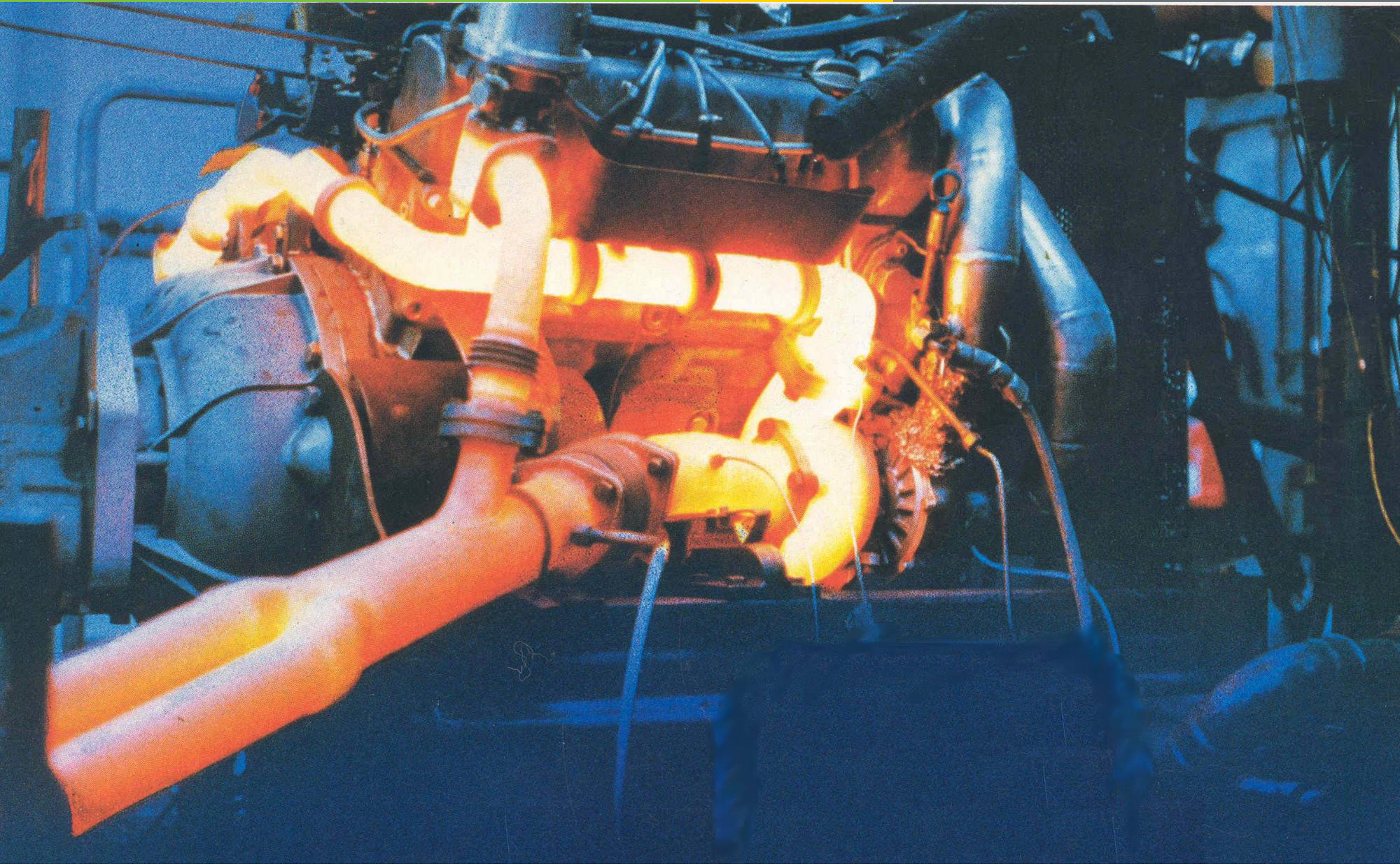
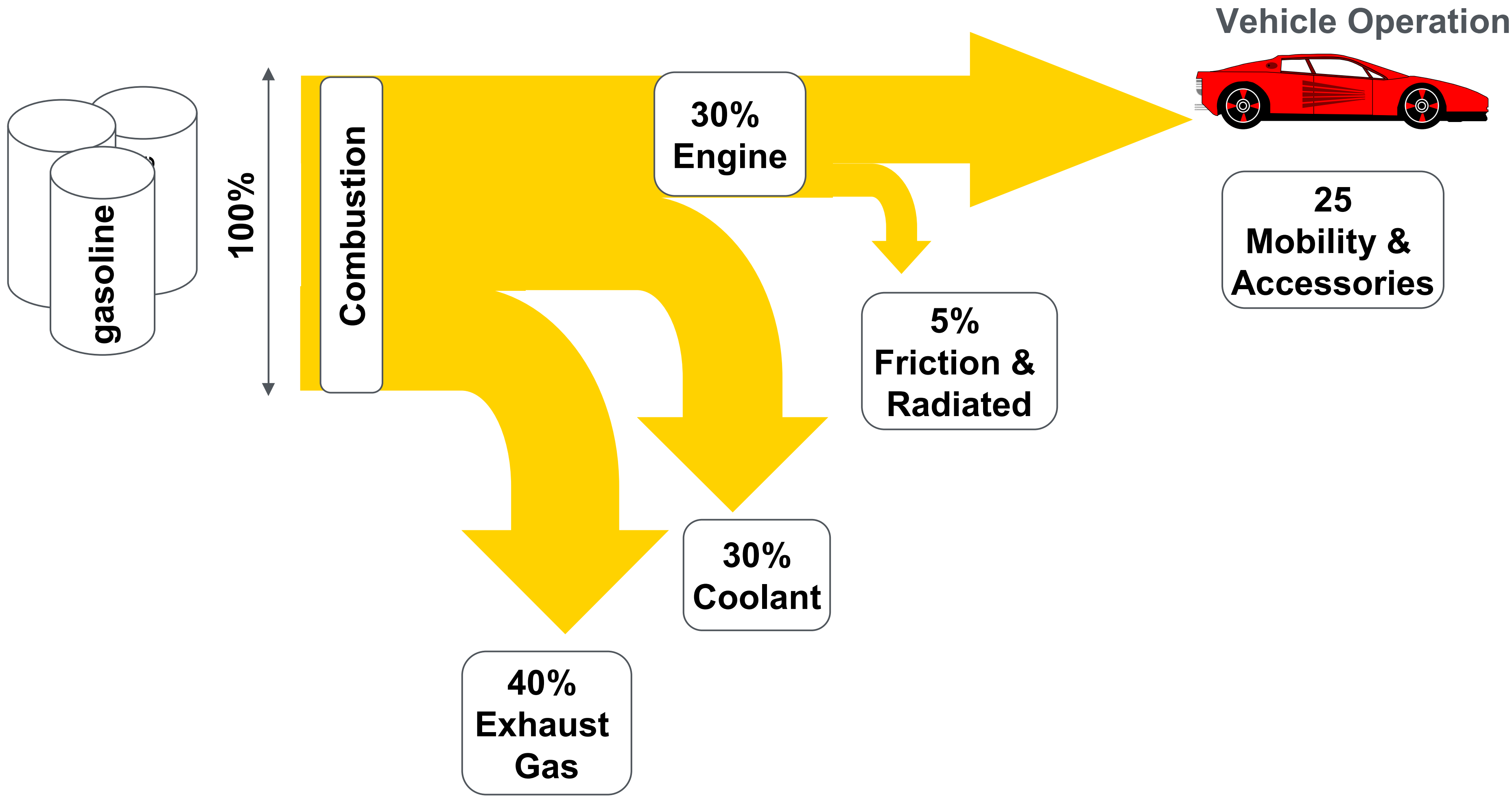
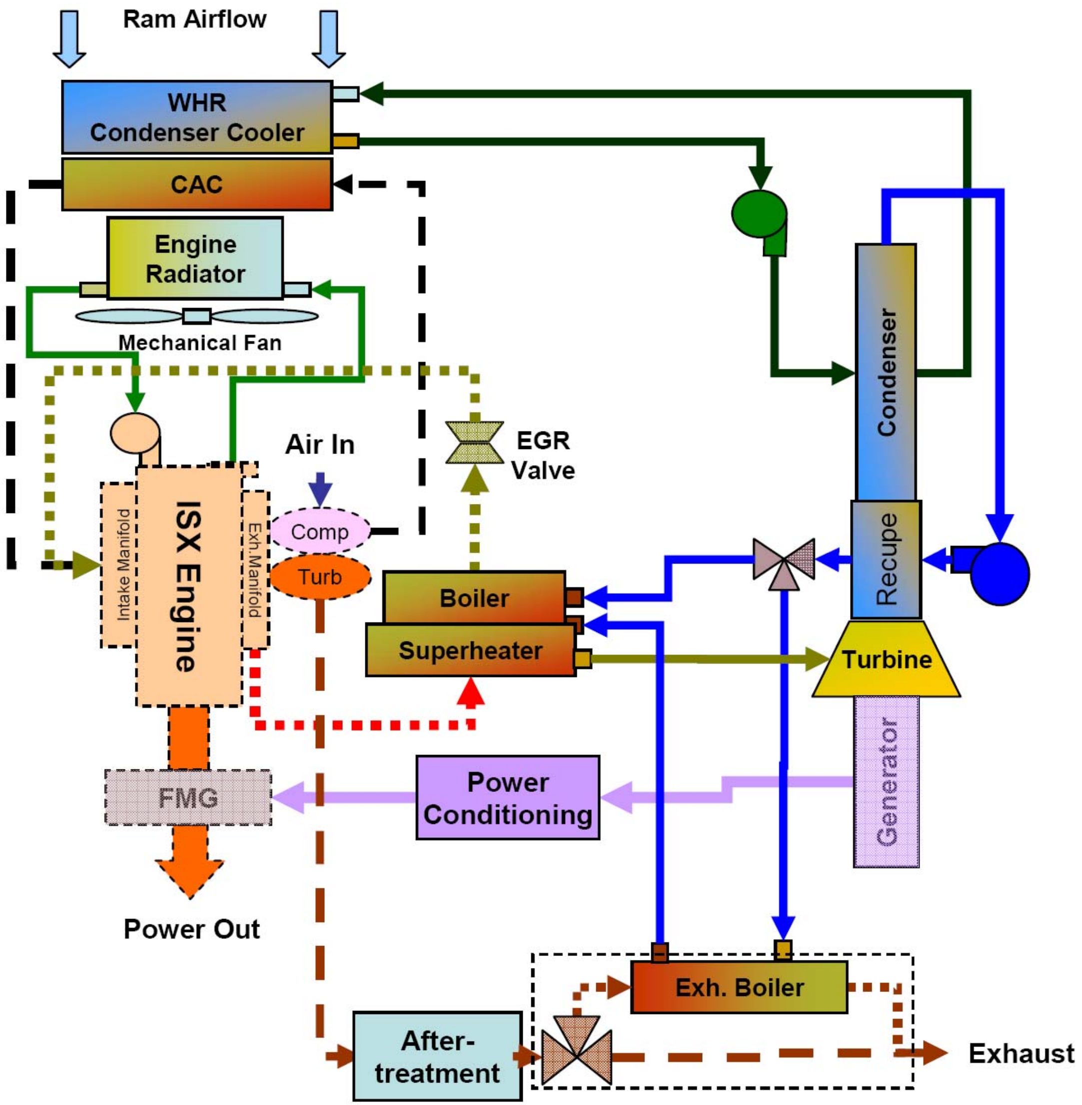


Potential Thermoelectric Heat Sources

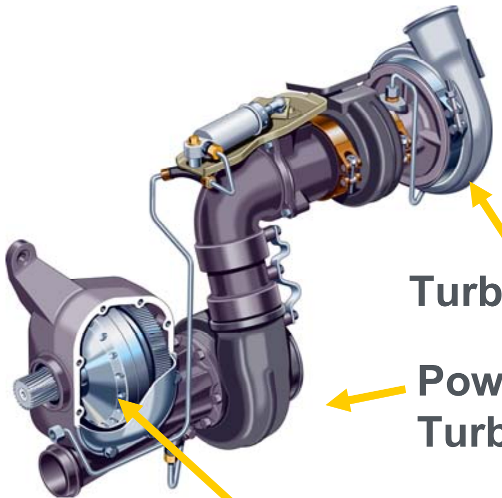


Spark Assisted Gasoline internal Combustion Engine (Light Truck or Passenger Vehicle)

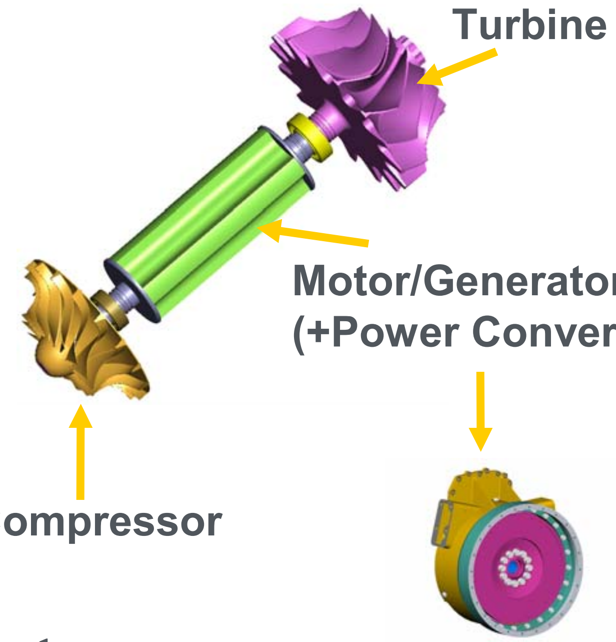
Organic Rankine Bottoming Cycle for Heavy-Duty Diesel Engine Waste Heat Recovery (Cummins Engine Co.)



Mechanical System

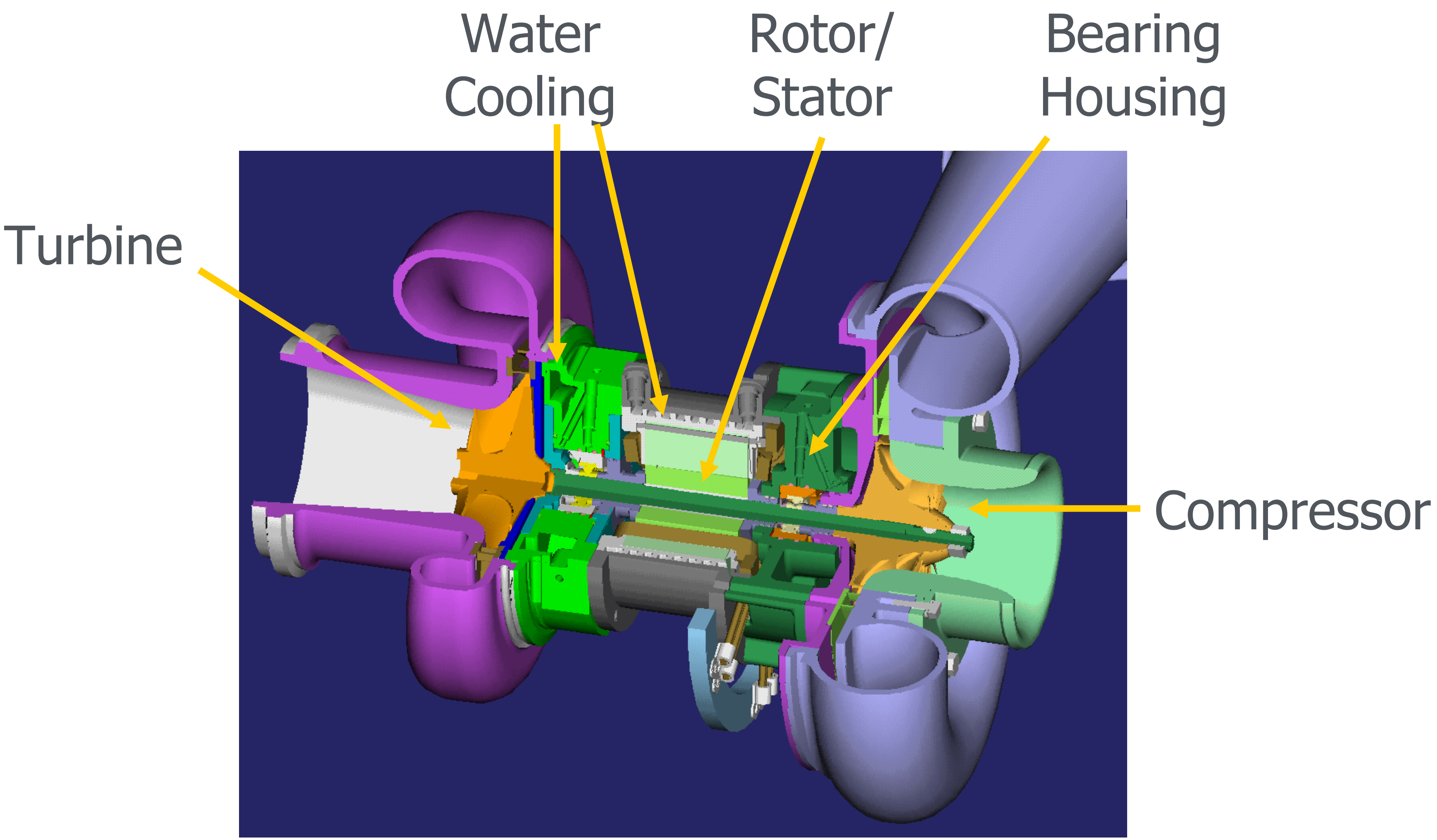


Electrical System

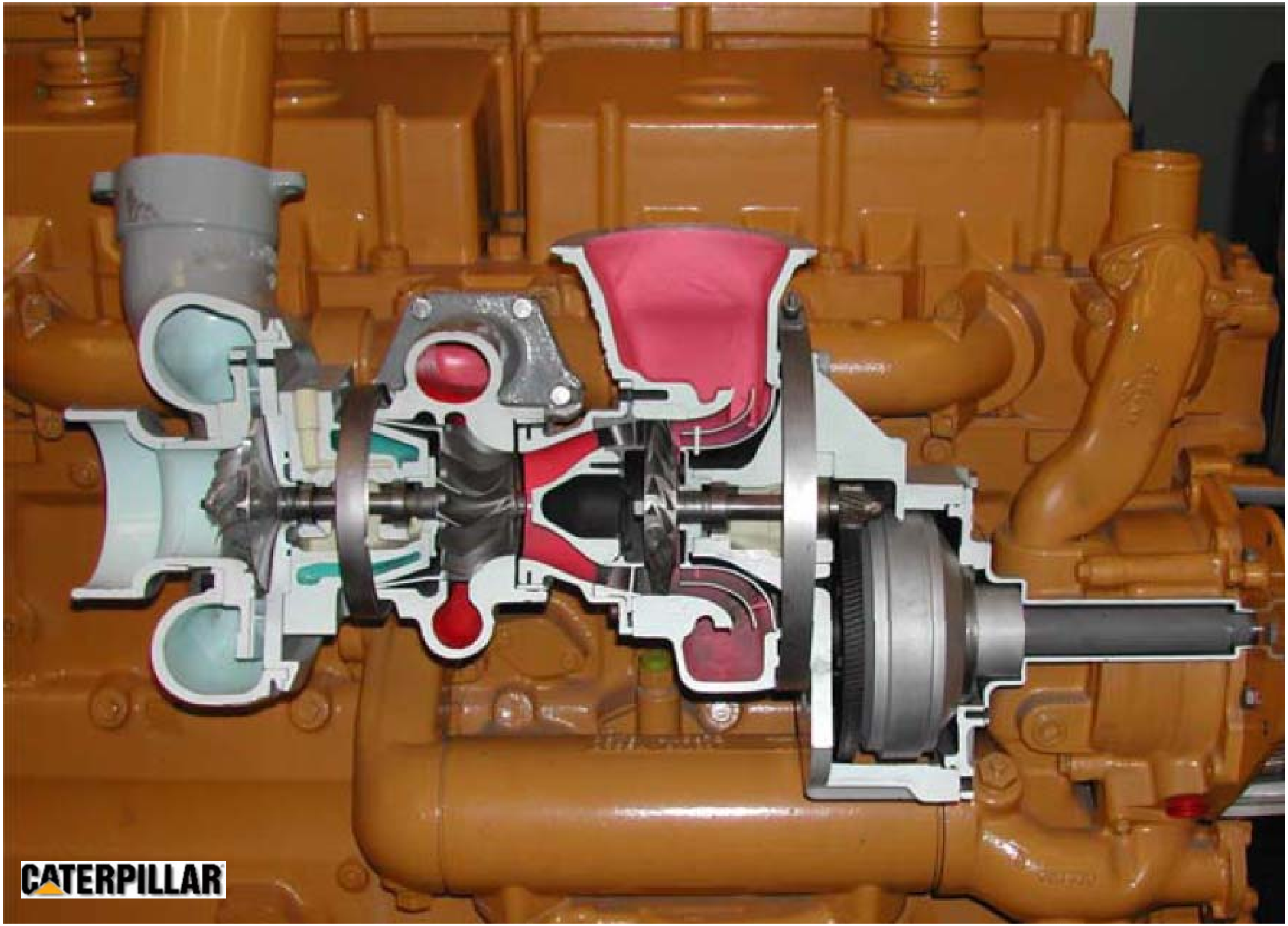


- ETC system has been designed and analyzed
- 5% - 10% fuel economy improvement potential
- Opportunity for reduced emissions and improved driveability

