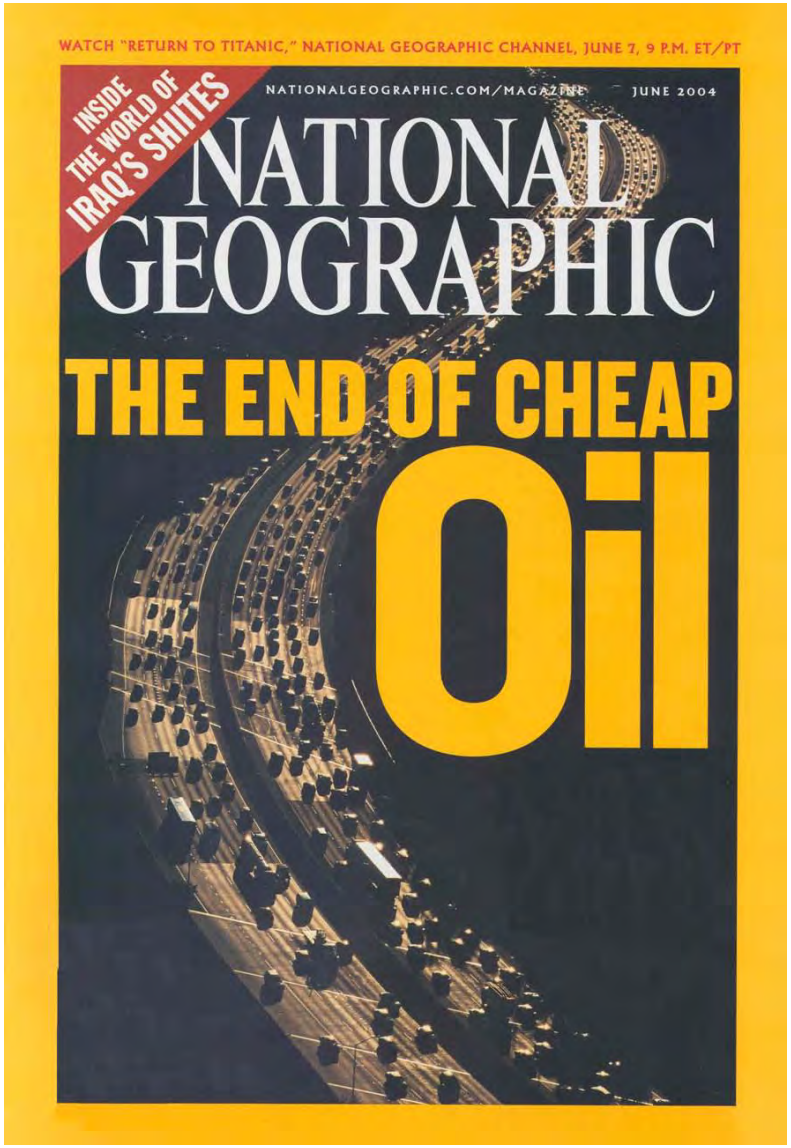
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Thermoelectrics: The New Green Automotive Technology

John W Fairbanks
Vehicle Technologies Program
US Department of Energy
Washington, DC

Presented at the
2011 Annual Merit Review
DOE Hydrogen and Fuel Cells Program
and Vehicle Technologies Program
Washington, DC
May 9-13, 2011

Petroleum Market Forecast



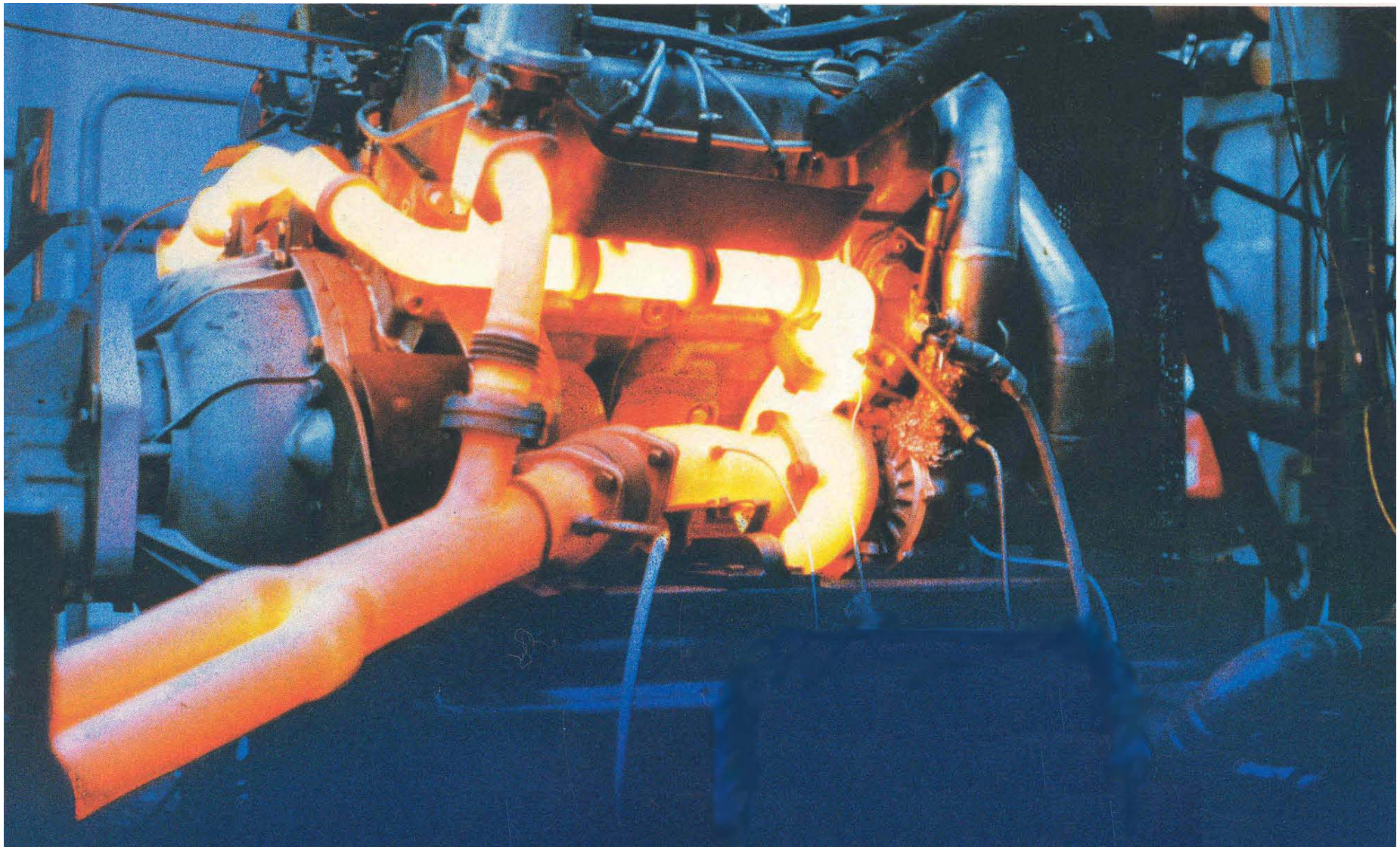
Gasoline Prices 201X…

Gasoline Prices 201X…

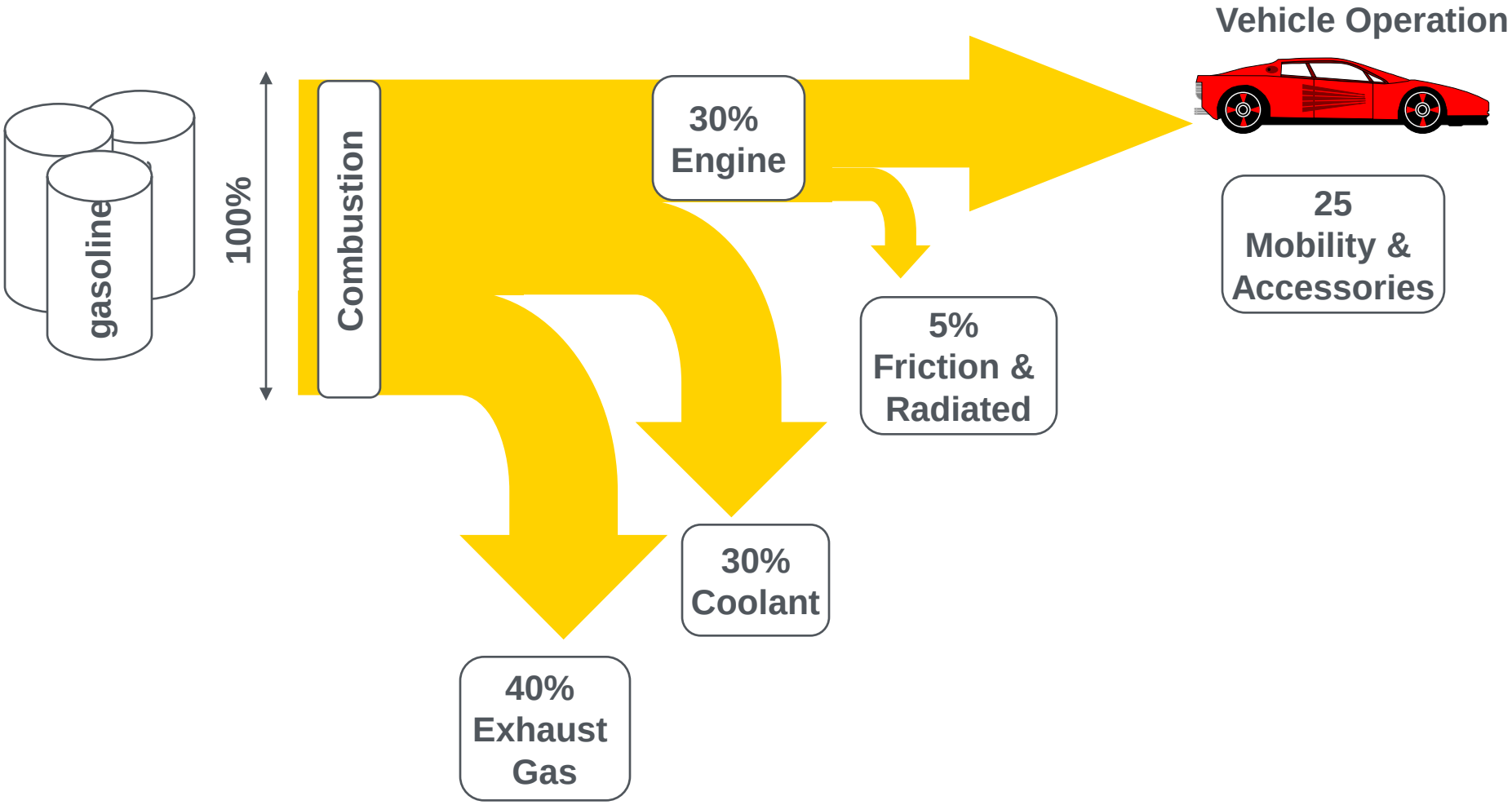
DOE's First Generation Vehicular (TEG) Program Objectives

- **Use Thermoelectrics to generate electricity for powering auto components**
  - **(lights, pumps, occupant comfort, stability control, computer systems, electronic braking, drive by wire, audio and video systems, TE HVAC.)**
- **Reduce size of alternator (target: 1/3rd reduction in size)**
- **Improve fuel economy (targets: 5% to 6%)**
- **Reduce Regulated Emissions and Greenhouse Gases**

Gasoline Engine Waste Heat



Typical Waste Heat from Gasoline Engine Mid Size Sedan



Combustion of Hydrocarbon Fuels Releases Carbon

Gasoline C_7H_{16}

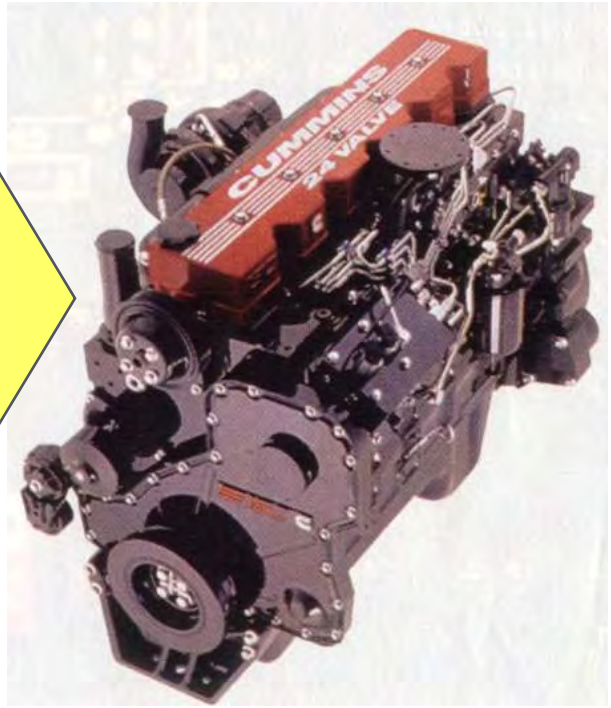
Diesel $C_{18}H_{30}$

Methanol CH_3OH

Ethanol C_2H_5OH

Natural Gas (Primarily Methane, CH_4)

Propane C_3H_8



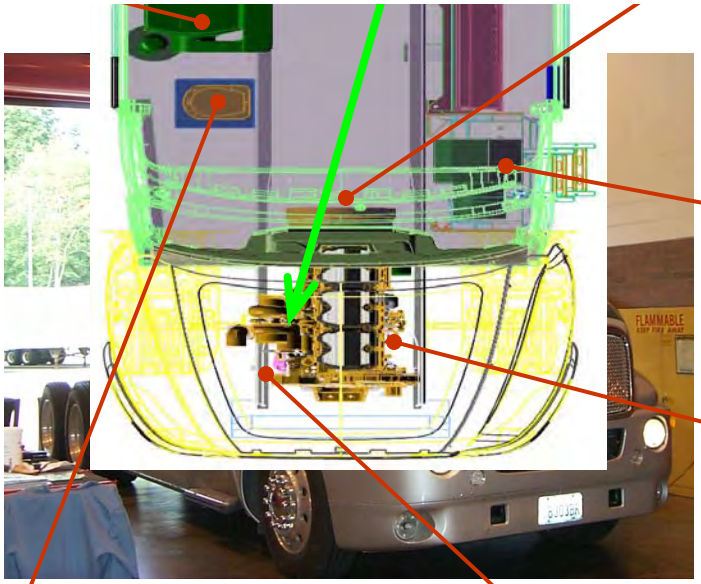
Carbon

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

Beltless or More Electric Engine

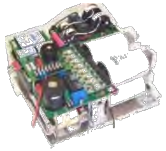
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Truck Electrification Demonstration



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

Electric Oil Pump
Variable speed
Higher efficiency

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

CAT®

Vehicular Thermoelectric Applications

- Air Conditioner / Heater (TE HVAC)
- Engine Waste Heat Generator (TEG)
- Pre-start Engine Oil and Transmission Fluid warm up.
- Battery Thermal Management
- Beverage Cooler/Warmer
- Computer and Radar (Collision Avoidance) Cooling