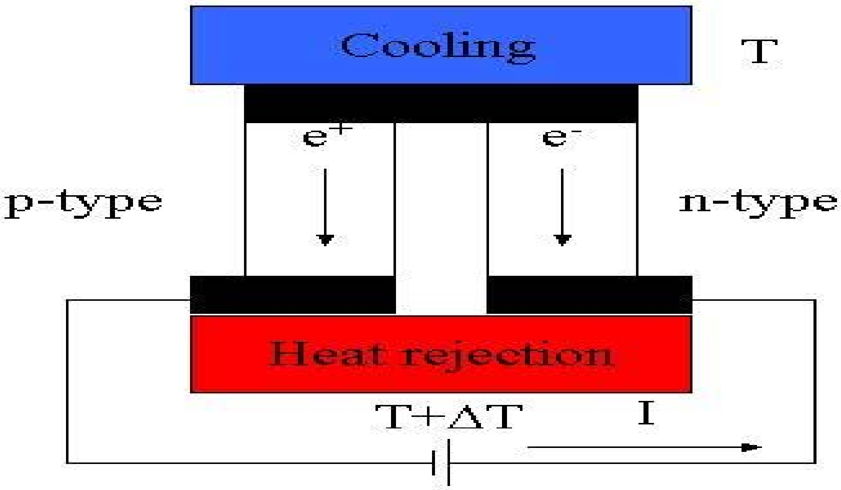
ETC: Prototype Design



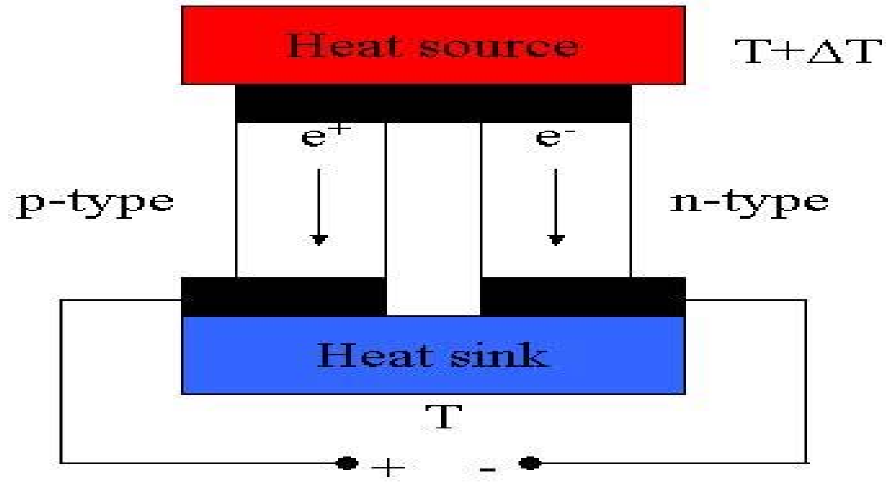
Turbo-Compound System for Engine Waste Heat Recovery



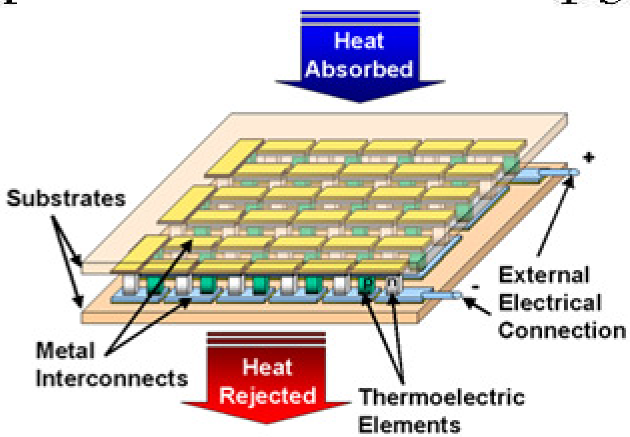
Thermoelectric Generator and HVAC



Refrigeration



Power generation



U.S. Spacecraft Using Radioisotope Thermoelectric Power Generators

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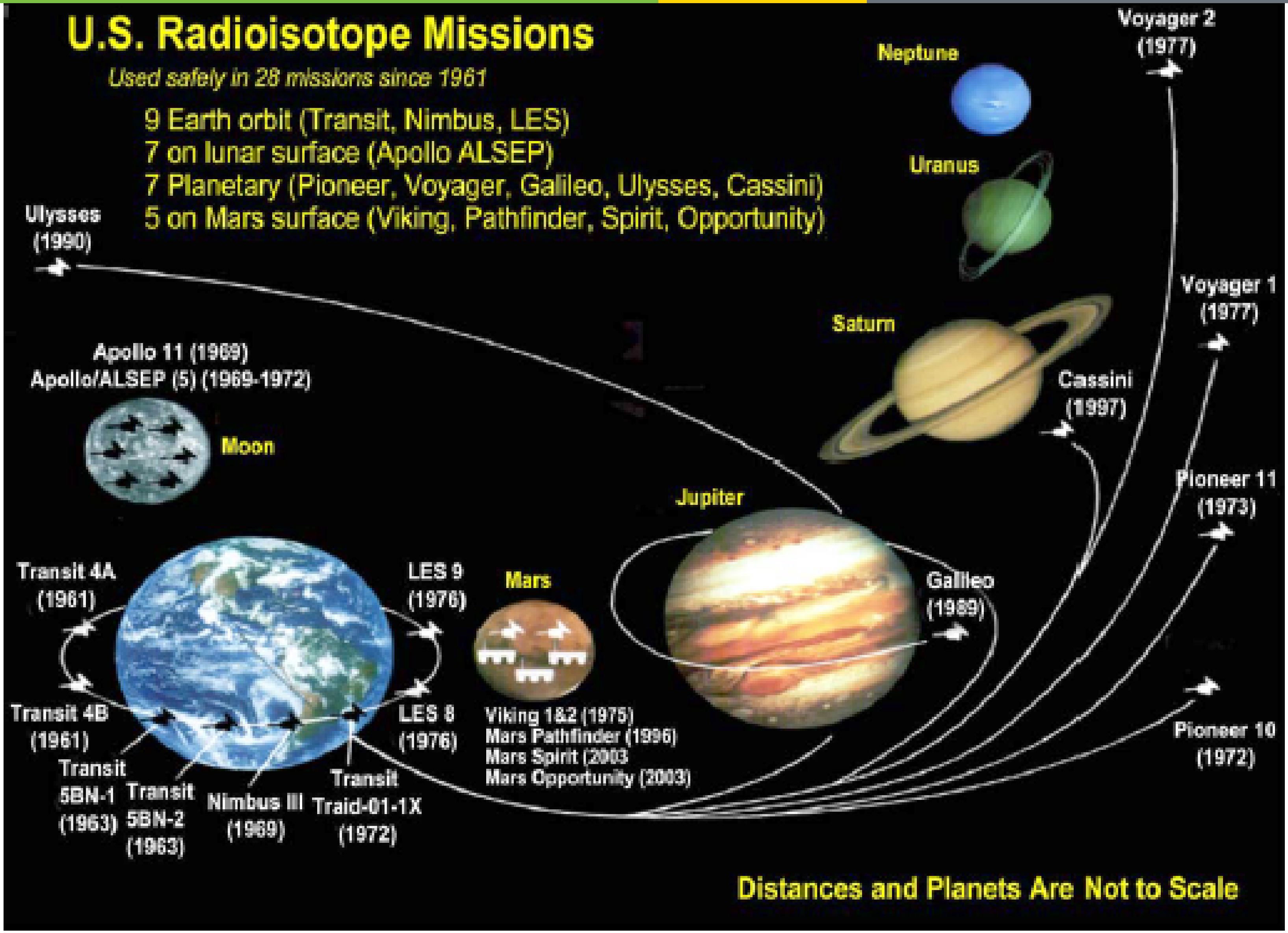


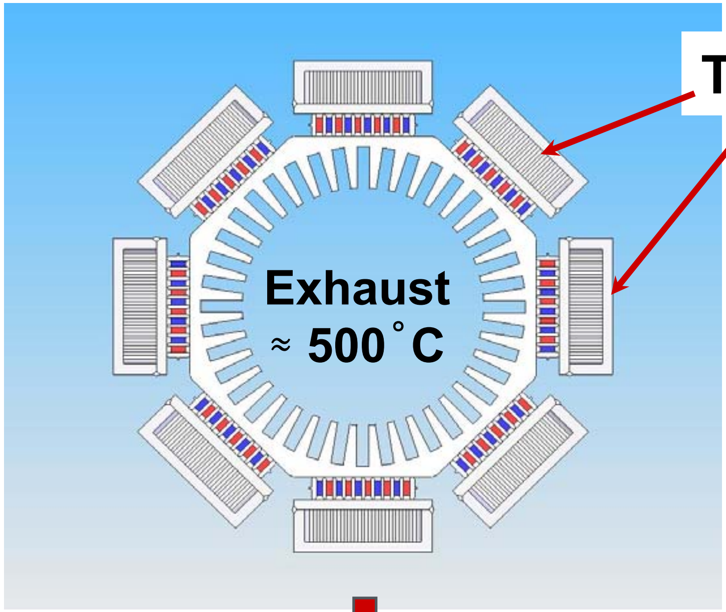
TE Power Generation from Engine Waste Heat (Clemson)

Heat Rejection
Waste Heat > 60%

$T_H \approx 500^\circ C$

$T_C \approx 110^\circ C$

TE Devices



Carnot Efficiency

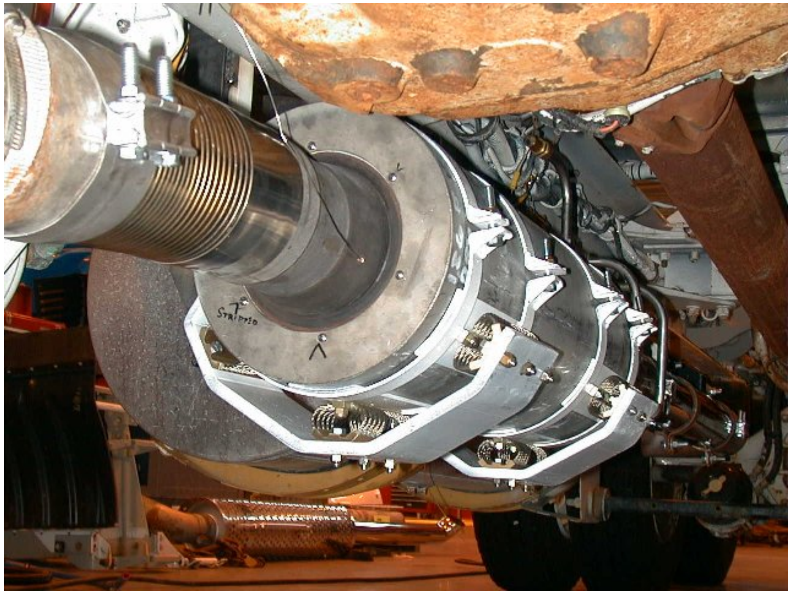
$$\eta_C = \frac{T_H - T_C}{T_H}$$

TE Efficiency

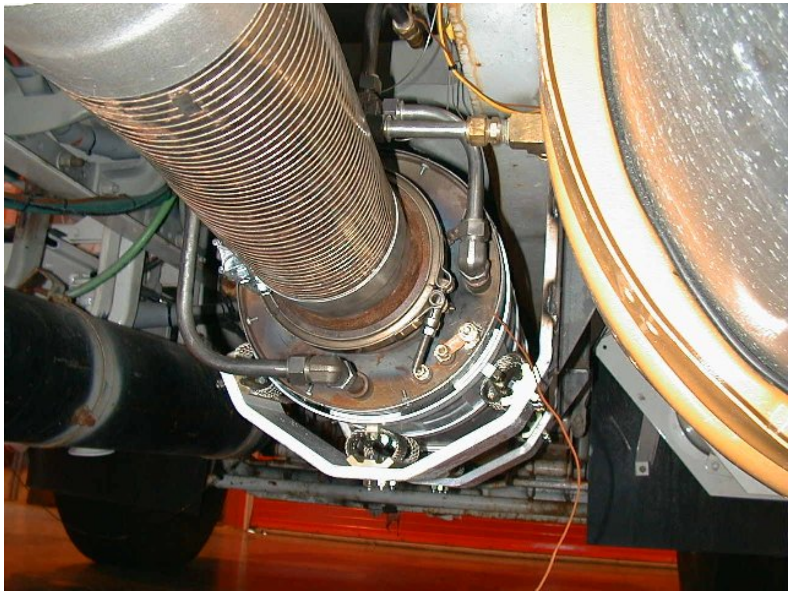
$$\eta = \left(\frac{T_H - T_C}{T_H}\right)\left(\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_C/T_H}\right)$$

Waste Heat Recovery
Goal > 10% Increase in fuel economy

Installed Thermoelectric Generator on Heavy Duty Truck



Front View



Rear View

First Vehicle with Thermoelectric Generator

Engine – Caterpillar 3406E, 550 HP Diesel Engine Heavy Duty Truck

PACCAR's 50 to 1 test track

Standard test protocols used each evaluation

Heavy loaded (over 75,000 lbs)

Hi-Z Technology's Nominal 1 kW Bi_2Te_3 TEG installed in exhaust gas path after turbocharger and emissions reduction system

Survived equivalence of 550,000 highway miles

High Efficiency Thermoelectrics

Awardees	Additional Team Members
General Motor Corporation and General Electric	University of Michigan, University of South Florida, Oak Ridge National Laboratory, RTI International, Marlow Industries
BSST, LLC.	Visteon, BMW-NA, Ford, ZT Plus
Michigan State University	NASA Jet Propulsion Laboratory, Cummins Engine Company, Tellurex, Iowa State

TE materials performance: Figure of Merit (ZT)

Electrical conductivity

Seebeck coefficient or thermopower ($\Delta V/\Delta T$)

$$ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \cdot T$$

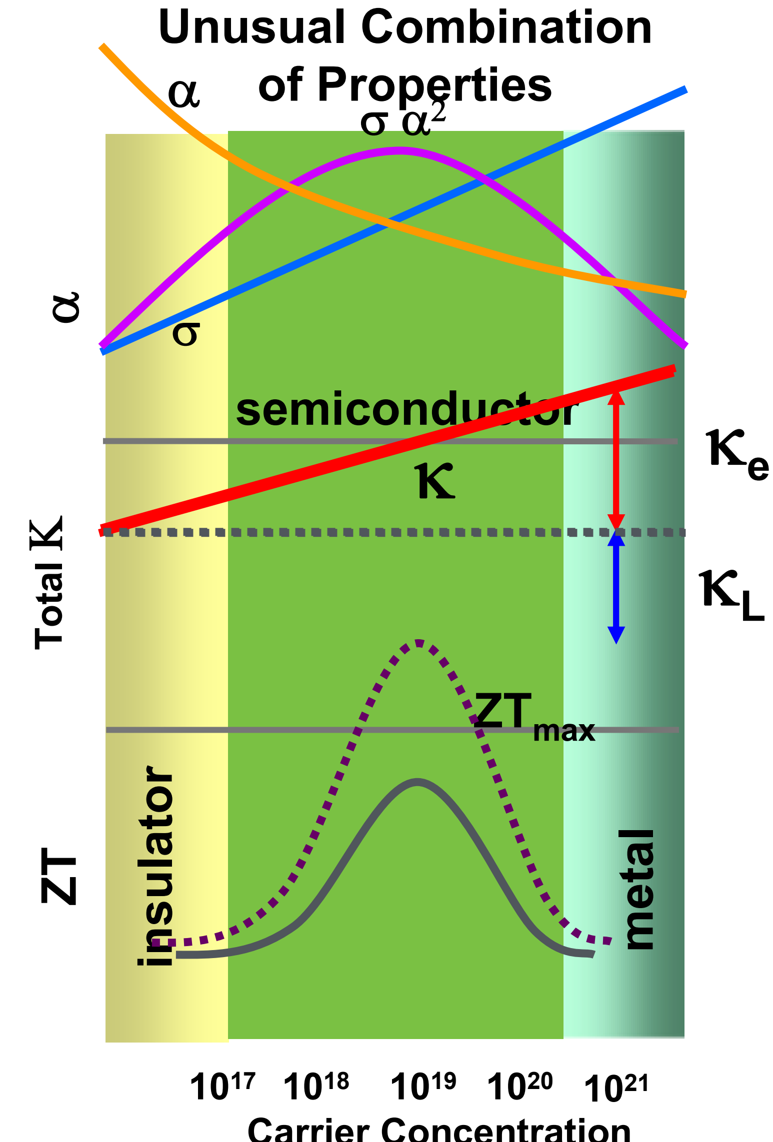
Total thermal conductivity

$\sigma\alpha^2 =$ Power Factor

$\sigma = 1/\rho =$ electrical conductivity

$\rho =$ electrical resistivity

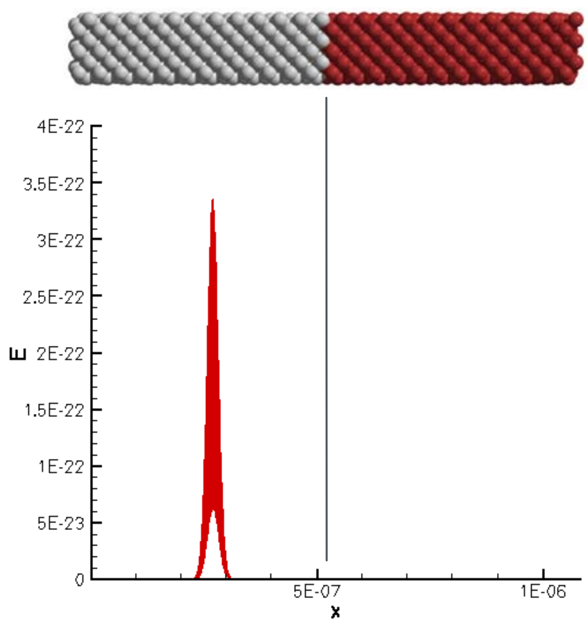
[courtesy of Oregon State]

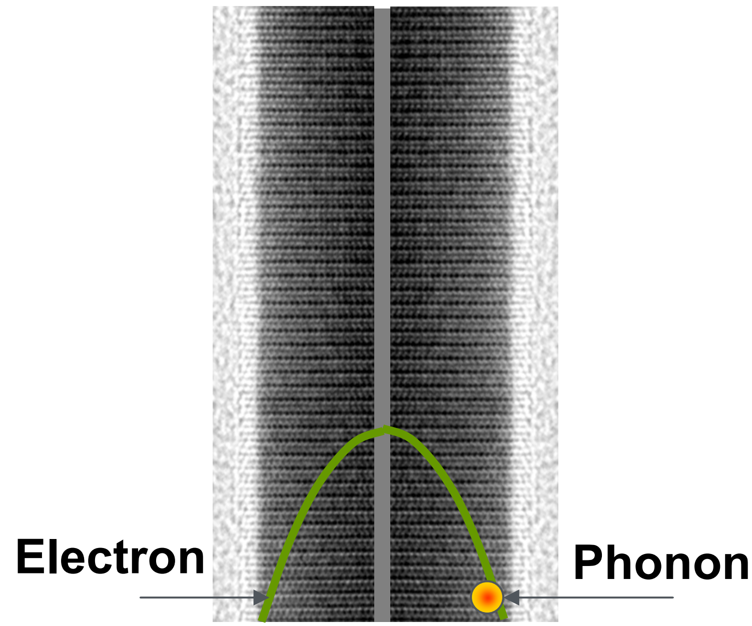


Nanoscale Effects for Thermoelectrics

Interfaces that Scatter Phonons but not Electrons

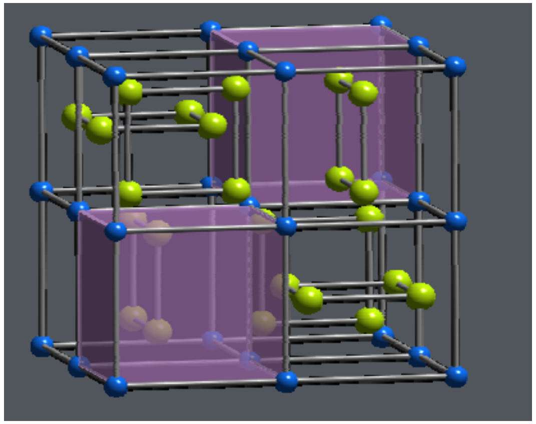
	Electrons	Phonons
Mean Free Path	Λ=10-100 nm	Λ=10-100 nm
Wavelength	λ=10-50 nm	λ=1 nm



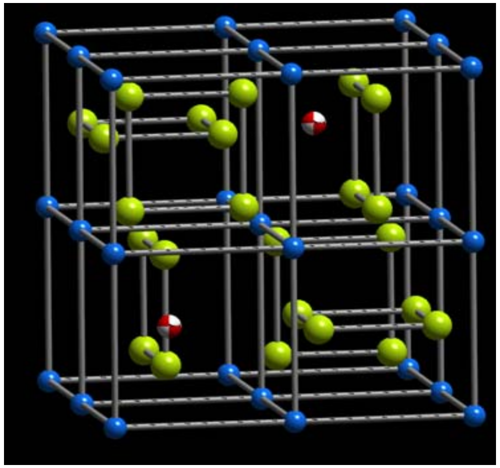


[Courtesy of Millie Dresselhaus, MIT]

Crystal Structure of Skutterudites



$CoSb_3$ $[Co_8(Sb_4)_6]$



R_xCoSb_3

- Cobalt atoms form a *fcc* cubic lattice
- Antimony atoms are arranged as square planar rings
- There are 8 spaces for the Sb_4 units
- 6 are filled and 2 are empty

Atoms can be inserted into empty sites. Atoms can "rattle" in these sites – scatter phonons and lower the lattice thermal conductivity.

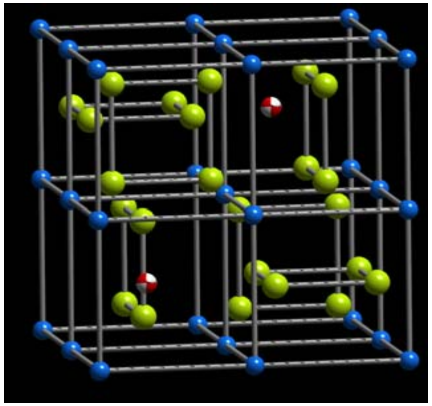
[Courtesy of Oregon State]

High Temperature TE based on Skutterudites: $In_{0.15}R_{0.10}Co_4Sb_{12}$

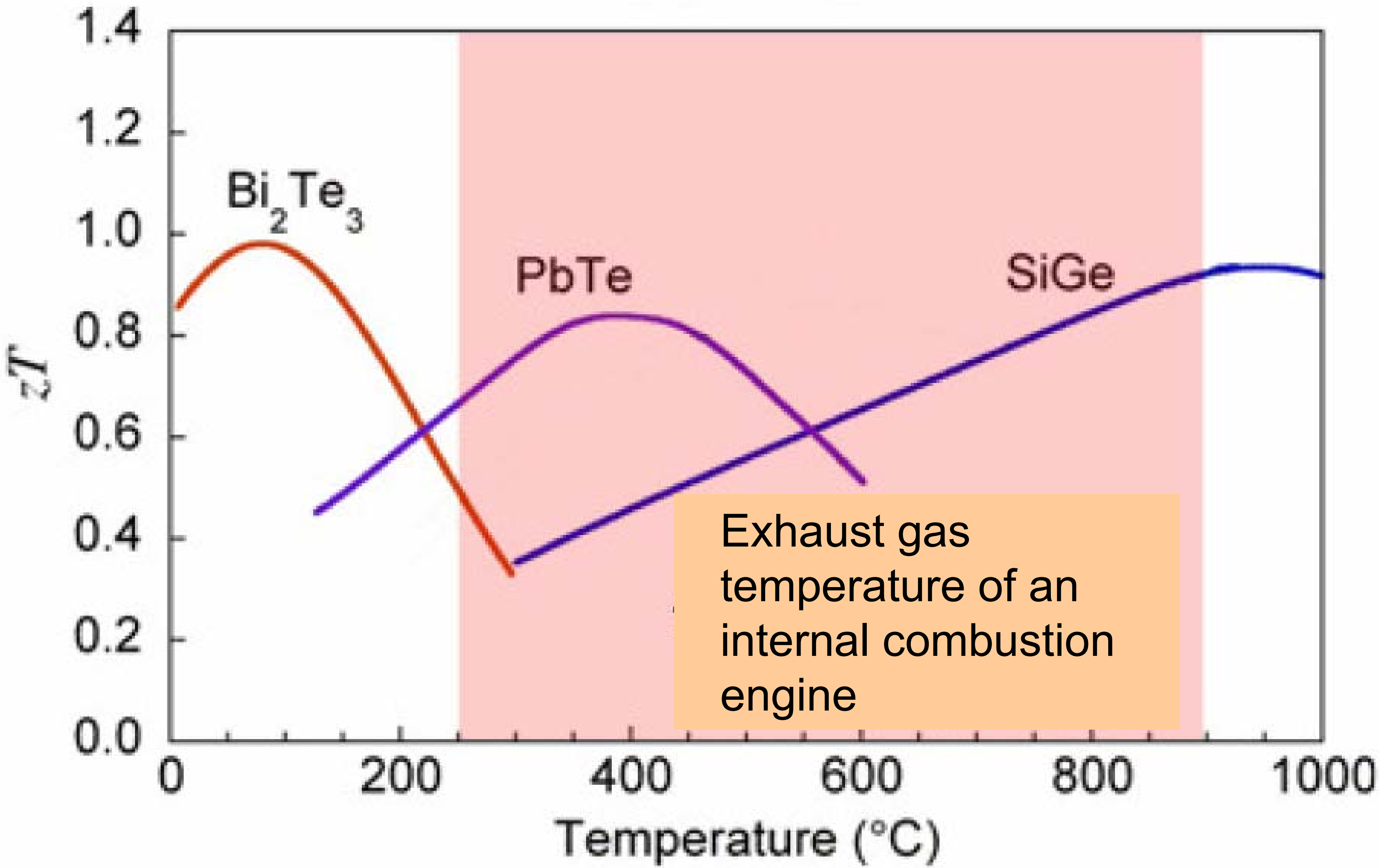
Rattlers → R: La, Ce, Nd, Er, Yb,

Co → Mn, Fe, Ni, Cu, Pd, Pt, Rh, Ru

$R_xCo_4Sb_{12}$



TEG Candidate Materials – 2005



Thermoelectric Modules Optimized for Thermal Zones

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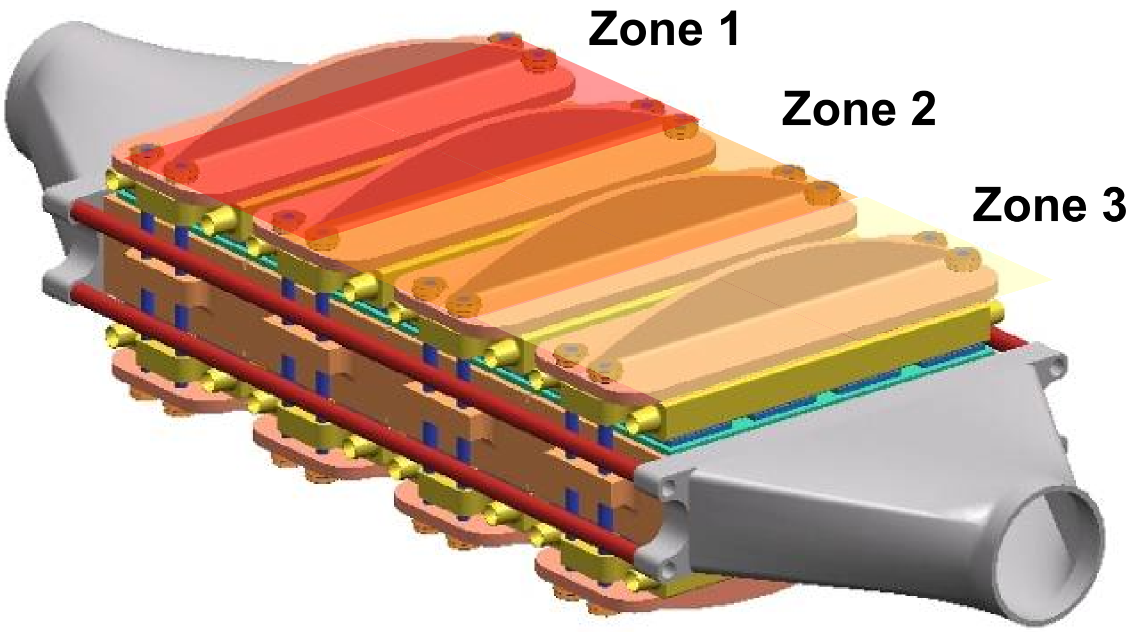
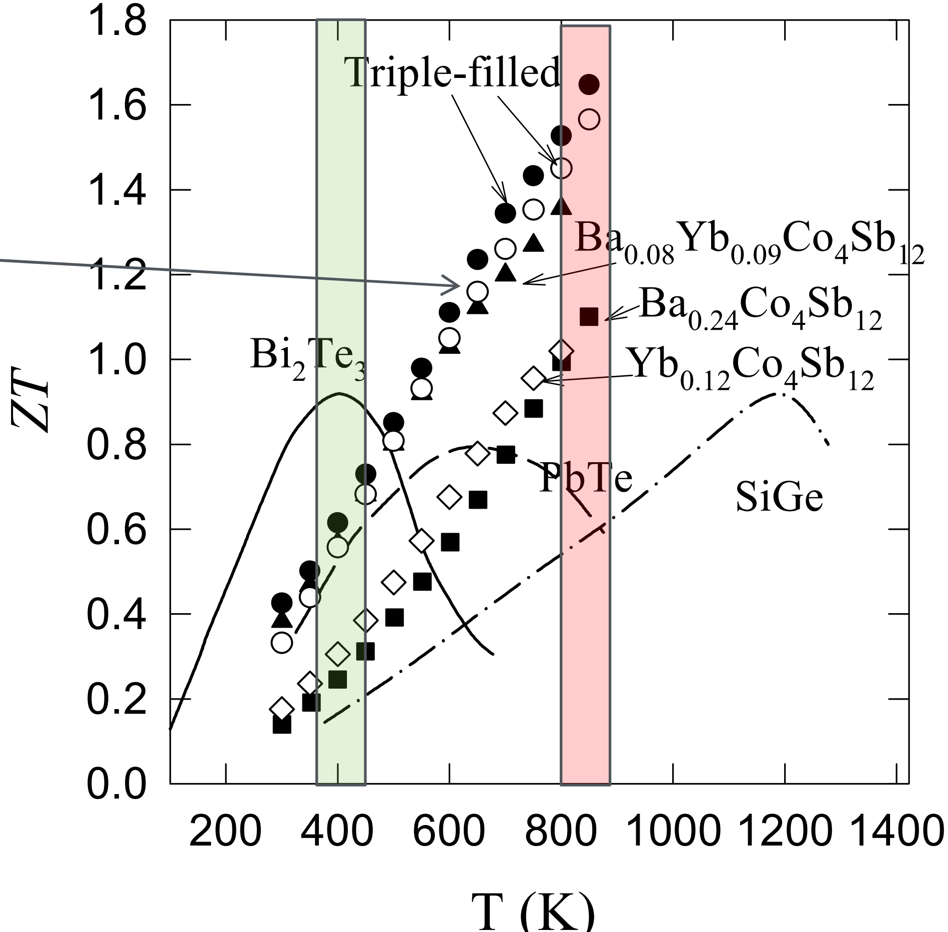


Highest ZT Achieved in Triple-filled Skutterudites

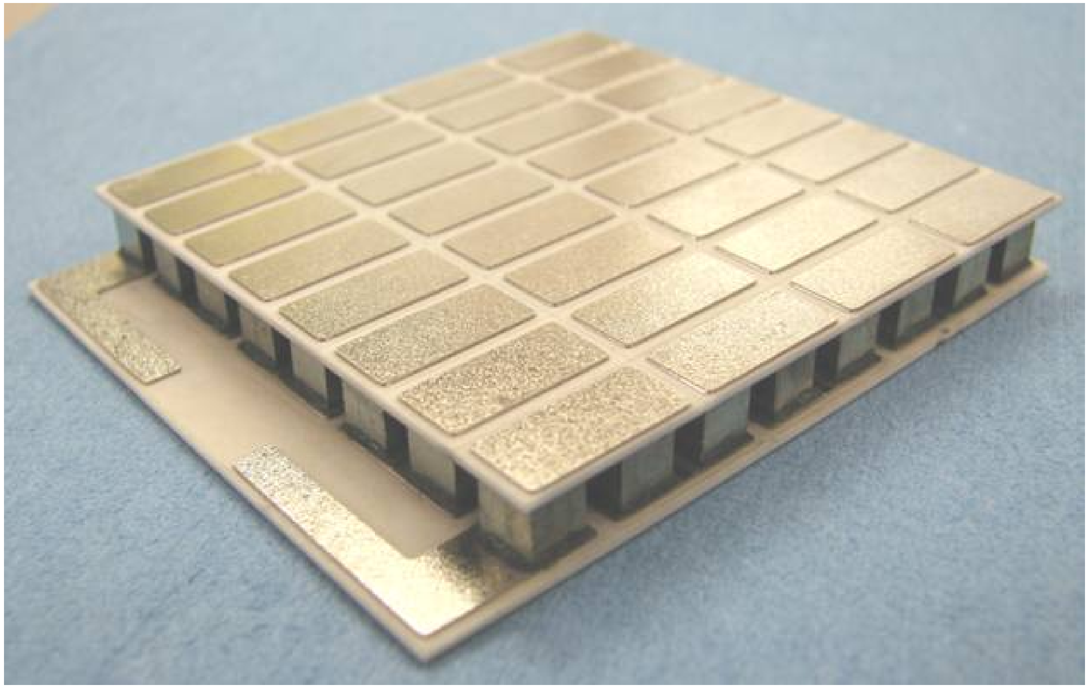
• $Ba_{0.08}La_{0.05}Yb_{0.04}Co_4Sb_{12.05}$
o $Ba_{0.10}La_{0.05}Yb_{0.07}Co_4Sb_{12.16}$

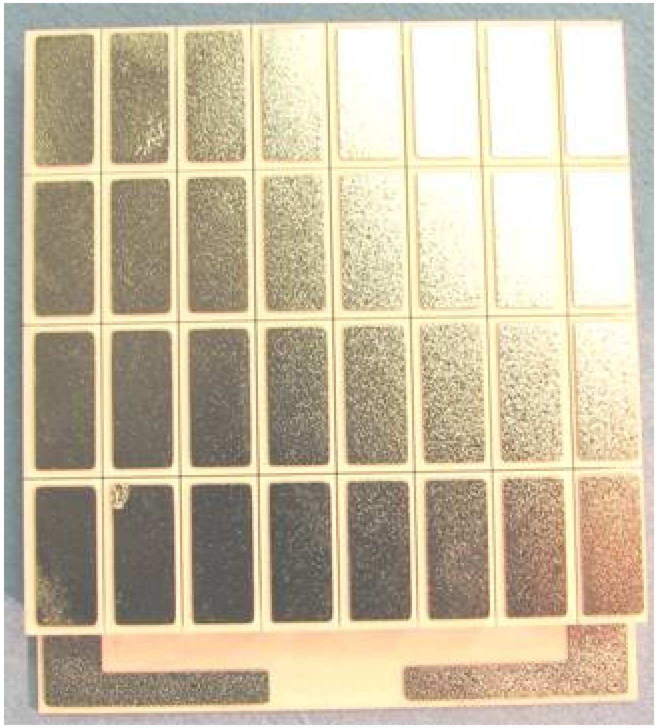
$ZT_{ave} = 1.2$



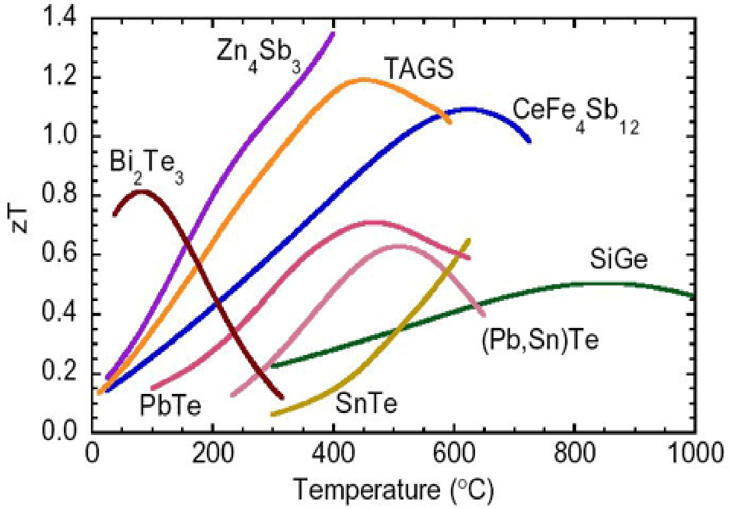
1. X. Shi, et al. Appl. Phys. Lett. **92**, 182101 (2008)
2. X. Shi, et al., submitted (2009)