TE Materials Performance: Figure of Merit (ZT) *[Oregon State]*

Electrical conductivity

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

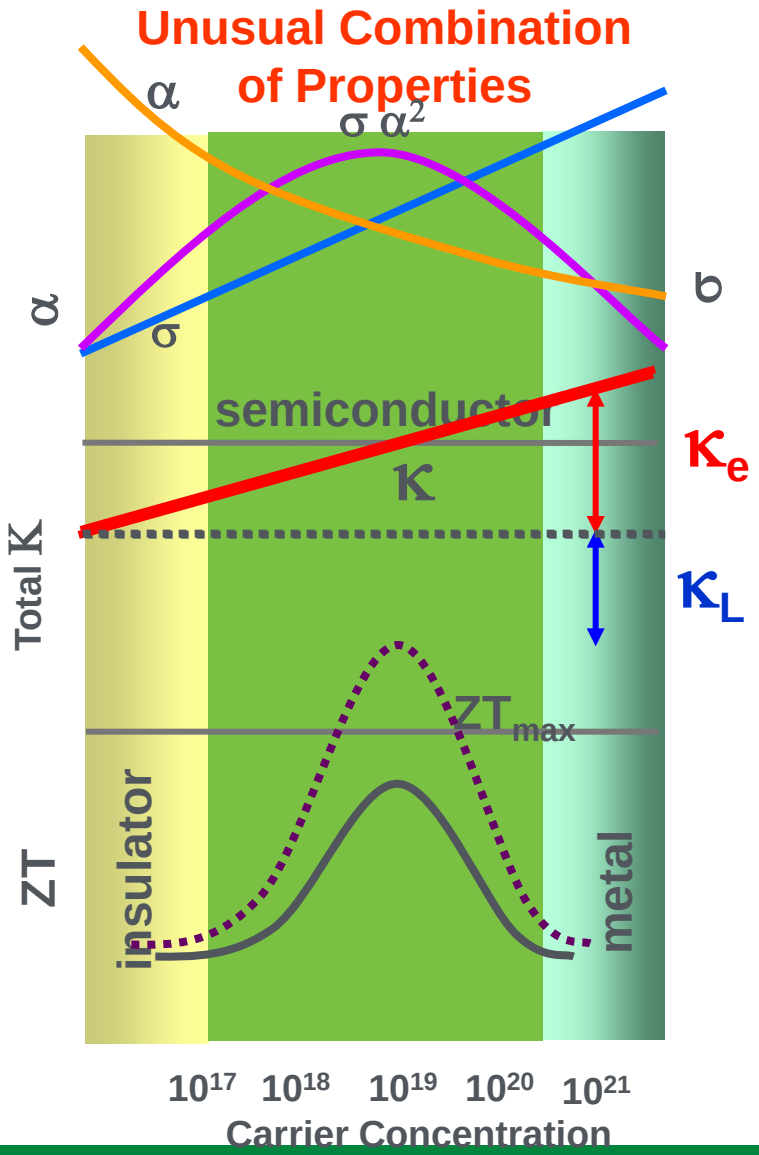
$$ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \bullet T$$

Total thermal conductivity

$\sigma\alpha^2$ = **Power Factor**

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

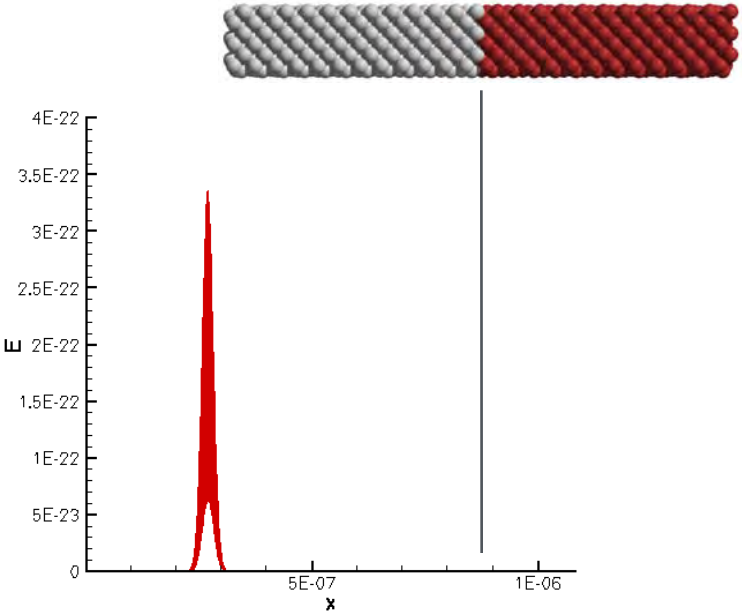
ρ = **electrical resistivity**

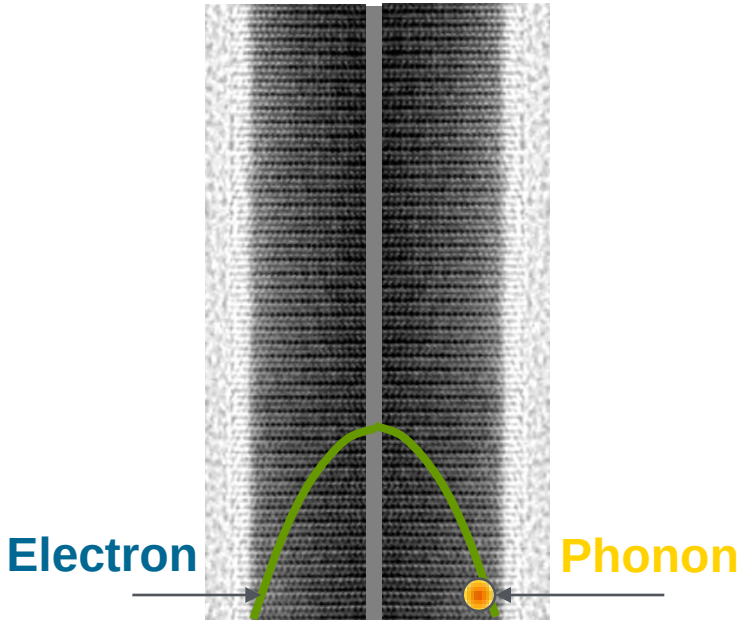


Nanoscale Effects for Thermoelectrics (courtesy Millie Dresselhaus, MIT)

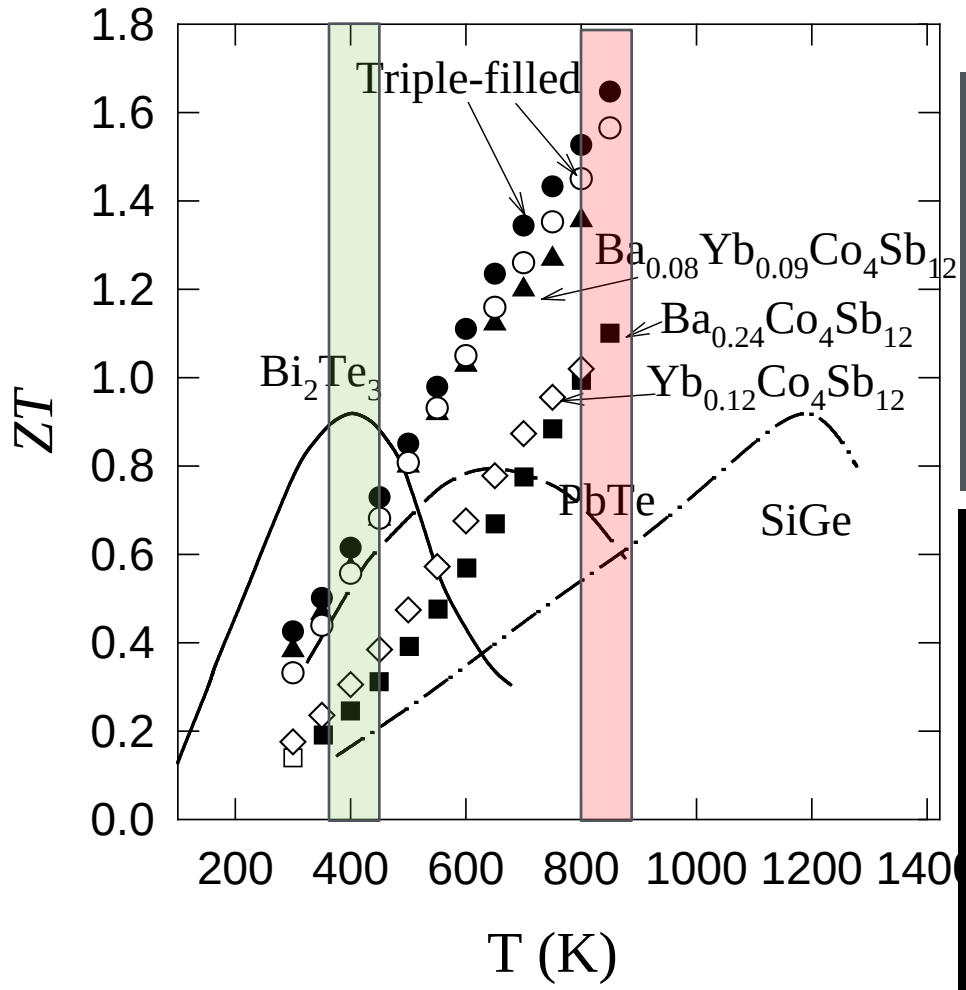
Interfaces that Scatter Phonons but not Electrons