Prototype Modules

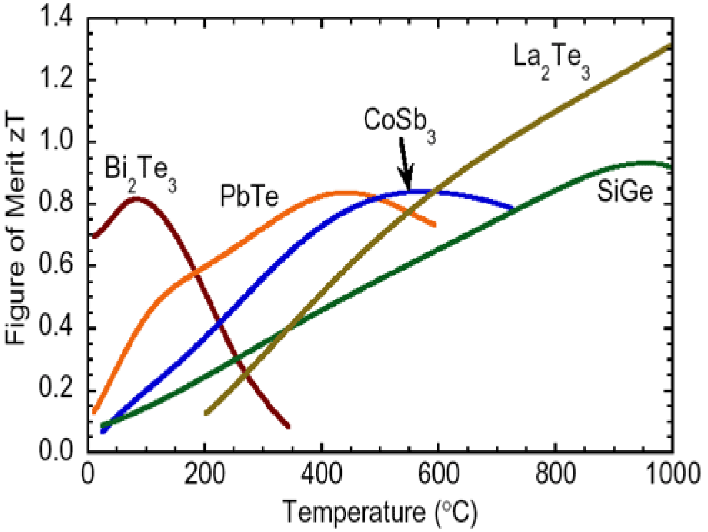




Current TE Materials



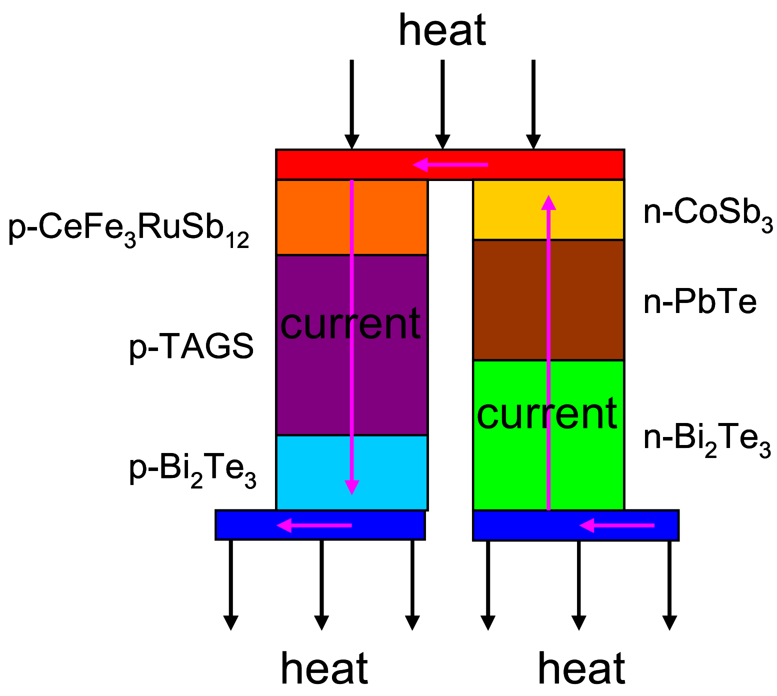
P-type TE material

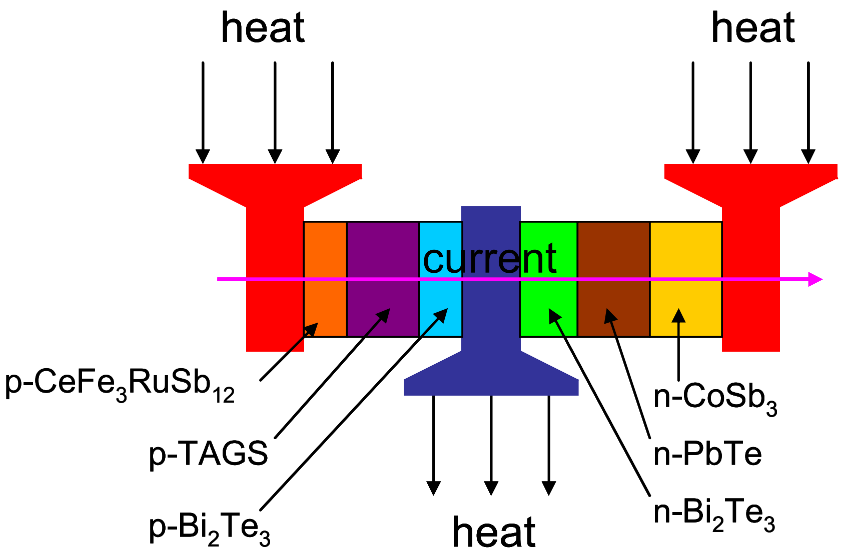


N-type TE material

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

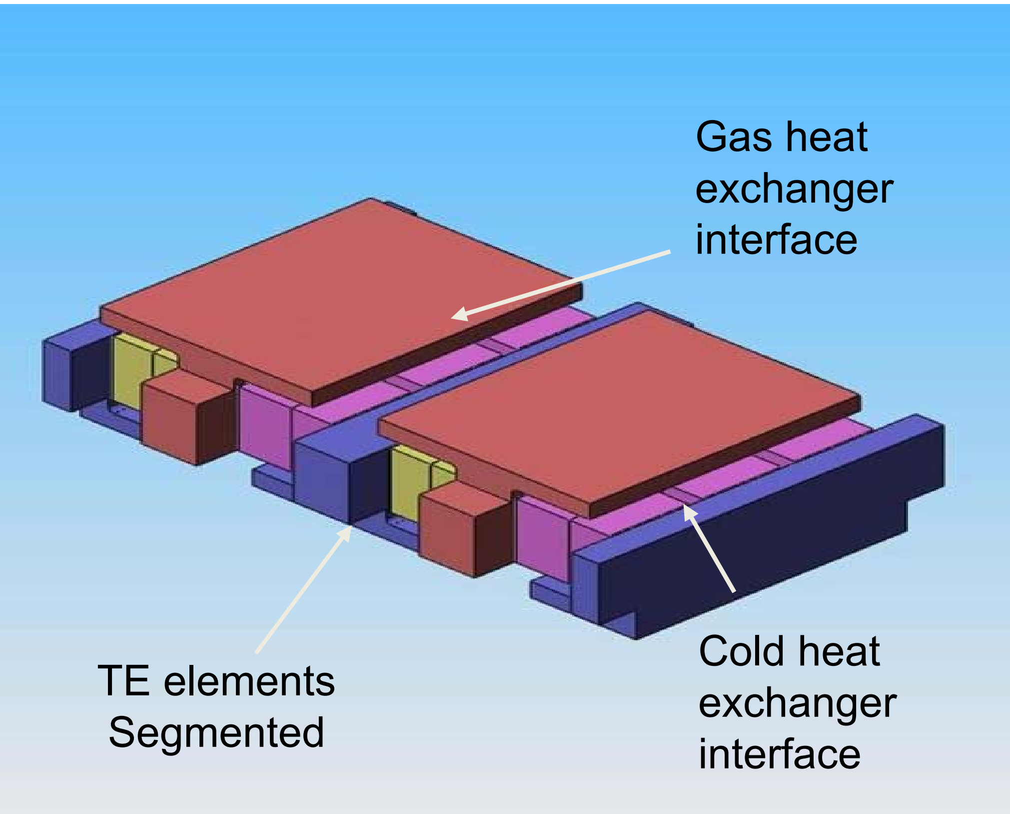
BSST Y Segmented TE Configuration

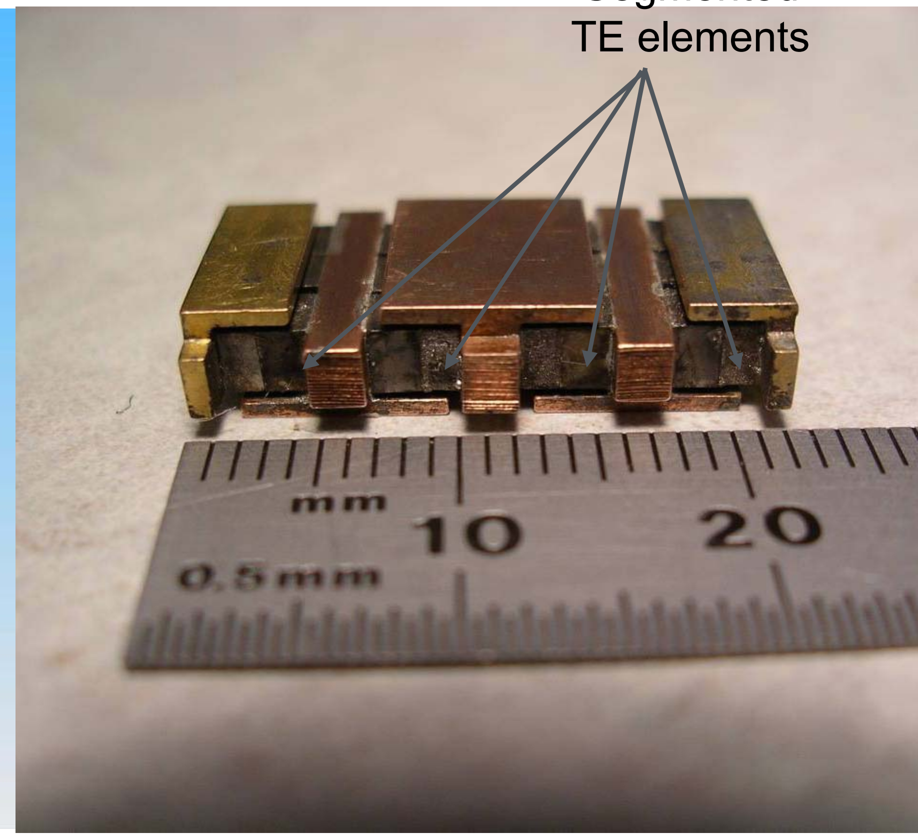




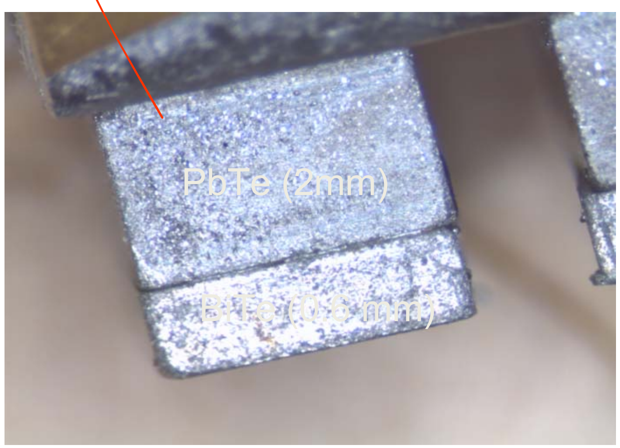
- Traditional configuration
- BSST "Y" configuration

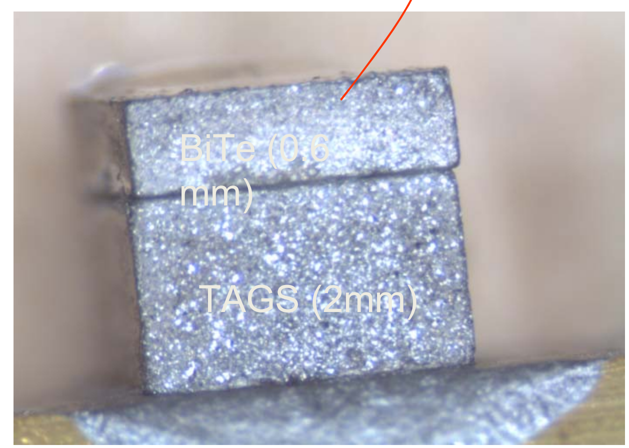
High Temperature 2nd-Stage Segmented Element Subassembly





Segmented Couple TAGS/PbTe-Bi_2Te_3





Exhaust Flow and Temperatures for a 4- Cylinder Engine

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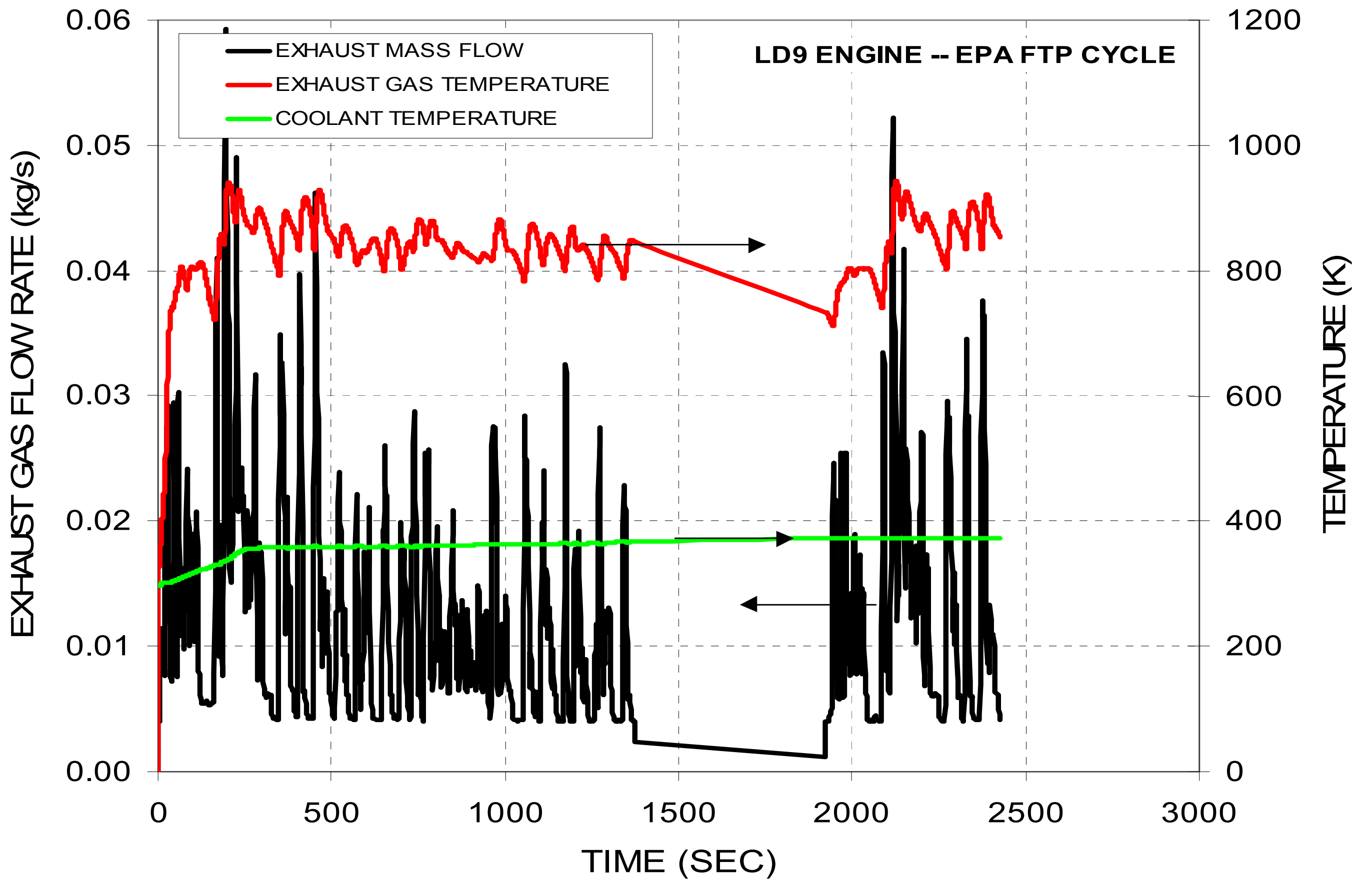
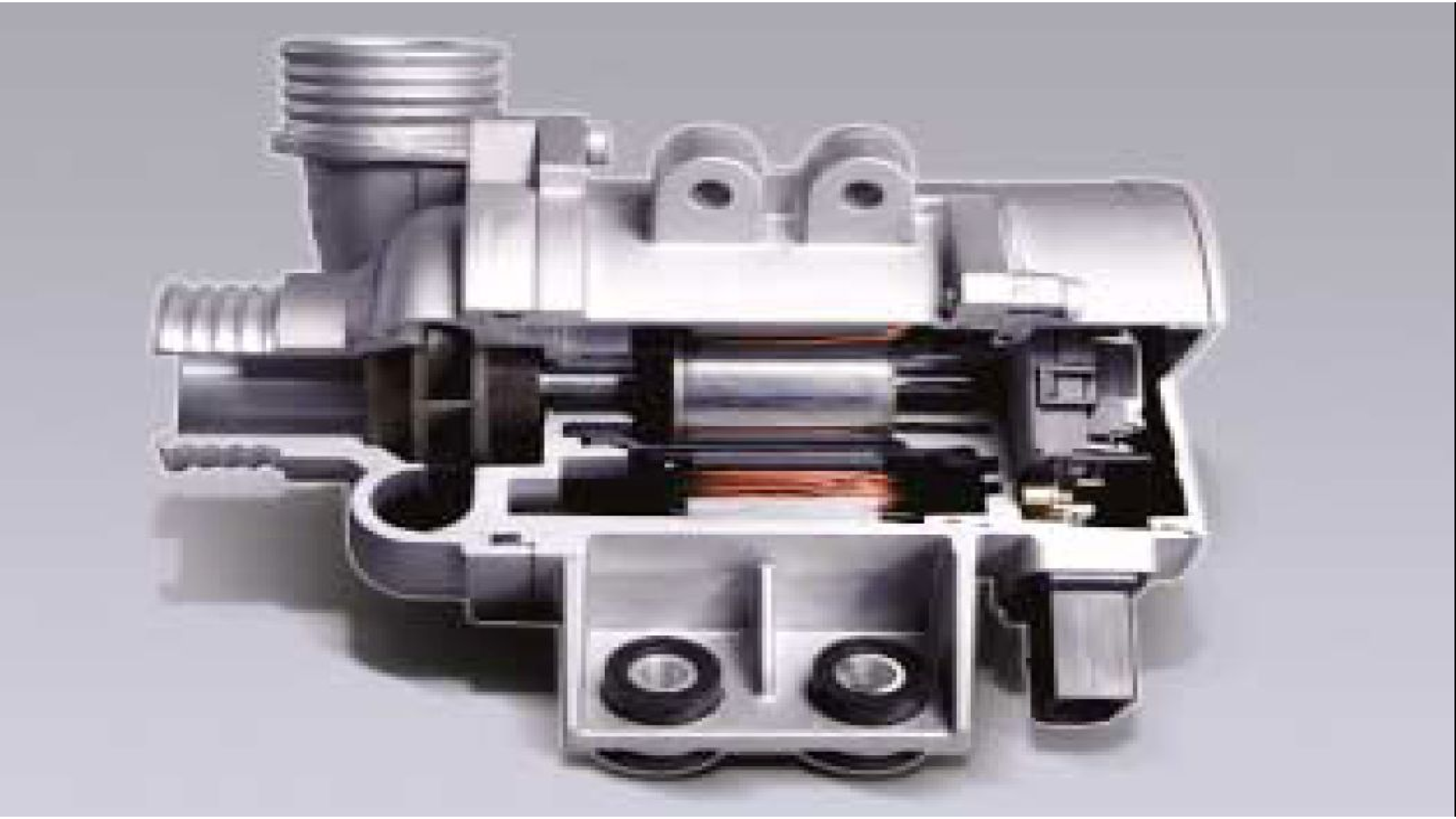


There are tens of kW heat energy in the exhaust & coolant

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



BMW Series 5 , Model Year 2011, 3.0 Liter Gasoline Engine w/ Thermoelectric Generator

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FreedomCAR & Fuel Partnership