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

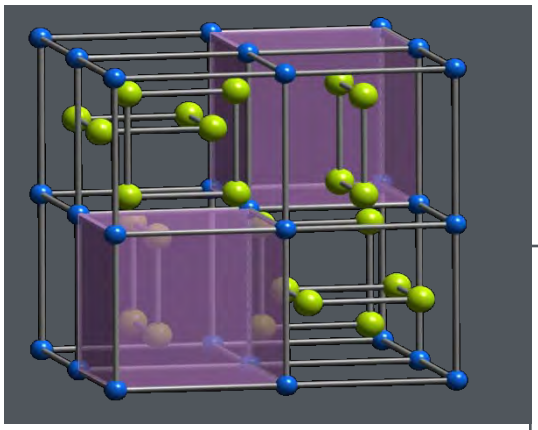


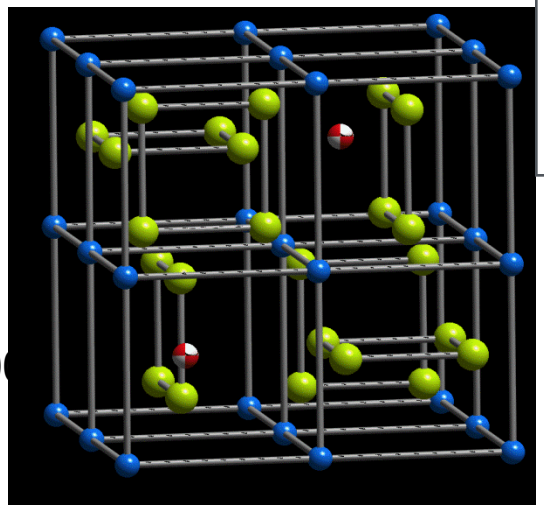


Highest ZT Achieved with Triple-filled Skutterudites (GM and U of Michigan)



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



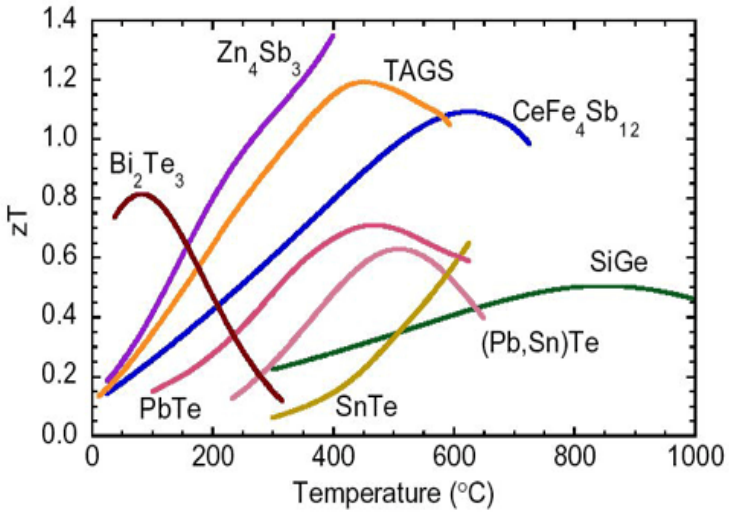


Atoms can be inserted into empty sites. Atoms can "rattle" in these sites – scatter phonons and lower the lattice thermal conductivity.

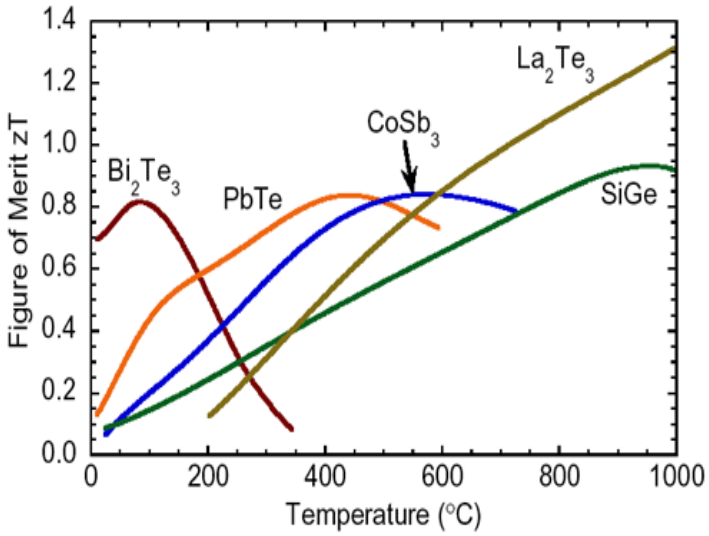
1. X. Shi, et al. Appl. Phys. Lett. **92**, 182101 (2008)
2. X. Shi, et al., submitted (2009)

R_xCoSb

Current TE Materials



P-type TE material

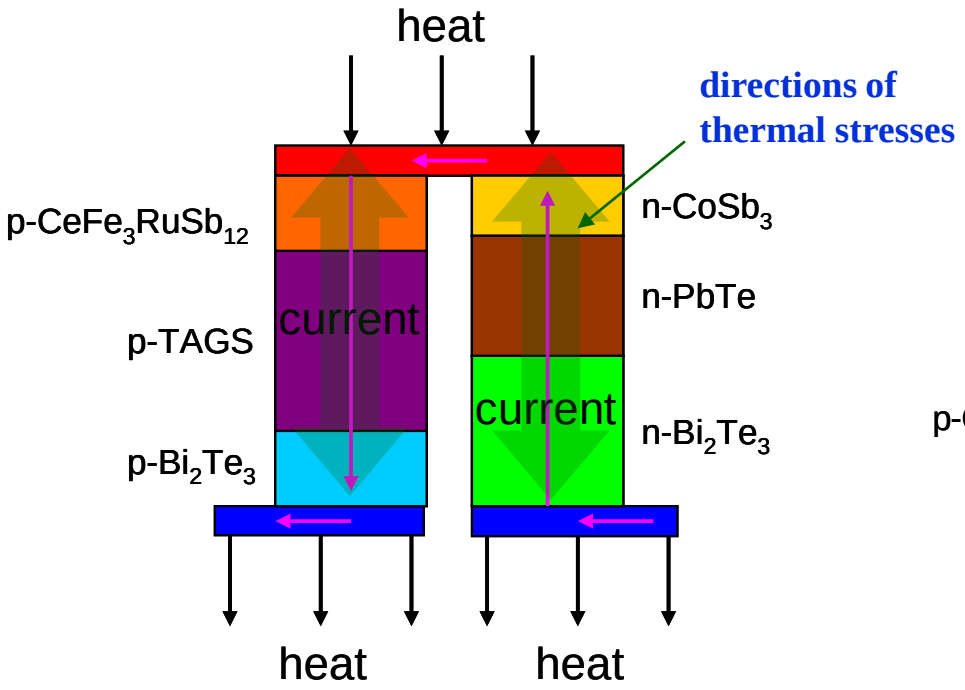


N-type TE material

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

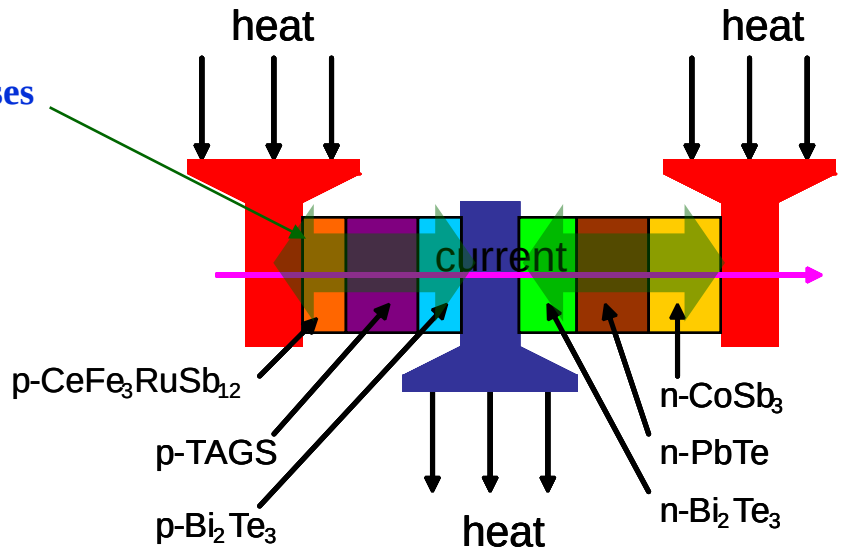
Segmented Thermoelectric Couple Configurations