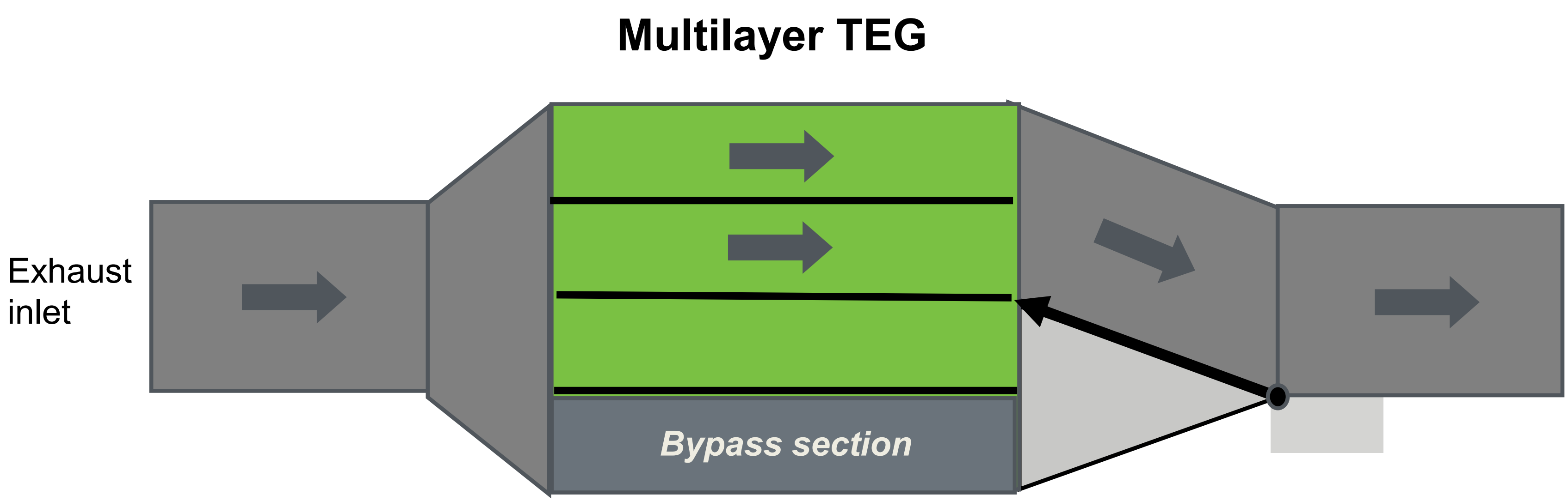
Visteon®

BSST innovative solutions in temperature control

BMW

MINI

Computer Controlled Butterfly Valve to Optimize Vehicular TEG Performance

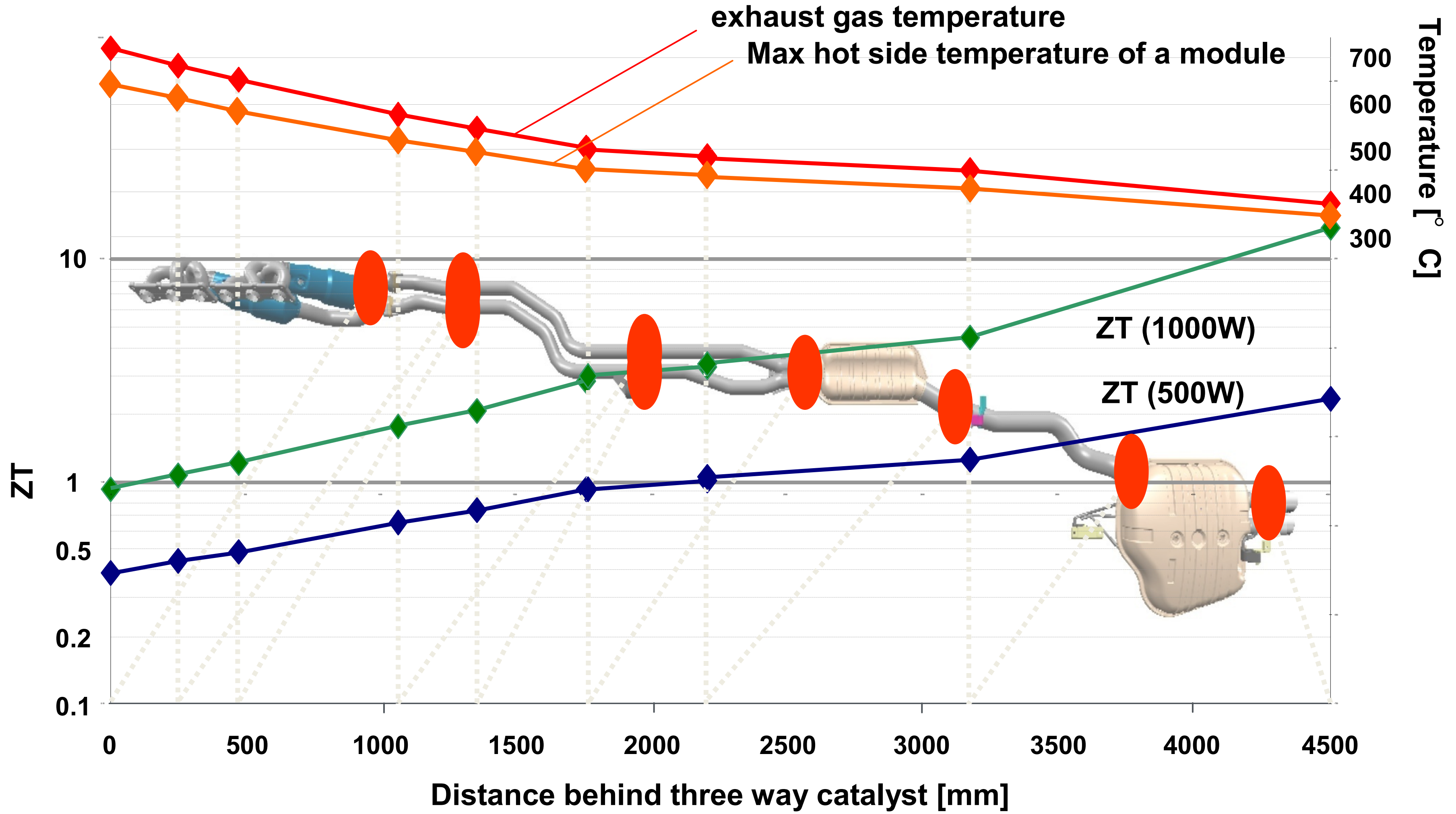


Exhaust gas enters a diffusor upstream from the multi-layer TEG

The number of TEG layers exposed to exhaust gas is proportional to total mass flow

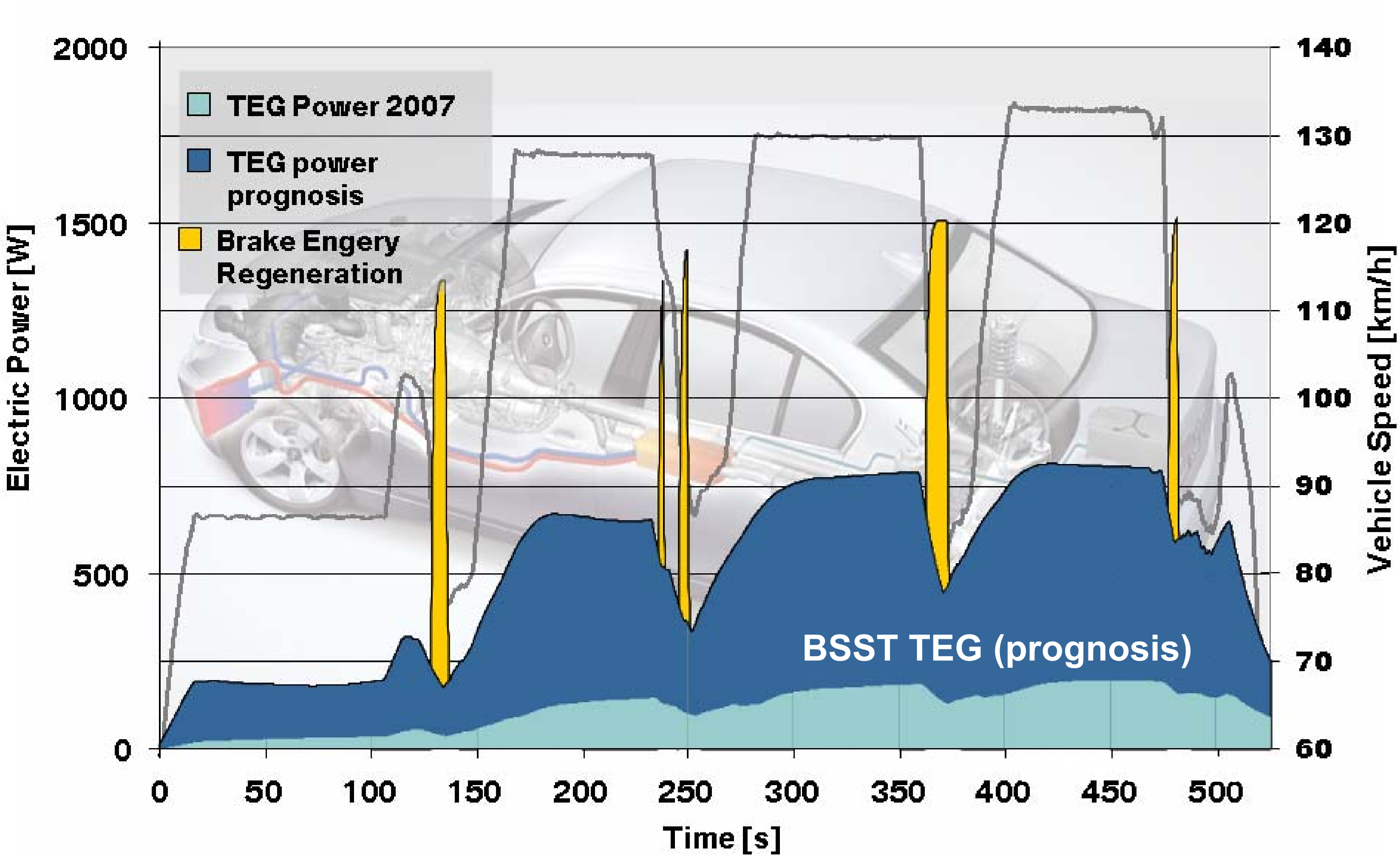
An exhaust gas valve controls gas distribution to layers downstream from the TEG

TEG SI Engine Waste Heat Recovery. Need High ZT Material & By-pass (BMW)



Vehicle 530iA at 130 km/h, Exhaust gas back pressure limited to 30mbar at 130km/h

TEG is Ideally Compatible with Regenerative Braking (BMW)



TEG Demonstrator Installed on BMW Series 5 Test Vehicle

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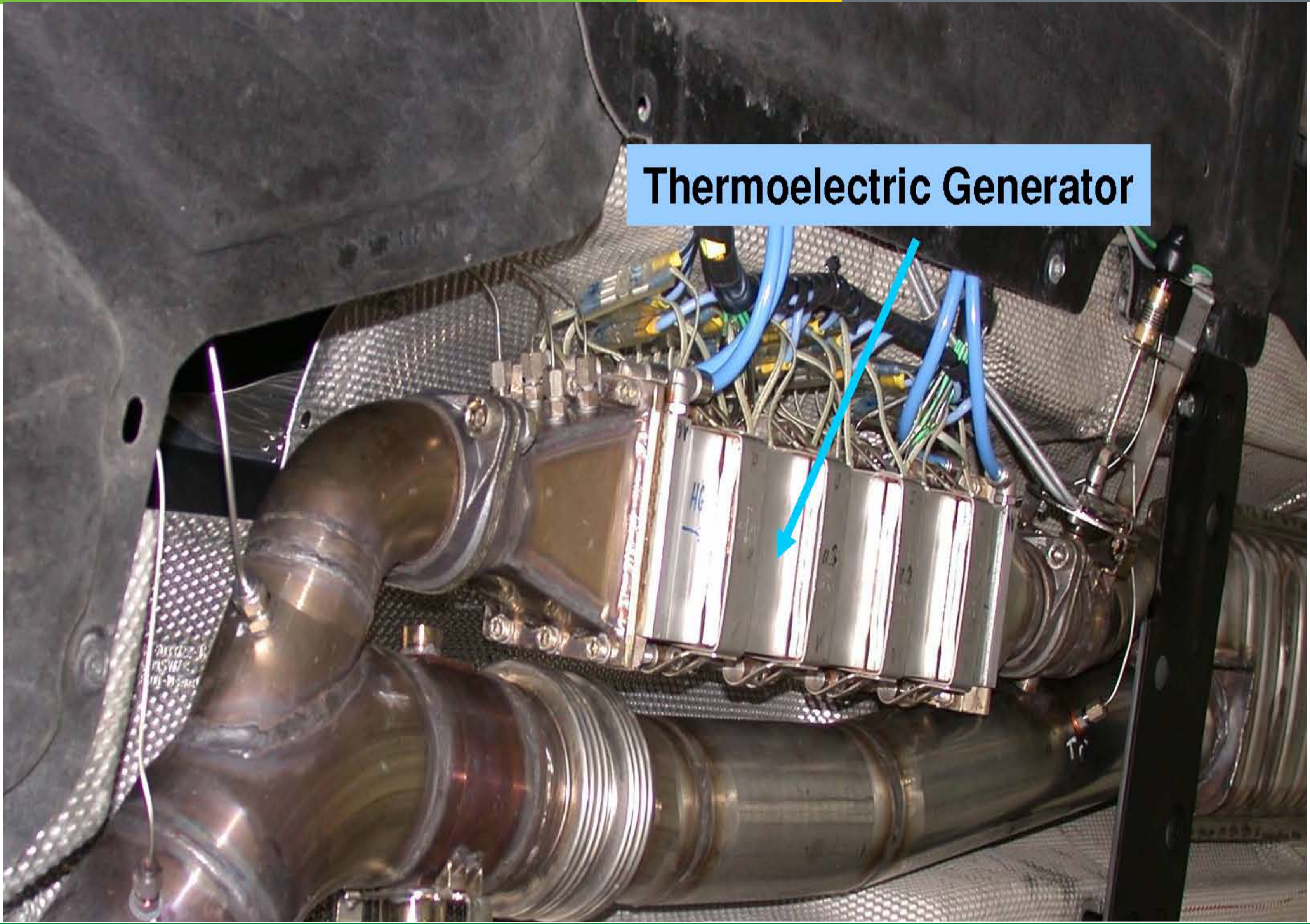
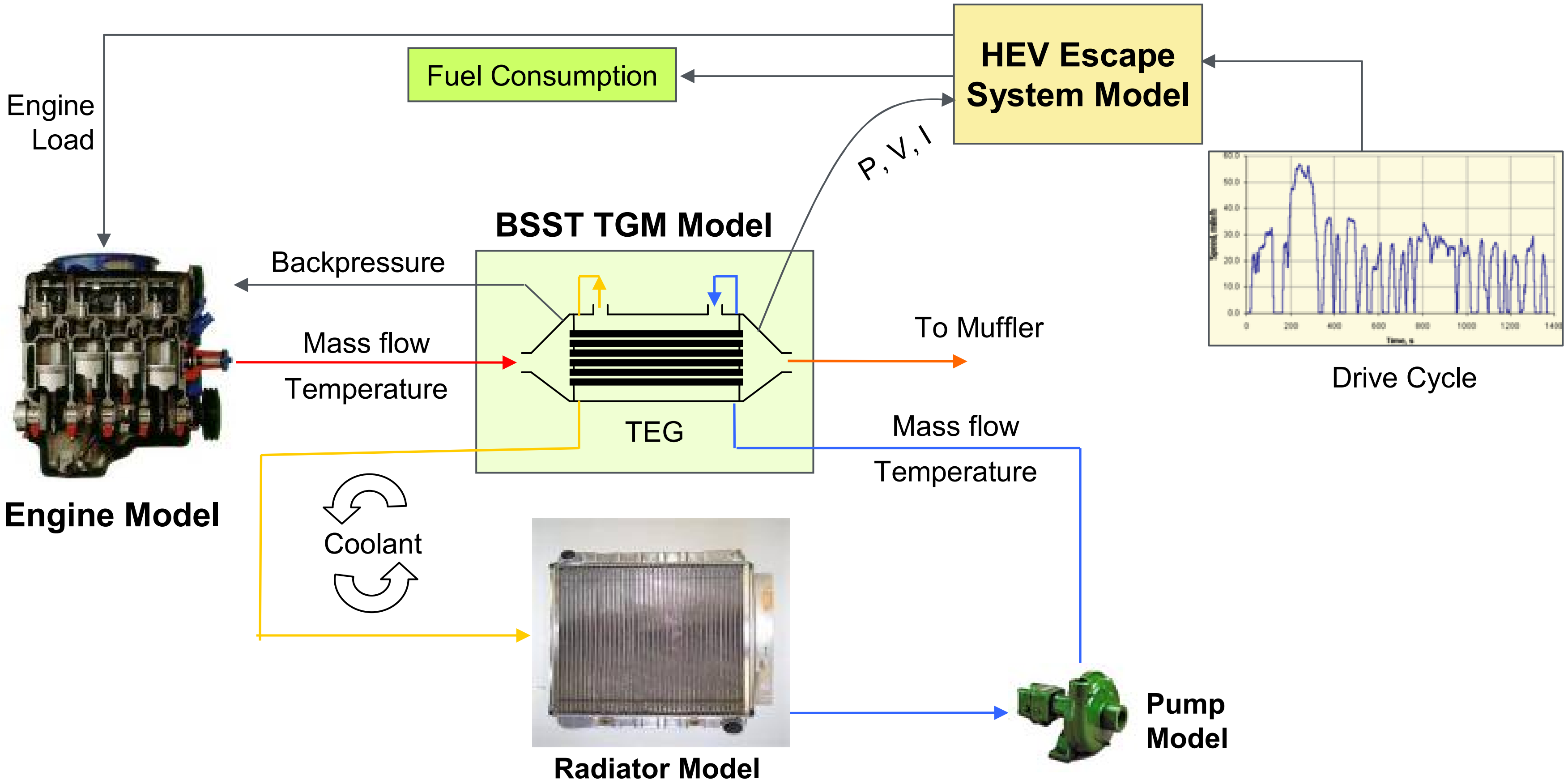


TEG Installed in BMW Series 5 Sedan

BSST/BMW TEG Test Instrumentation

Thermoelectric Generator Performance BMW Sedans

Ford's Transient Modeling of a TEG for a HEV Application



- 2.5L Atkinson Engine in Ford Escape Hybrid Vehicle
- Major Design Constraints:

  TE Mass, Exhaust ΔP, Response Time

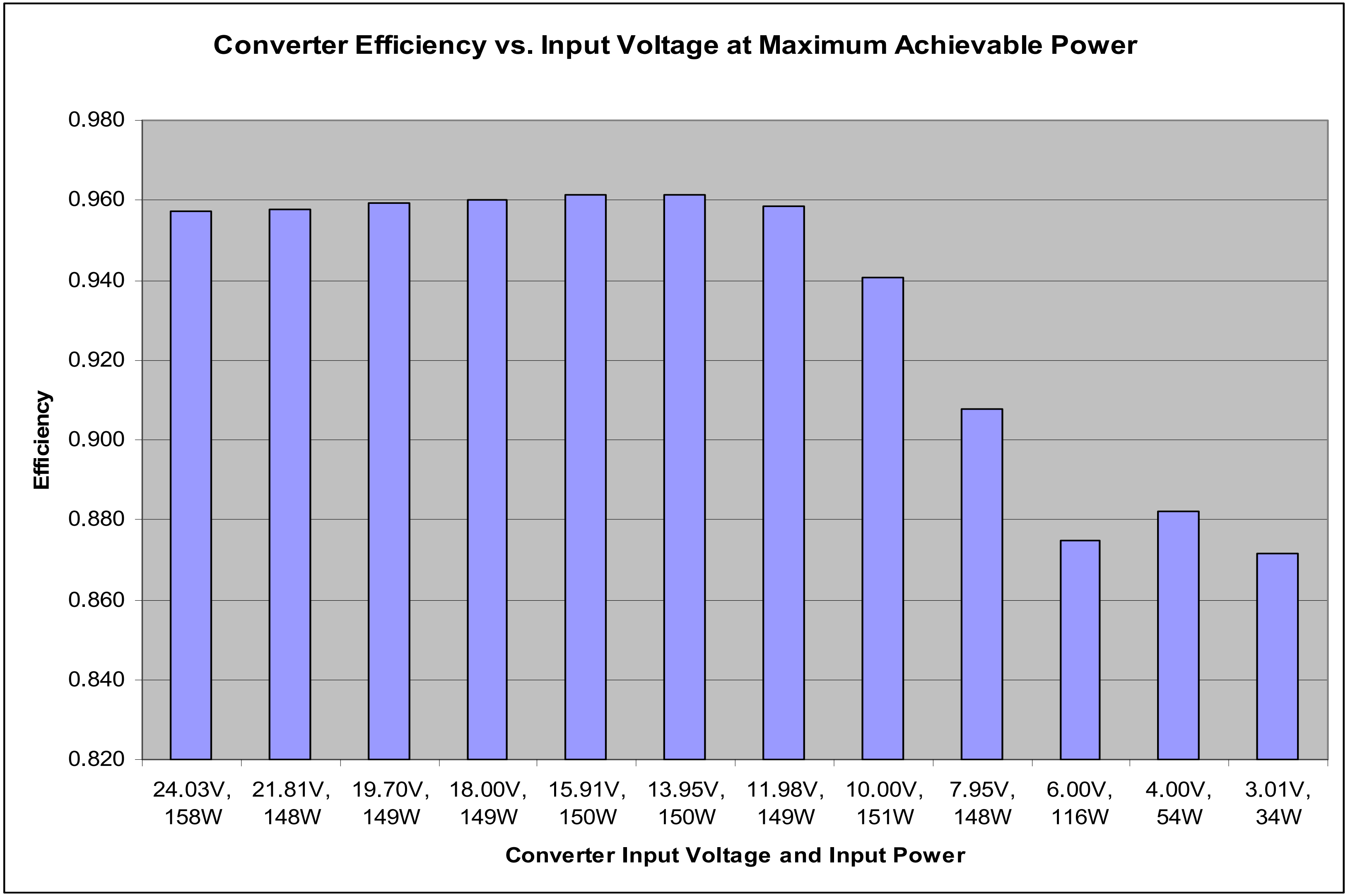
150 Watt TGM Integrated Buck/Boost Converter

The PCS produces a positive output voltage that is greater than, equal to or less than the input voltage in a single stage.

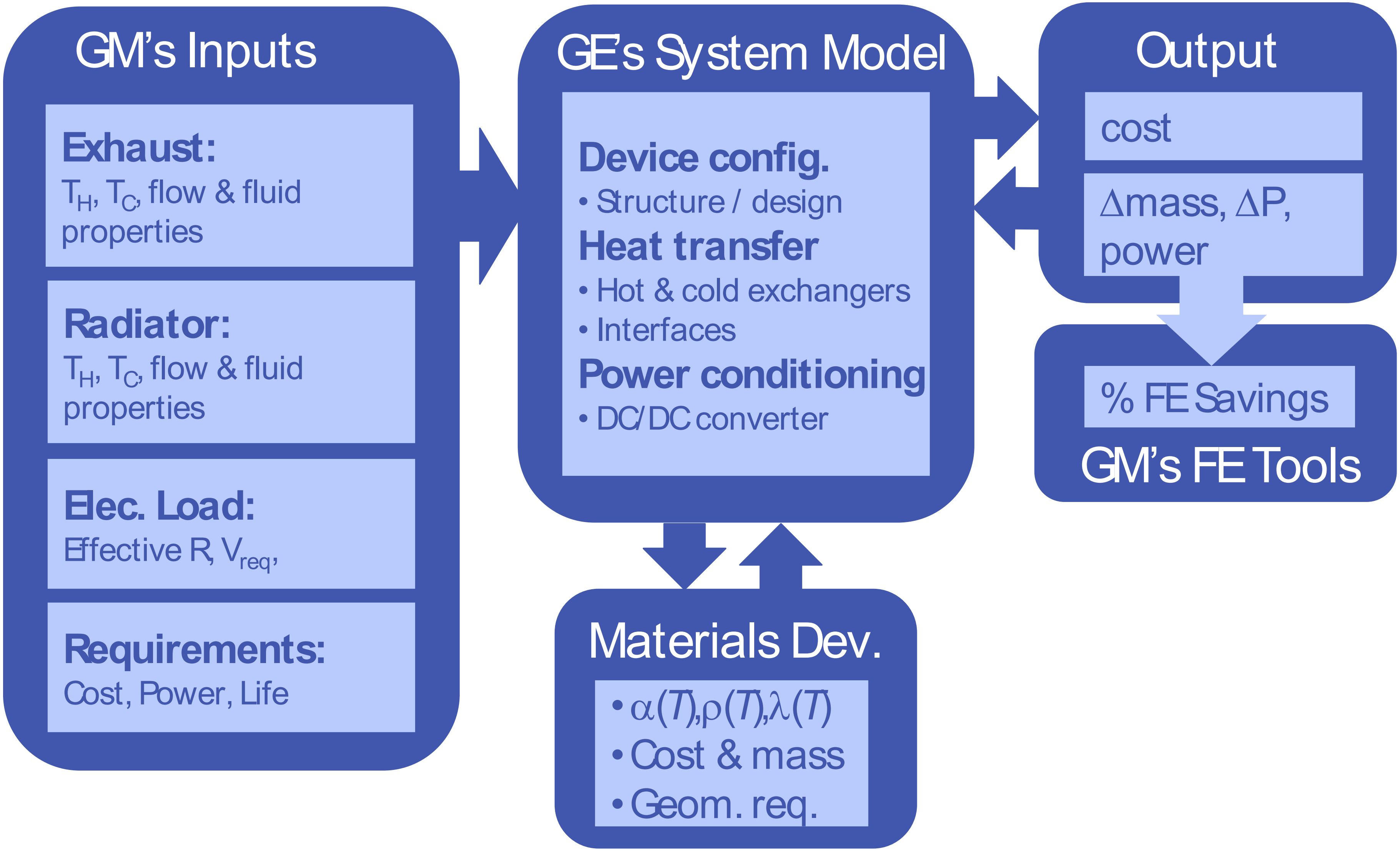
Minimizes cost, size and weight while maximizing power conversion efficiency.

Supports Maximum Power Point Tracking.

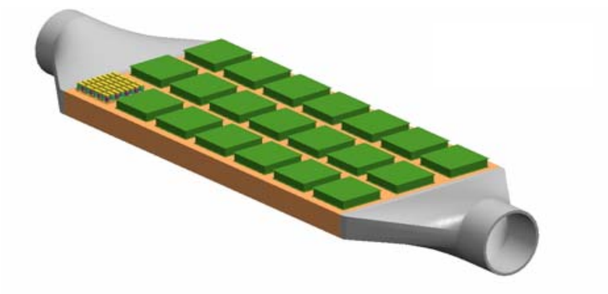
Power Converter Efficiency

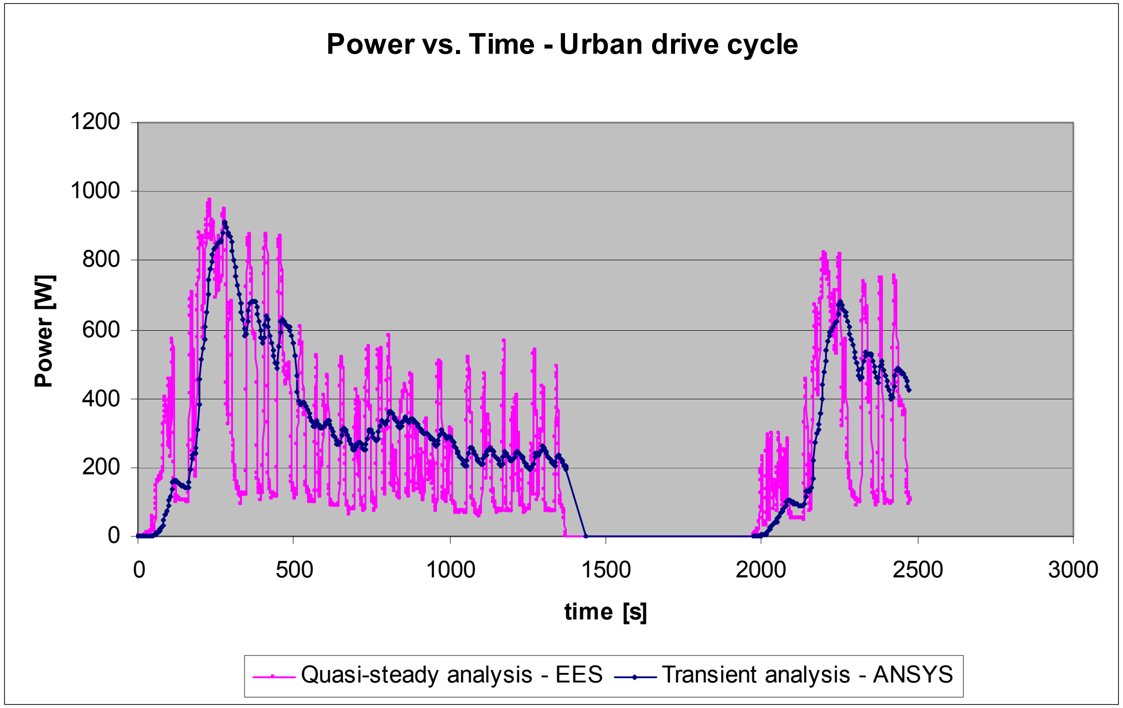


Program Flow Chart



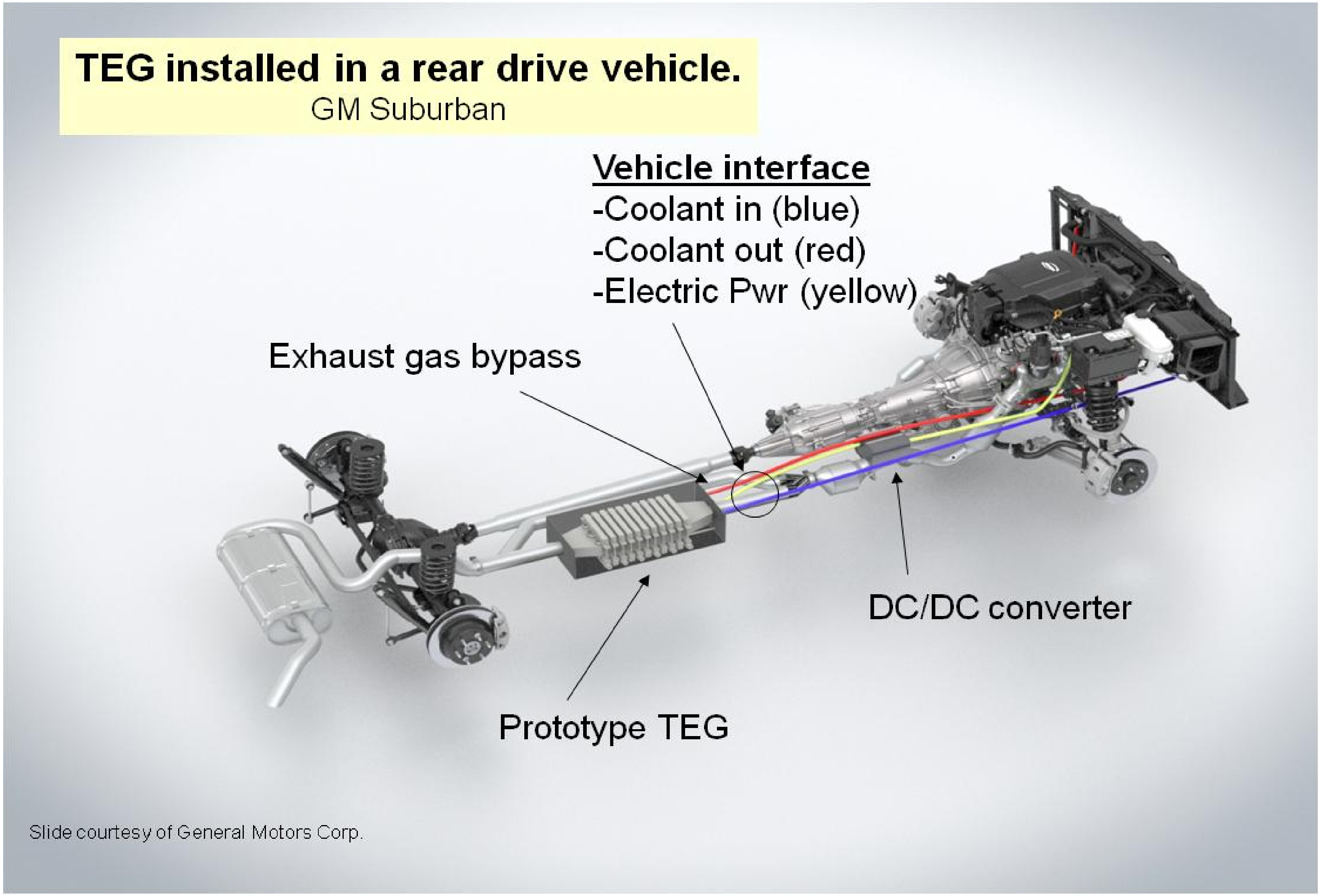
GM Thermoelectric Generator Analytical Predicts from Early Tests



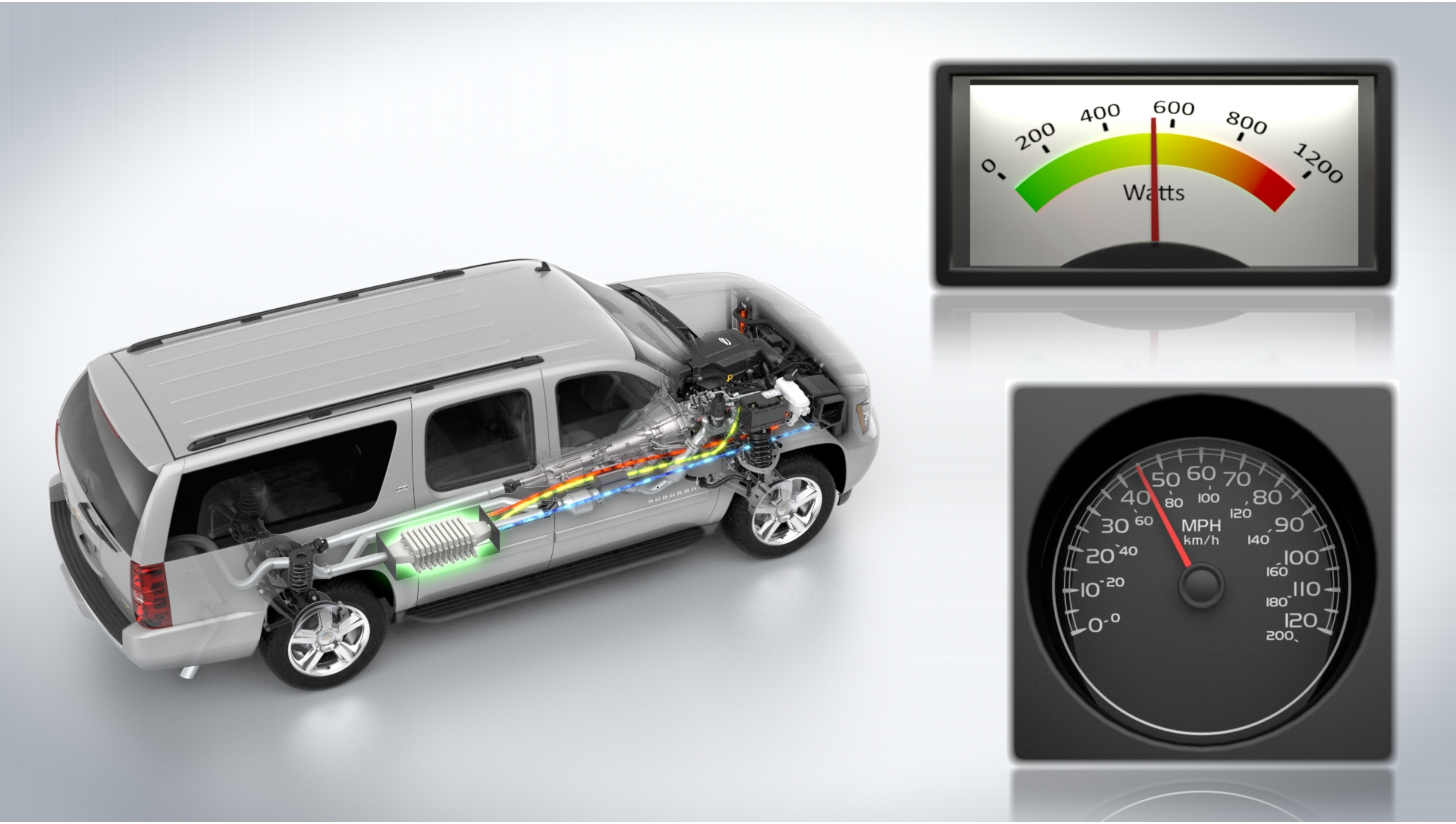


- Average output ~ 350 W and max. output ~ 914 W for city cycle
- Average output ~ 600 W for highway cycle
- An additional ~ 5% fuel economy improvement is expected

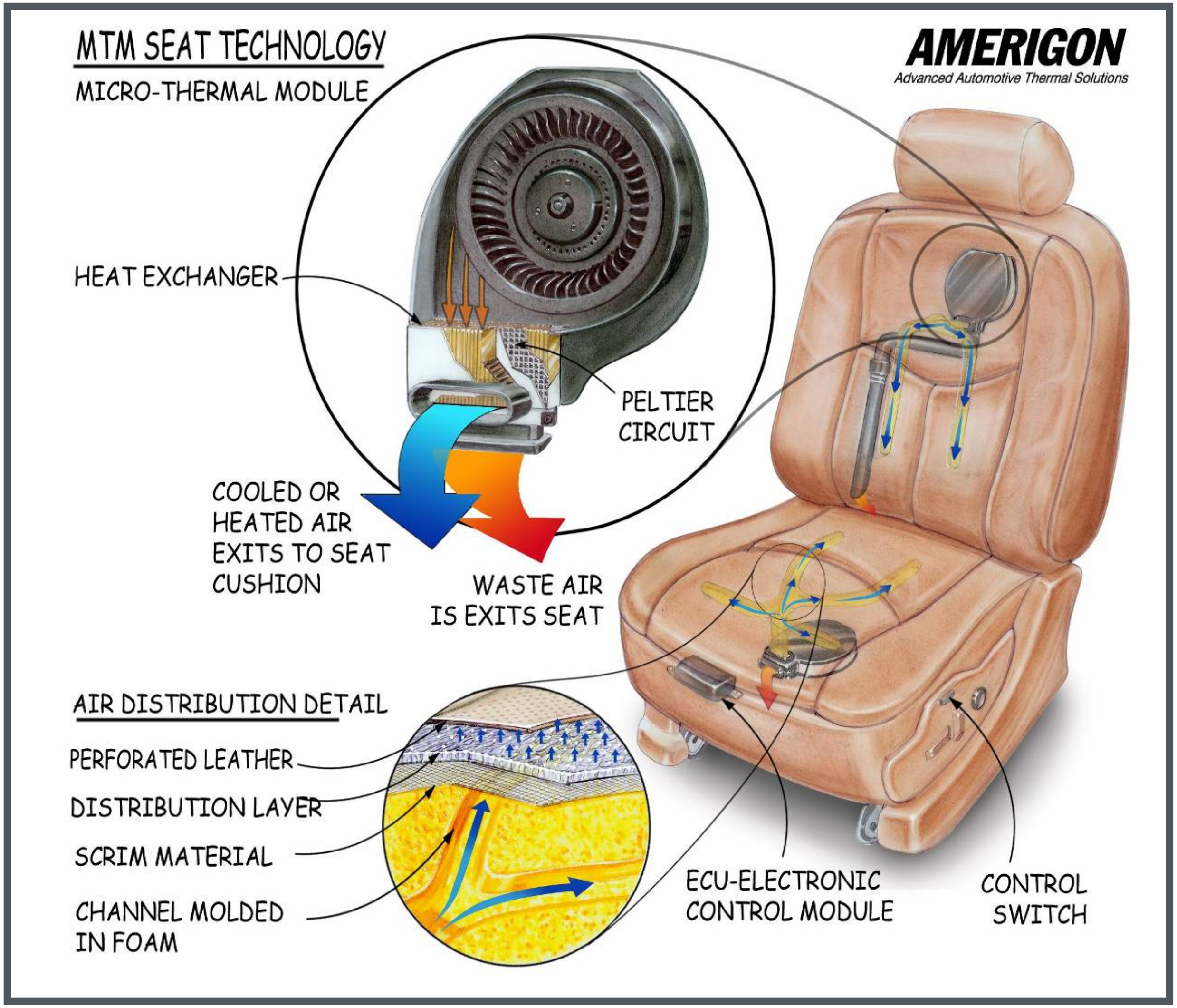
GM TE Generator on a Chevy Suburban



TEG Installation in Chevy Suburban



Climate Control Seat



Automotive TE HVAC (Thermoelectric Heating, Ventilating, and Air Conditioning)