conventional



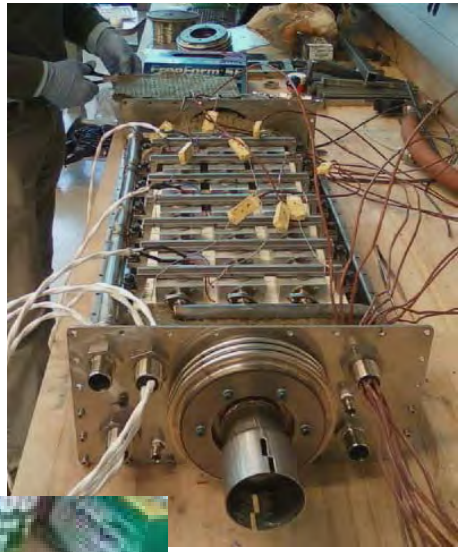
Thermal Mismatch Stresses can Separate Material Layers

BSST "Y" configuration

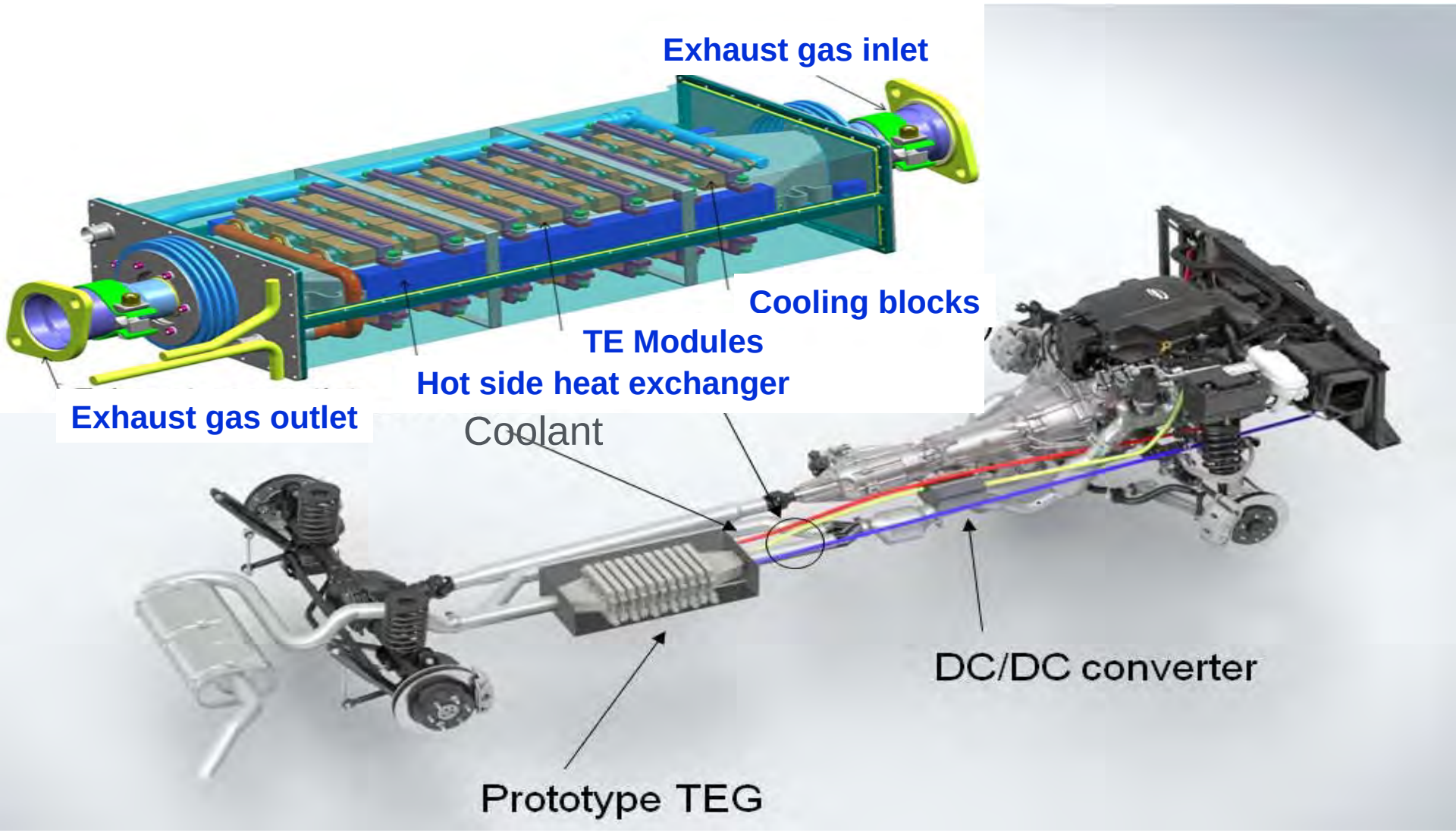


Thermal Mismatch Stresses are Significantly Reduced

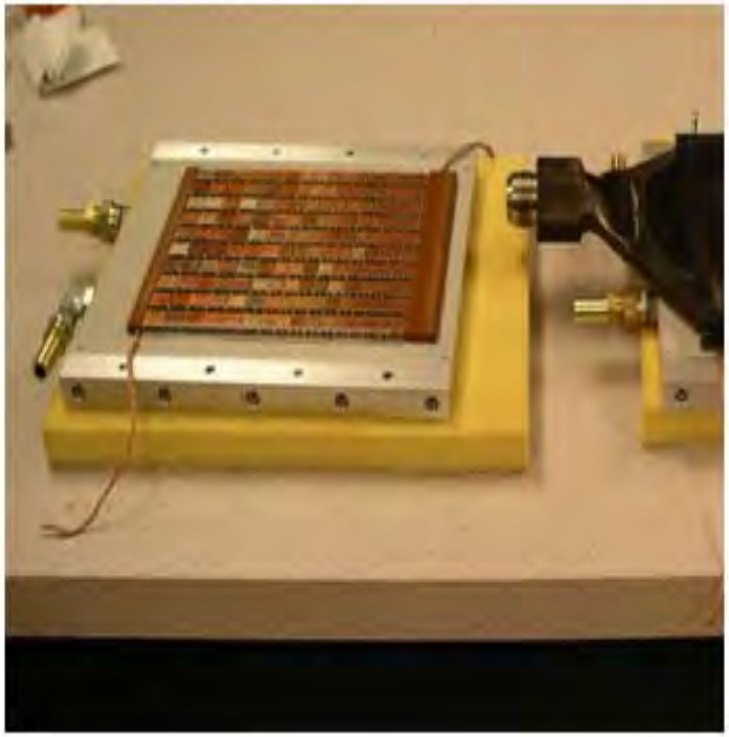
GM Prototype TEG Fabrication for Chevy Suburban