- **Competitive Awards to Ford and GM**
- **Co-Funded with the California Energy Commission**
- **Develop TE Zonal or Distributed Cooling/Heating System**
  - **Maintain Occupant Comfort without Cooling Entire Cabin**
  - **Reduce Energy used in Automotive HVAC's by >50%**
  - **Eliminate all Toxic, Greenhouse and Flammable Gases Associated with Automotive HVAC**

Vehicular TE HVAC

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- **No substance release**
  - **Therefore no ozone depletion, greenhouse gases, toxicity or flammability problems**
  - **No moving parts other than fan and coolant recirculation pump**
  - **Minimal maintenance cost**
- **Fuel Consumption**
  - **Zonal Concept cools/heats each occupant independently; not whole cabin**
  - **630 Watts to cool single occupant; current A/C's 3500 to 4500 watts cool entire cabin**
  - **Lighter weight**
  - **Large potential savings - 73 percent of personal vehicle miles driven with driver only**
- **First Approximation – Cost competitive**
  - **Semiconductor costs are significantly reduced with volume**
  - **Converts Air Conditioner to Heater by reversing DC polarity**

- Current Vehicular Air Conditioner (A/C) uses Compressed R134-a Refrigerant Gas
  - -- Vehicles leak 110 g/year R134-a
  - -- R134-a Has 1300 times the "Greenhouse Gas Effect" as Carbon Dioxide (CO2)
  - -- That is 143 kg/year CO2 equivalent per vehicle/year or

  34 Million Metric Tons of CO2 equivalents/year from personal vehicles in the US from operating air conditioners

  Plus additional 11Million Metric tons of CO2 equivalents/year released to atmosphere from vehicle accidents in the US

  Total of 45 Million Metric Tons of CO2 equivalents/year from regular and irregular leakage in the US enter the atmosphere

-- EU is proscribing use of R134-a

- **Occupant Heating During Battery Propulsion (No Engine Heat)**
  - **Inefficient Resistance Heating**

Occupant Cooling

- **Electric Compressor Refrigerant Gases**
  - **> Need R134-a Replacement**

Thermoelectric HVAC Zonal Concept

> Cooling COP 1.5

Augment or Replace Compressed Gas Unit

> Heating COP 2.5

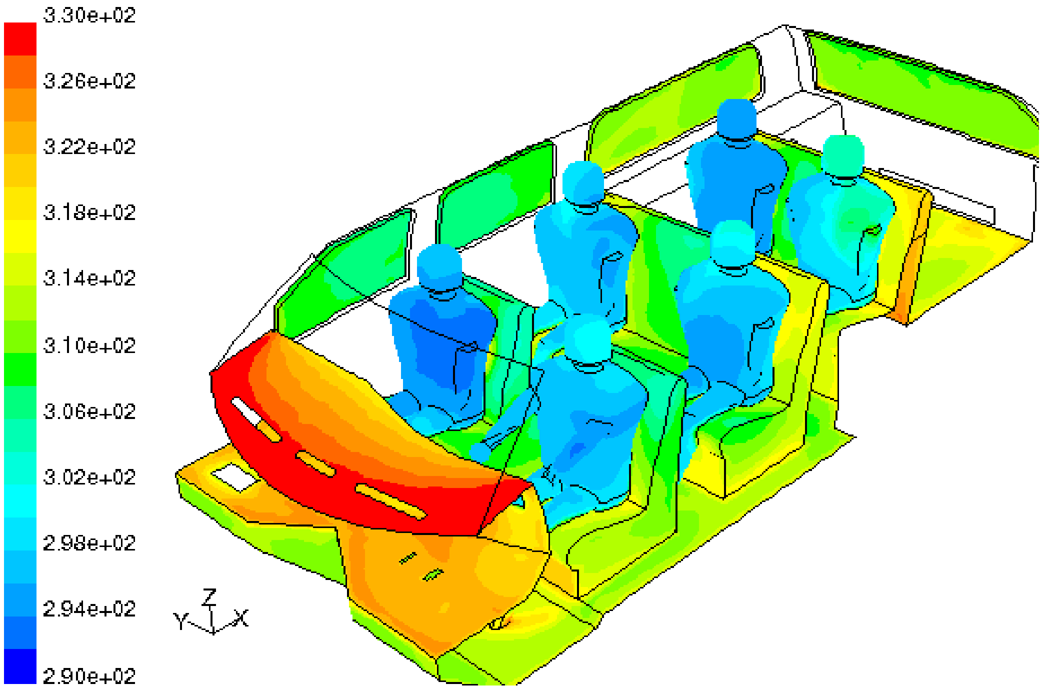
Replace Resistive Heaters

Typical COP 1.0

Zonal or Disbursed HVAC System

Zonal TE devices located in the dashboard, headliner, A&B pillars and seats / seatbacks

Zonal or Distributed Cooling with High Efficiency Vehicular TE HVAC (NREL)



- Reduce onboard AC without sacrifice passenger comfort level
- Improve fuel economy and reduce CO_2 emission

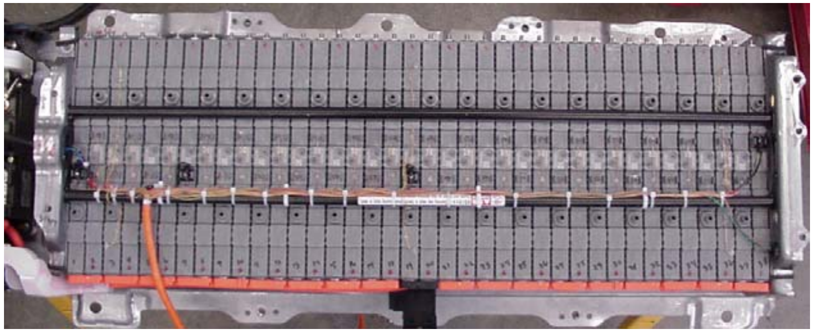
Vehicular TE HVAC

- While TE HVAC is beneficial to all vehicles, it is especially advantageous for:
  - Plug-in Hybrids,
  - Hybrids,
  - Electric Cars,
  - Fuel Cell Powered Vehicles and
  - Vehicles with Small, High-Efficiency, Low-Temperature Exhaust Engines
    - Inadequate heating first 20 something miles
    - Augment Occupant Comfort w/PCH Ceramic Resistive Heaters

- **Approach: Develop Zonal Thermoelectric based heating and cooling systems for cars, light trucks (SUV's, Pick-ups, Mini vans) and Heavy Duty Trucks 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**
      - **(Except for fans and heat transfer fluid circulating pump)**
    - **No refrigerant gas recharging**

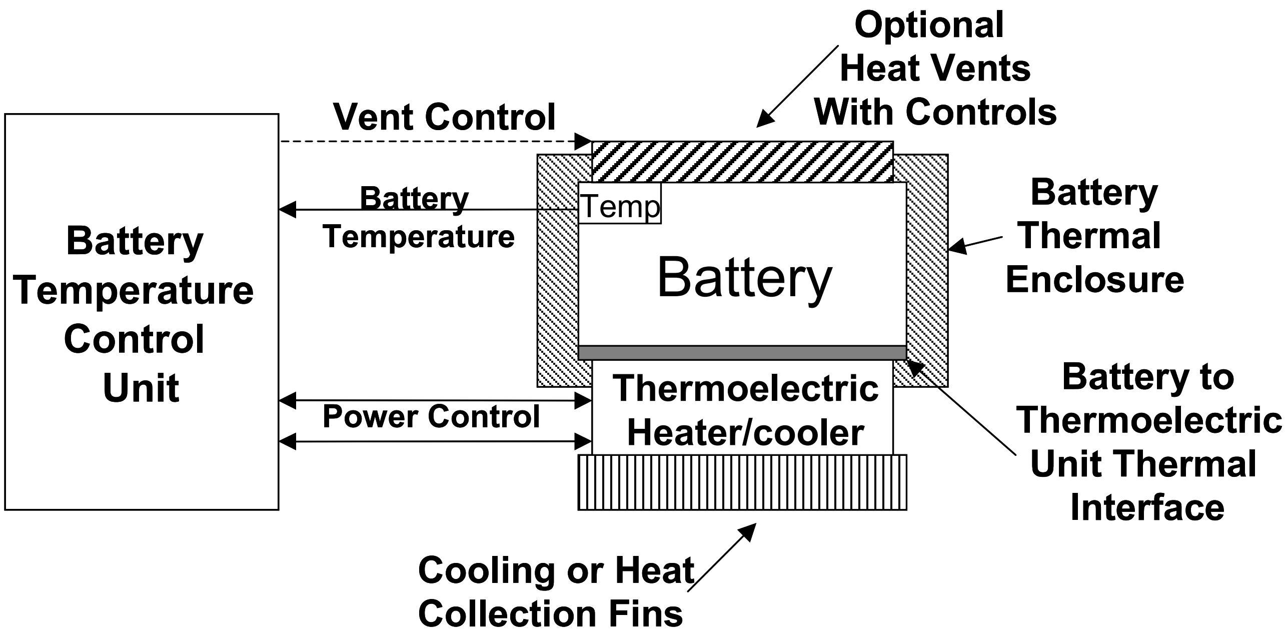
Battery Temperature Impacts HEV/EV Performance

- Temperature affects battery operation 24/7
- Round trip efficiency and charge acceptance
- Power and energy
- Safety and reliability
- Life and life cycle cost



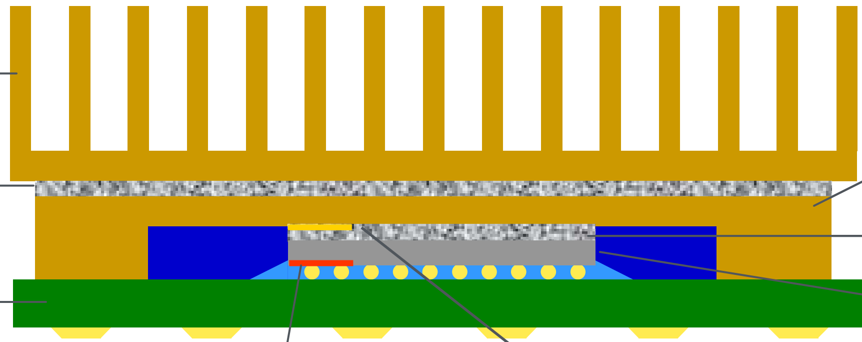
Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost

A Battery Temperature Control System



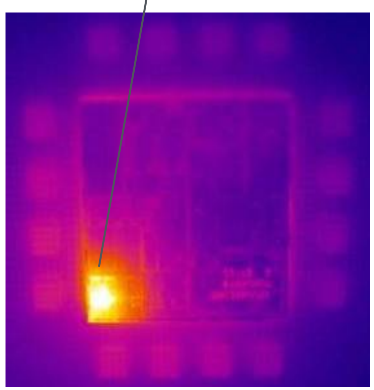
- significant warranty cost savings
- improved battery reliability
- improved battery efficiency & performance
- enables more flexible packaging

Embedded Semiconductor Cooling Remove Heat From Die to Heat Sink

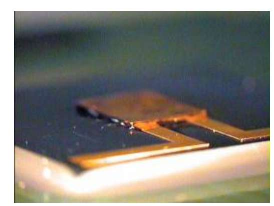


Hotspots effect

- ❑ Reliability
- ❑ Performance
- ❑ Package cost



Nextreme's solution



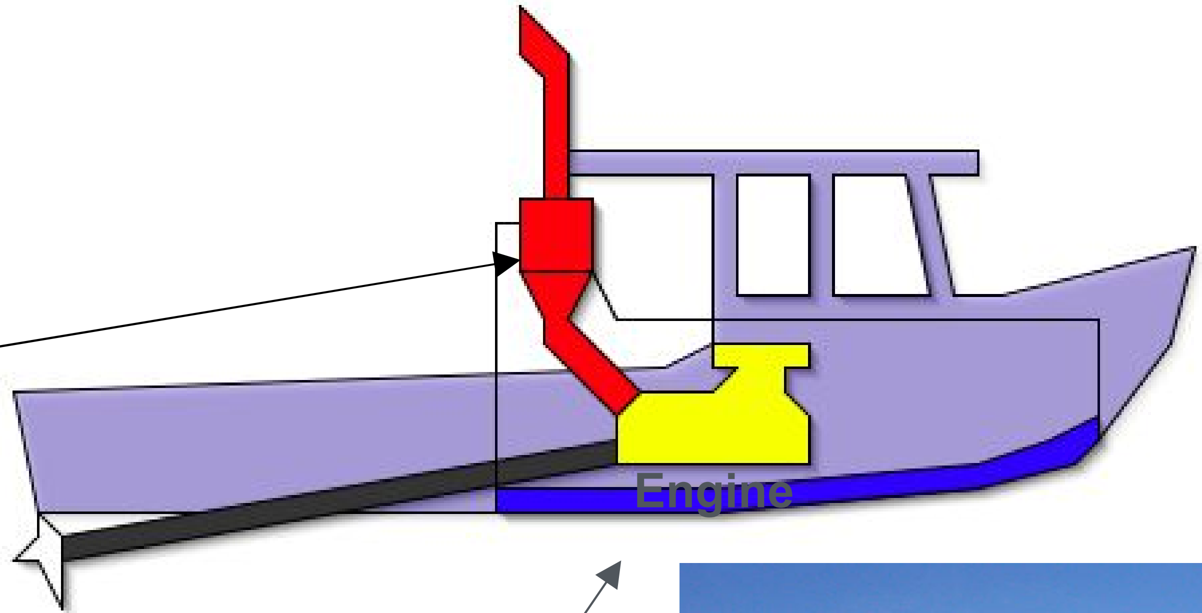
100 µm thickness

Embedded Thermoelectric in IC

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

Thermoelectric Generator on a Fishing Vessel's Engine Exhaust

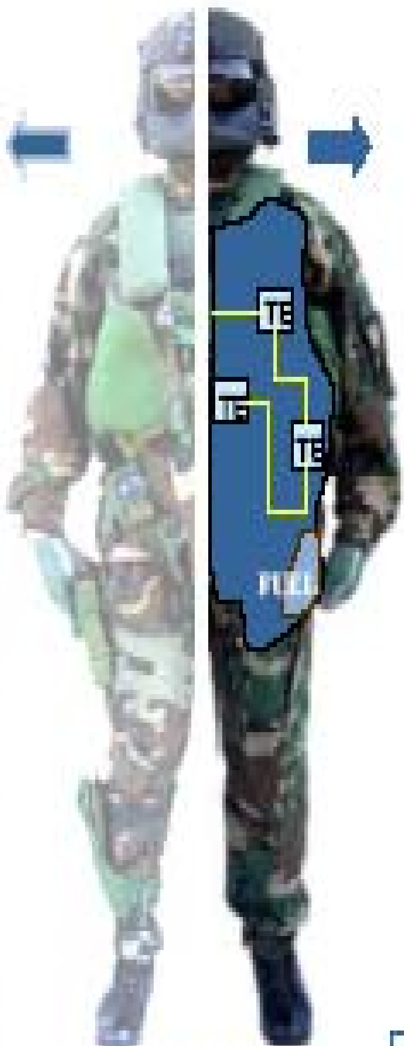
Seawater Cooled Exhaust Stack TE Generator



Keel Coolers

Maine Maritime Academy's "Fishing Vessel" R/V Friendship 47 Feet LOA

Advanced Thermal Comfort Management for Soldier of Tomorrow



COOLING/ HEATING
- None

WEIGHT (Power Source)
- 18 lbs battery

COOLING/ HEATING
- On-demand (ΔT = 40F)

WEIGHT (Power Source)
- 2 lbs fuel (Logistic Fuel)
- 3 lbs hardware

ENERGY
- 1000W fuel to 800W thermal (200W heat rejected)
- 800W thermal to 200W electrical (600W heat rejected)
- 100W electrical to power communication devices
- 100W electrical to dissipate 300W metabolic load (400W heat rejected)
  COP = 300Wth/100We = 3
- 1200W (200W + 600W + 400W) heat load rejected to atmosphere

Enabled by Thermoelectrics (TE)

Assumptions
12 hour mission @ 110F ambient temperature
ZT 2.5 for power, 25% conversion efficiency

USS DOLPHIN AGSS 555 Thermoelectric Air Conditioning Test for Silent Running

Thermoelectric Wristwatch

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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)