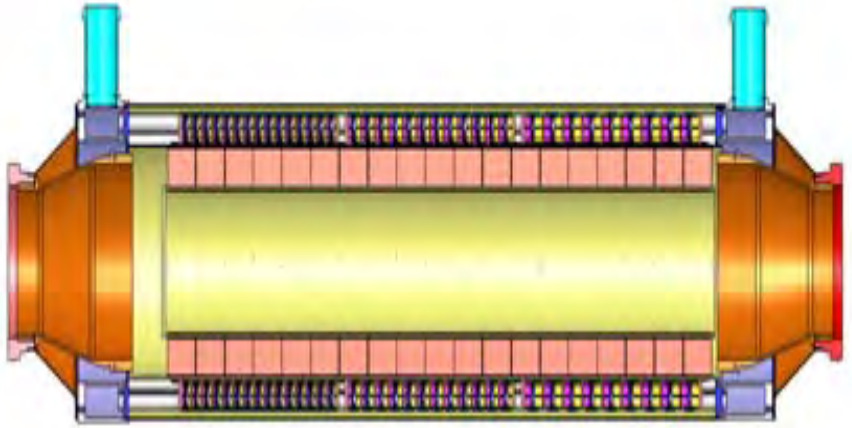


GM Prototype TEG Installation in a Chevy Suburban Chassis



BSST 2D to 3D TEG Design Iteration for BMW and Ford Autos

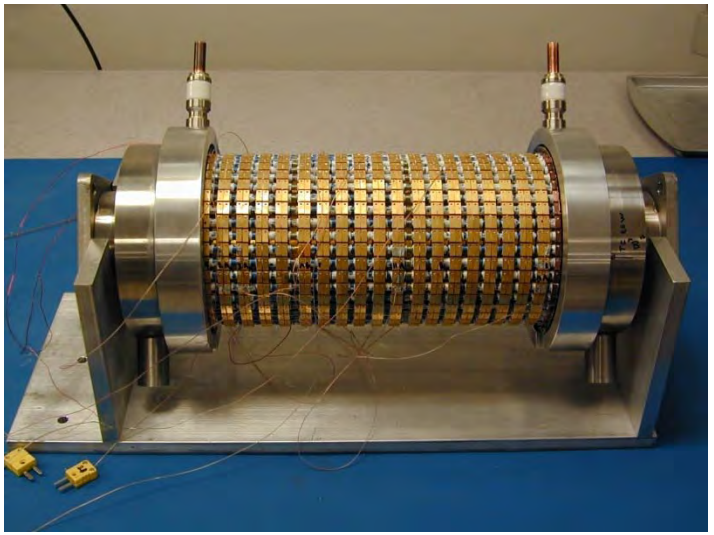




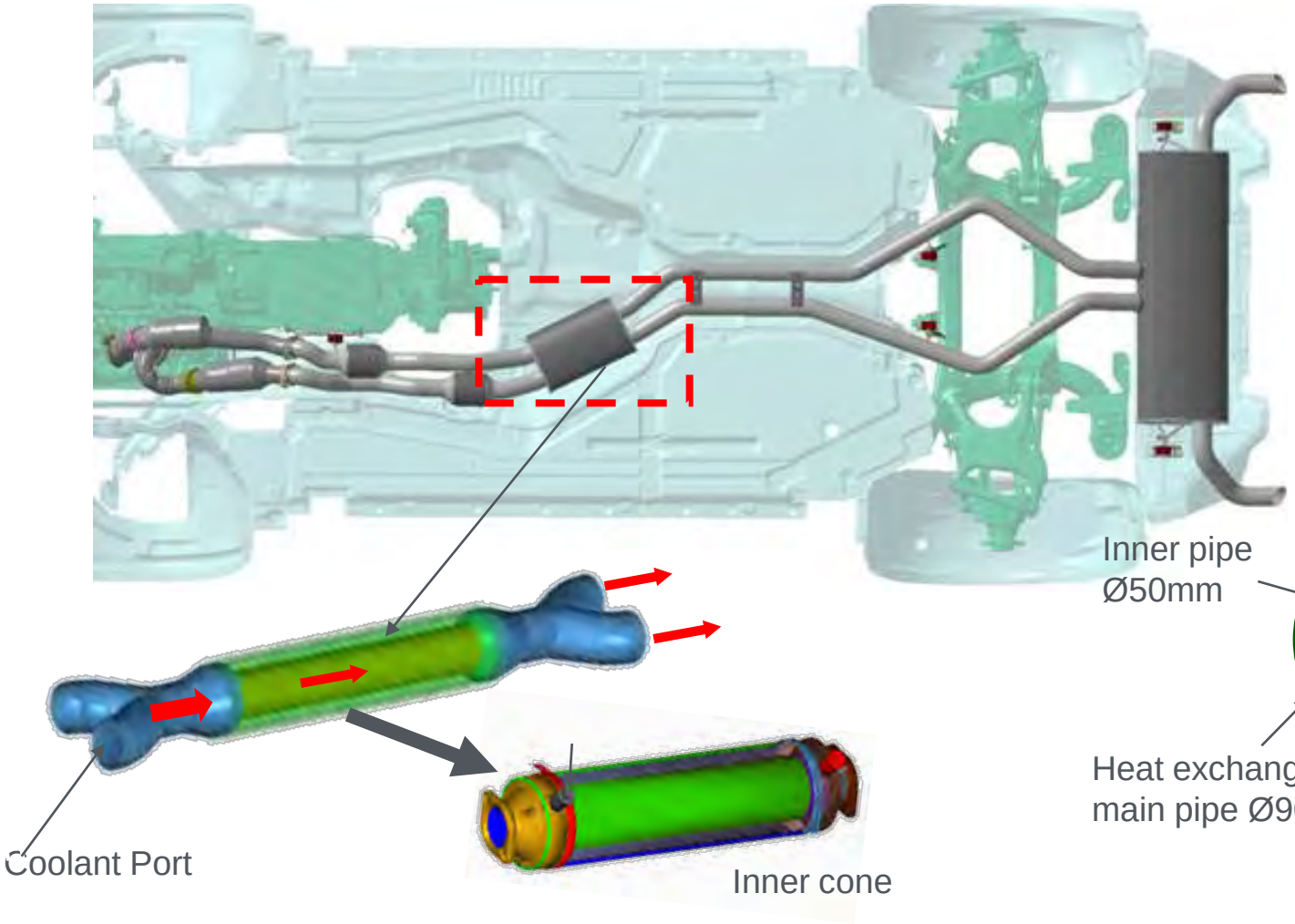
Cross Sectional View of Preproduction Waste Heat Recovery TEG

Amerigon/BSST TEG for Ford and BMW

- Final assembly TEG prior to installation in BMW X6 and Ford Fusion
- Cylindrical design TEG incorporates an internal bypass of exhaust gas for high engine load
- The TEG has 3 sections with different TE materials matched to the decreasing thermal power in the exhaust gas as passes through the TEG.



TEG Location on Ford Fusion:

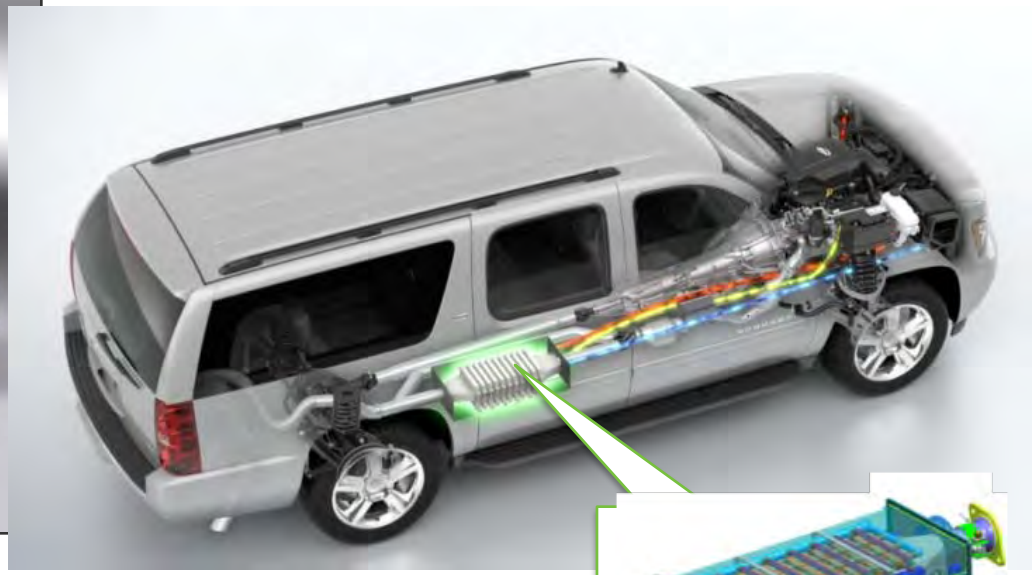


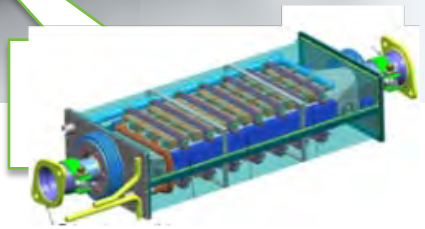
Amerigon/BSST TEG Installation in Vehicles

Amerigon and Faurecia are installing production prototype TEG's in the exhaust systems of BMW X6 and Ford Fusion.