Recent Advances in Efficiency of Thermoelectric Materials

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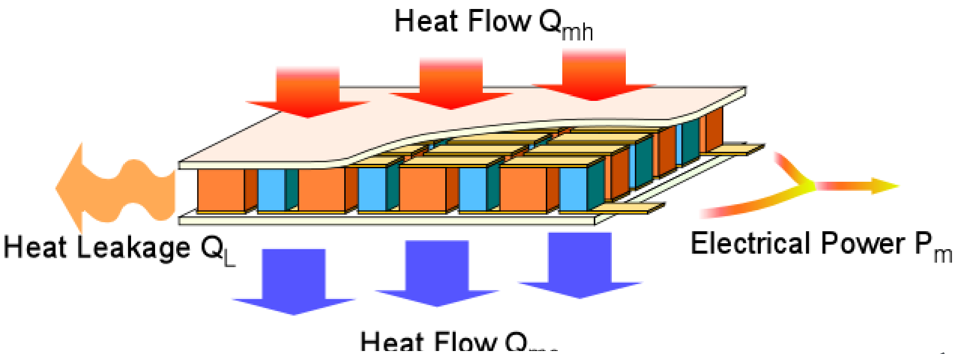
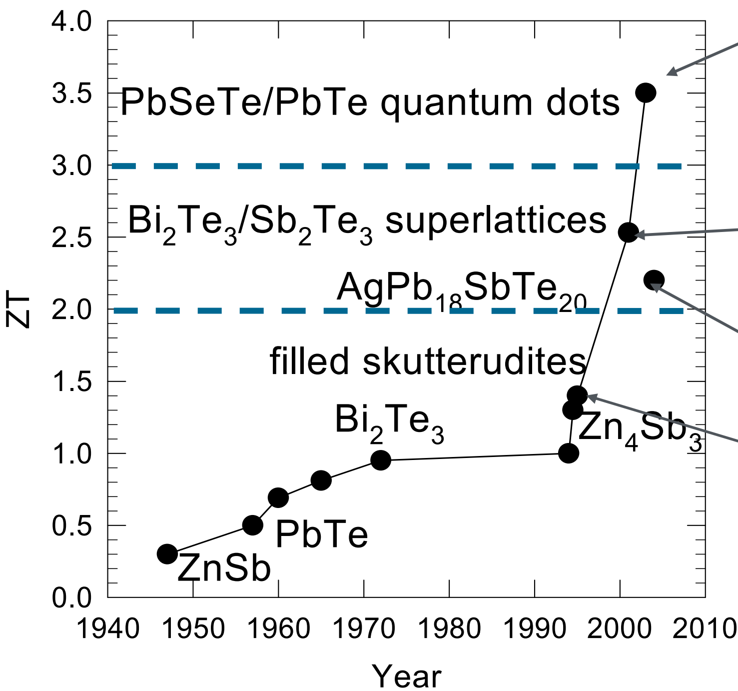
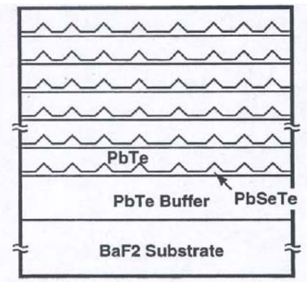
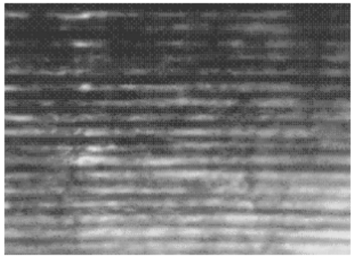


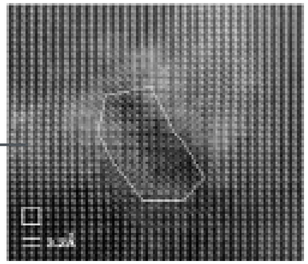
Efficiency:

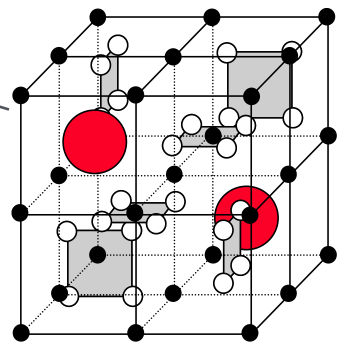
$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}}$$





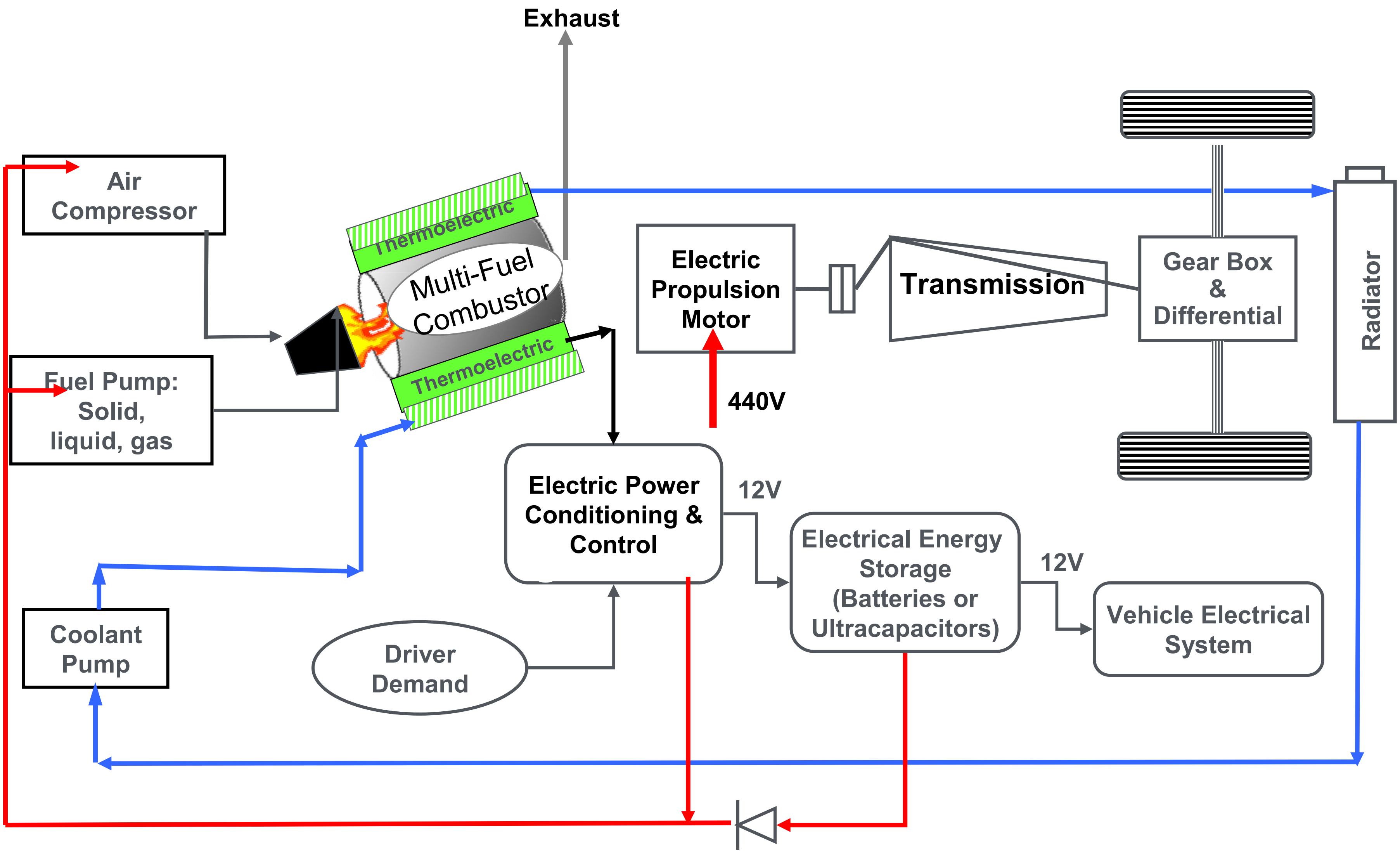






Many recent thermoelectric material advances are nano-based

Vehicular Multi-Fuel Thermoelectric Hybrid Electric Powertrain



Vehicular Thermoelectric Application Possibilities

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Near Term (3-6 yrs)

- Thermoelectric Generators (TEG's) providing nominal 10% fuel economy gain augmenting smaller alternator
- "Beltless" or more electric engines
- Thermoelectric HVAC augmenting reduced size A/C

Mid Term (7-15 yrs)

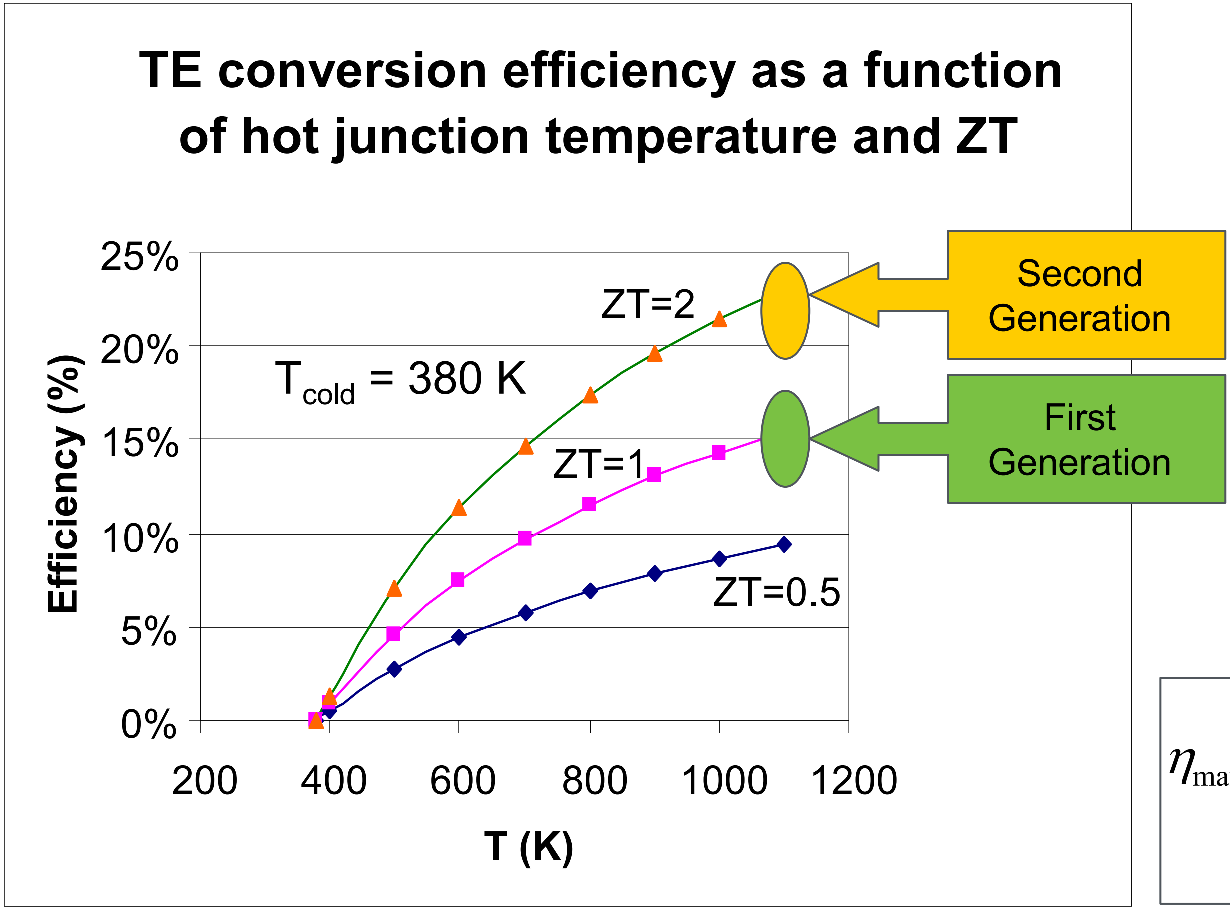
- TEG's installed in diesel or gasoline engine exhaust
  - 55% efficient heavy duty truck engine
  - 50% efficient light truck, auto
- 2nd Generation TEG's and TE HVAC w/o alternators or A/C
- Aluminum/Magnesium engine, frame & body replacing steel

  (Process waste heat recovery) mass market cars

Long Term (16-50 yrs)

- 30% efficient Thermoelectrics w/ 500 ^{0}C ΔT
  - Replace Internal Combustion Engine (ICE)
  - Dedicated combustor burns any fuel
  - Terrestrial RTG TEG powered busses, light rail

TE Materials Performance Objective



TE Materials for Vehicular TE Generators

$$\eta_{\max} = \frac{T_{hot} - T_{cold}}{T_{hot}} \; \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_{cold}}{T_{hot}}}$$

Carnot *TE Materials*

DOE VTP Program Objectives & Potential Spin -Offs

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- DOE/VT R&D Objectives
  - Commercially viable ZT_{avg} > 1.7, 320K – 820K

- Program Planning
  - DOE/NSF Non-Telluride TE materials development
  - DOE/VT Scale-up advanced materials & Increase production capability
  - Develop 2nd Generation Vehicular TEG's and TE HVAC

  - Potential Spin-off Applications
    - Industrial Processes
    - Stationary Power
    - Geothermal
    - Aircraft
    - Rail
    - Marine
    - Spacecraft
    - Military

If the 220 M Personal Vehicles in the US had Thermoelectric Generators powering Thermoelectric Coolers/Heaters (HVAC)

- Save 4.5 Billion gals/year of fuel
- Reduce Greenhouse Gases by 69.5 Million Metric Tons of CO_2/year

THERMOELECTRIC GENERATORS COULD SAVE YOU 10% OF CAR/LIGHT TRUCK FUEL CONSUMPTION

Thermoelectrics – They Are Not Just For Outer Space!!!

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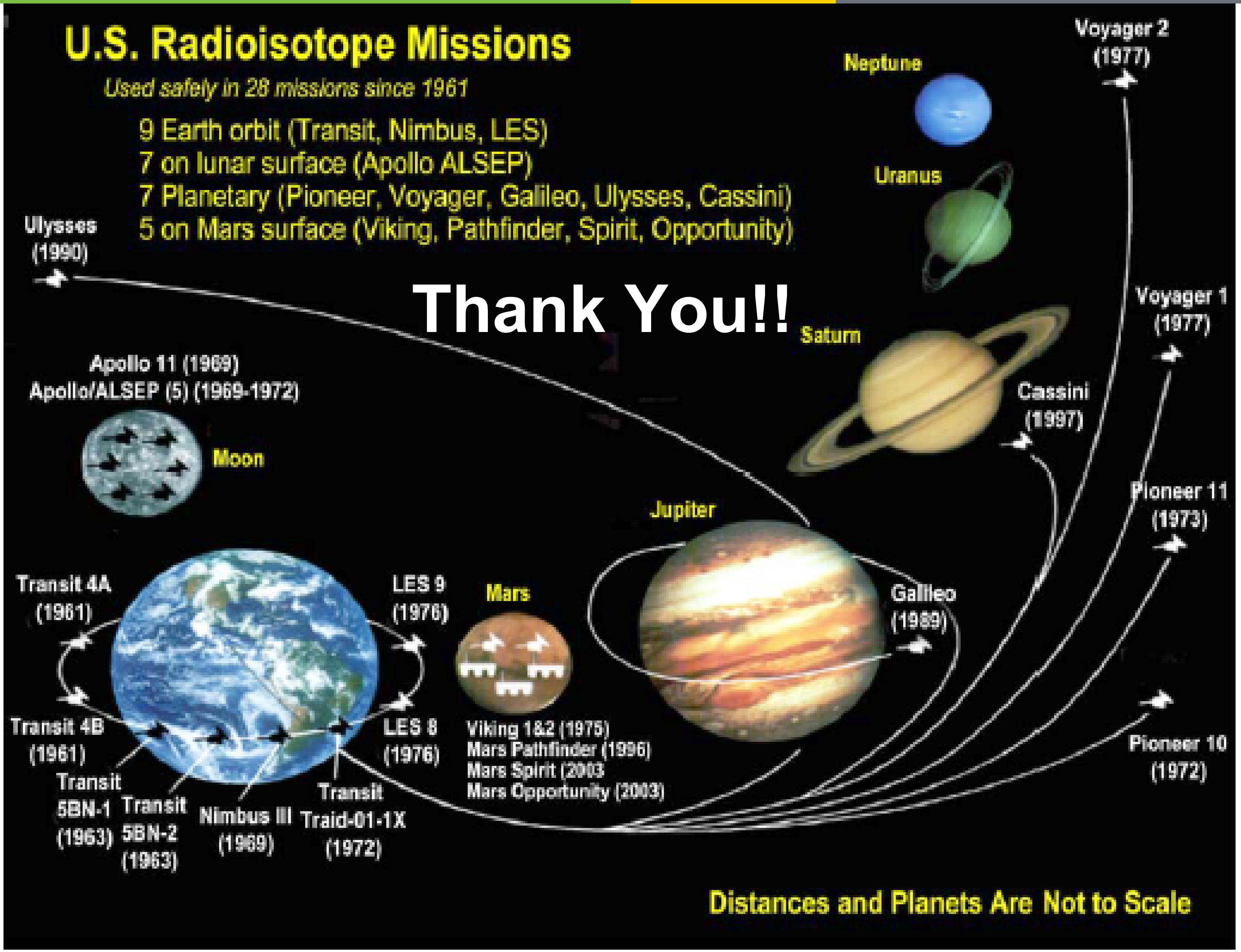
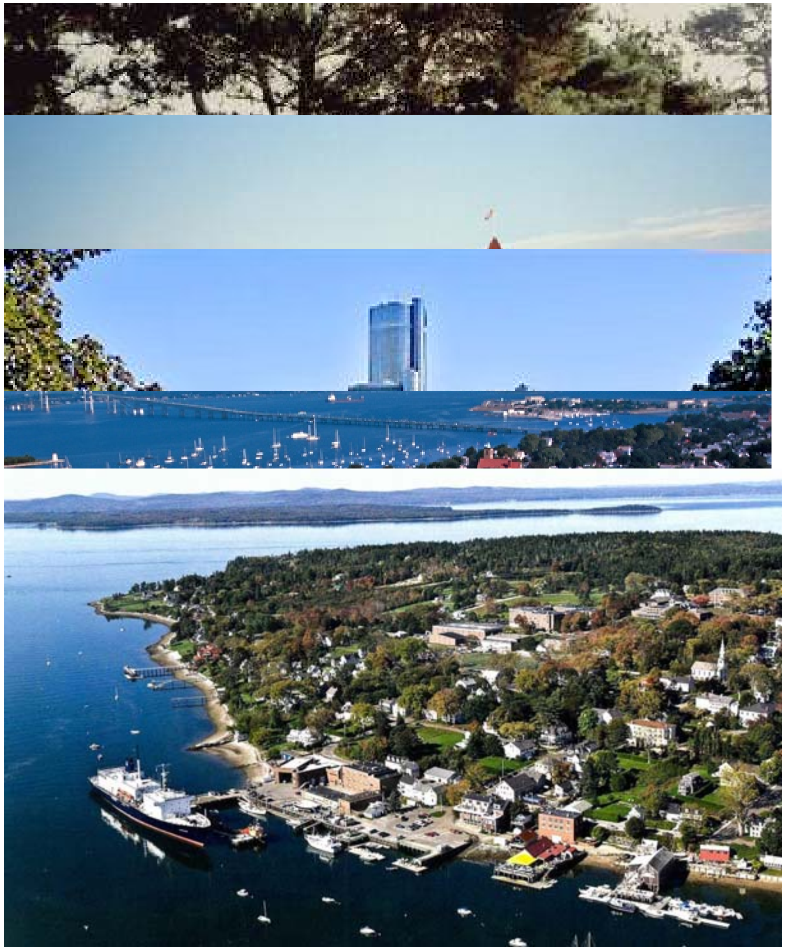


Thank You!!

Possible Venues: 2010 Thermoelectric Applications Workshop

- Monterey
- San Diego
- Detroit, MI
- Newport, RI
- Castine, ME



DOE SBIR call for proposals

Advanced cooling technologies

- Looking for advanced **thermoelectric technology** for applications in *building, industry and vehicles* for:

Cooling applications

Waste heat recovery

- Phase I proposals should include:
    - a preliminary **design**
    - a characterization of **laboratory-scale devices** using the best measurements available, including a description of the **measurement methods**
    - a road map showing **major milestones** that would lead to a system that would be built and tested in **Phase II**

DOE SBIR call for proposals

Advanced cooling technologies

- The targeted areas or cooling and waste heat recovery are:
  - new thermoelectric **materials** that have
  - a **high figure of merit** (ZT) and the potential
  - for **large-scale production**,
  - at costs **competitive** with conventional technologies
  - considering the full system over its lifetime;
  - modules to **house** thermoelectric materials
    that mitigate **thermal expansion** issues
    that can cause failure; and
  - thermoelectric **systems** that address all of the
  - **thermal interface,**
  - **materials compatibility, and**
  - **thermal management** issues of the integrated system.

Proposals that address all three of the above subjects are preferred.
Collaborations with OEM's (Original Equipment Manufacturer) are encouraged.

Contact: Dr. Sam Baldwin, Sam.Baldwin@ee.doe.gov,
202-586-0927
http://www.science.doe.gov/SBIR