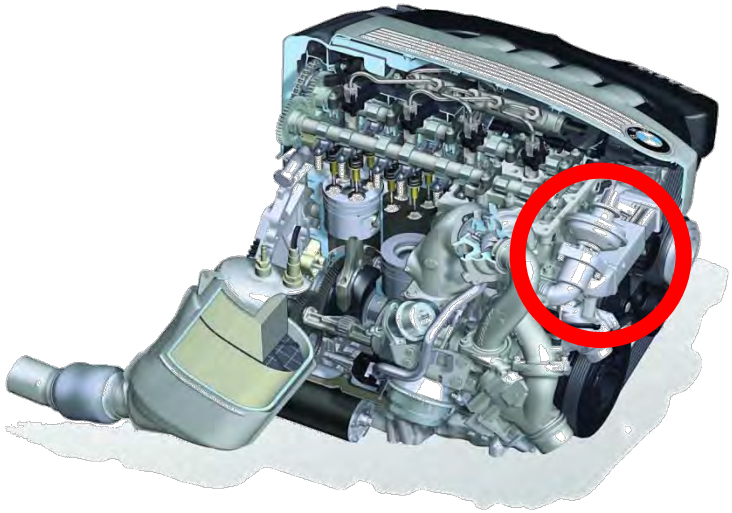
Prototype TEG's In Ford Fusion, BMW X6 and Chevy Suburban- DOE Programs

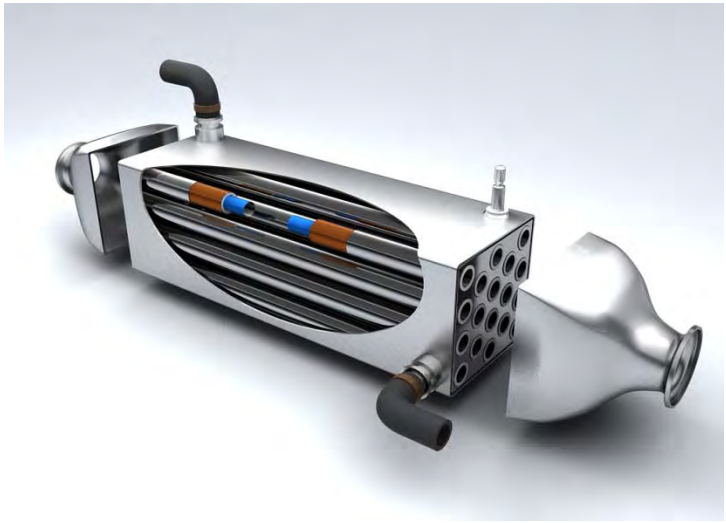
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

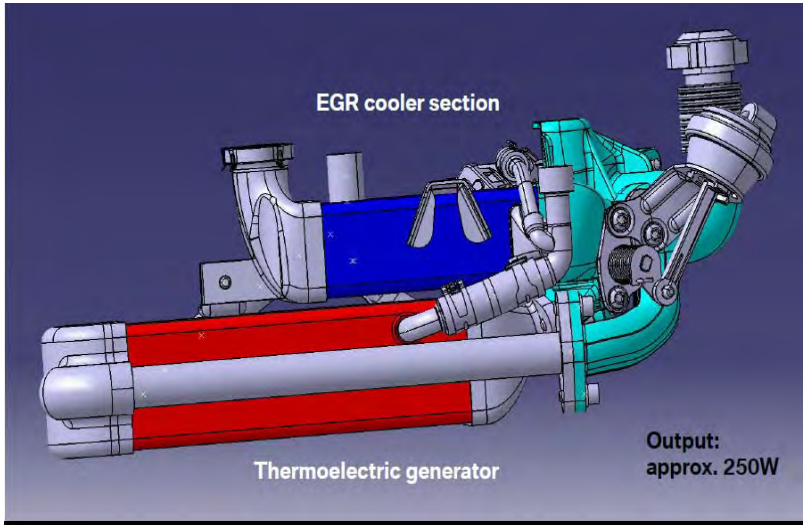




BMW Exhaust Gas Recirculation (EGR) Cooler-TEG on Diesel Engine







DOE's Objectives: Second Generation Automotive TEG's

- Commercially Viable Thermoelectric Modules

  $ZT_{avg} = 1.6$

  Temperature range 350 - 900^{o}K

- Eliminate the Alternator Entirely

- Provide a 10 Percent Reduction in On-Highway Fuel Use with Associated Reduction in Regulated Emissions and "Greenhouse Gases"

DOE/CEC's Automotive TE HVAC Program (Thermoelectric Heating Ventilation & Air Conditioning)

- Competitive Awards to Teams Led by Ford and GM 09/09
- Co-Funded with the California Energy Commission
- Develop TE Zonal or Distributed Cooling/Heating Concept Maintain Occupant Comfort without Cooling Entire Cabin
- Reduce Energy used for Automotive HVAC's by >30%
- Eliminate all Toxic, Greenhouse and Flammable Gases Associated with Automotive HVAC

DOE/CEC Program Objectives: Ford & GM Vehicular TE HVAC Teams

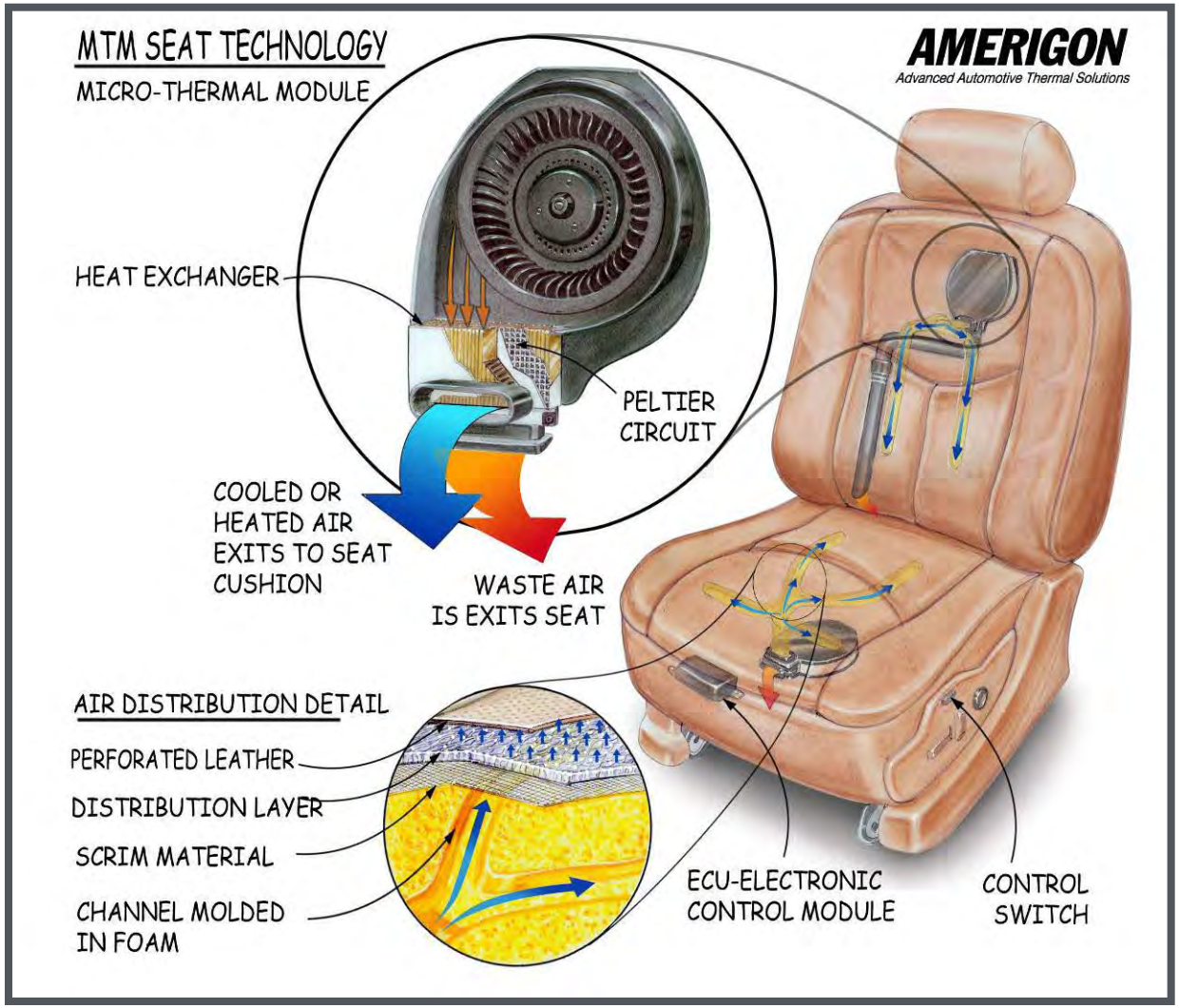
- Maintain Occupant Comfort while Reducing Fuel Consumption
- Develop TE HVAC with:
  - COP Cooling > 1.3
  - COP Heating > 2.3
- Integrate with Compressor Downsized by ~1/3
- Develop Production Prototype
- Integrate, Test and Deliver TE HVAC in a 5 Passenger Vehicle

Electrically Assisted Vehicle 2011 Car of the Year

Thermoelectric HVAC and Generators Improve the Volt's Range and Fuel Economy

- The Volt's range is significantly reduced when providing thermal comfort to occupants under hot or cold weather conditions
- Developing localized cooling and heating concept
  - to directly cool and heat occupants instead of controlling temperature of entire passenger cabin
  - to downsize the A/C compressor and replace the resistive heater with efficient thermoelectrics
- Investigating thermoelectric generator application where unique On/Off operation of the Volt's engine should accommodate a simplified system design

Climate Control Seat™



Energy Requirements (Analytical)

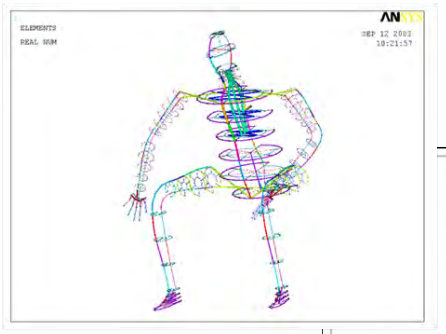
- Zonal Concept cools/heats each occupant independently
  - **680** Watts to cool single occupant
  - Current A/C's **3500 to 4500** Watts cool entire cabin

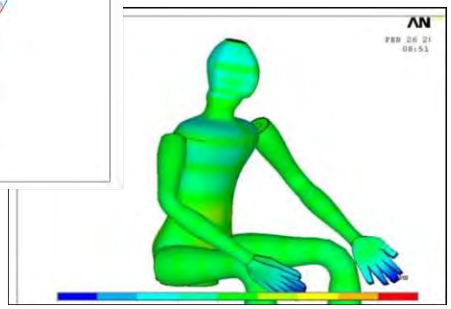
Concept of Zonal Thermoelectric Air Conditioner/Heater (HVAC)

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

NREL's Support of Ford's Team TE HVAC Zonal Occupant Comfort Development:

- Test and Evaluate Candidate Zonal TE HVAC systems
- Analysis and Design Optimization





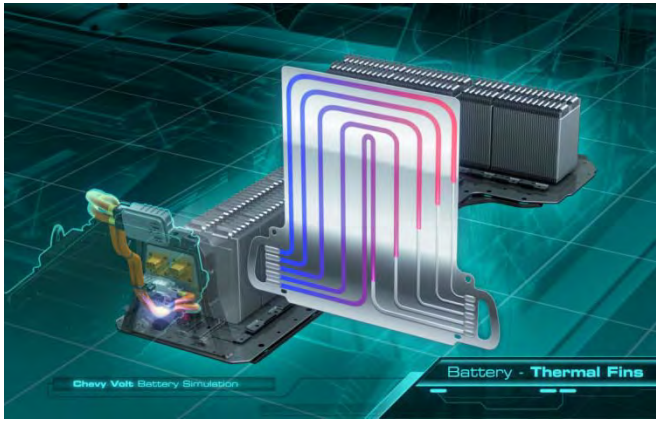
NREL's Human Physiological Model

ThermoAnalytics Physiological Model

NREL's Thermal Manikin (ADAM)

Battery Temperature Impacts PHEV, HEV and EV Performance and Service Life

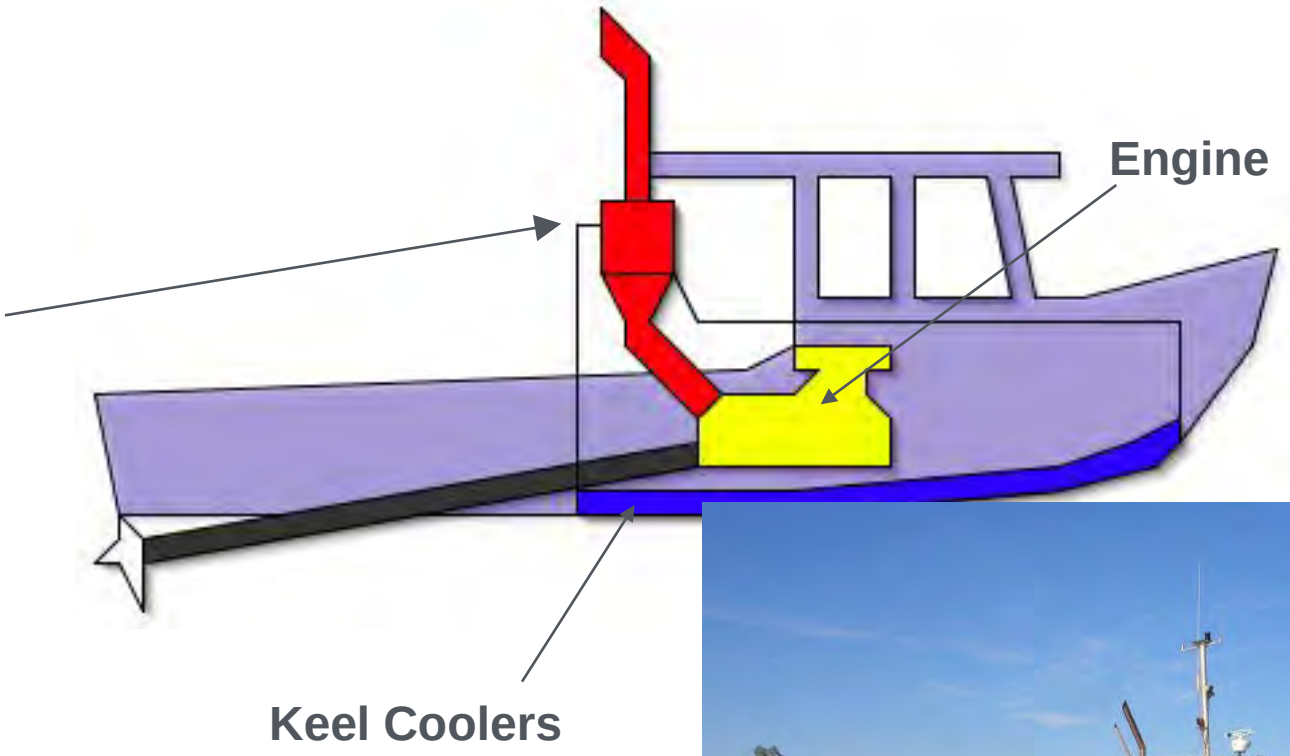
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



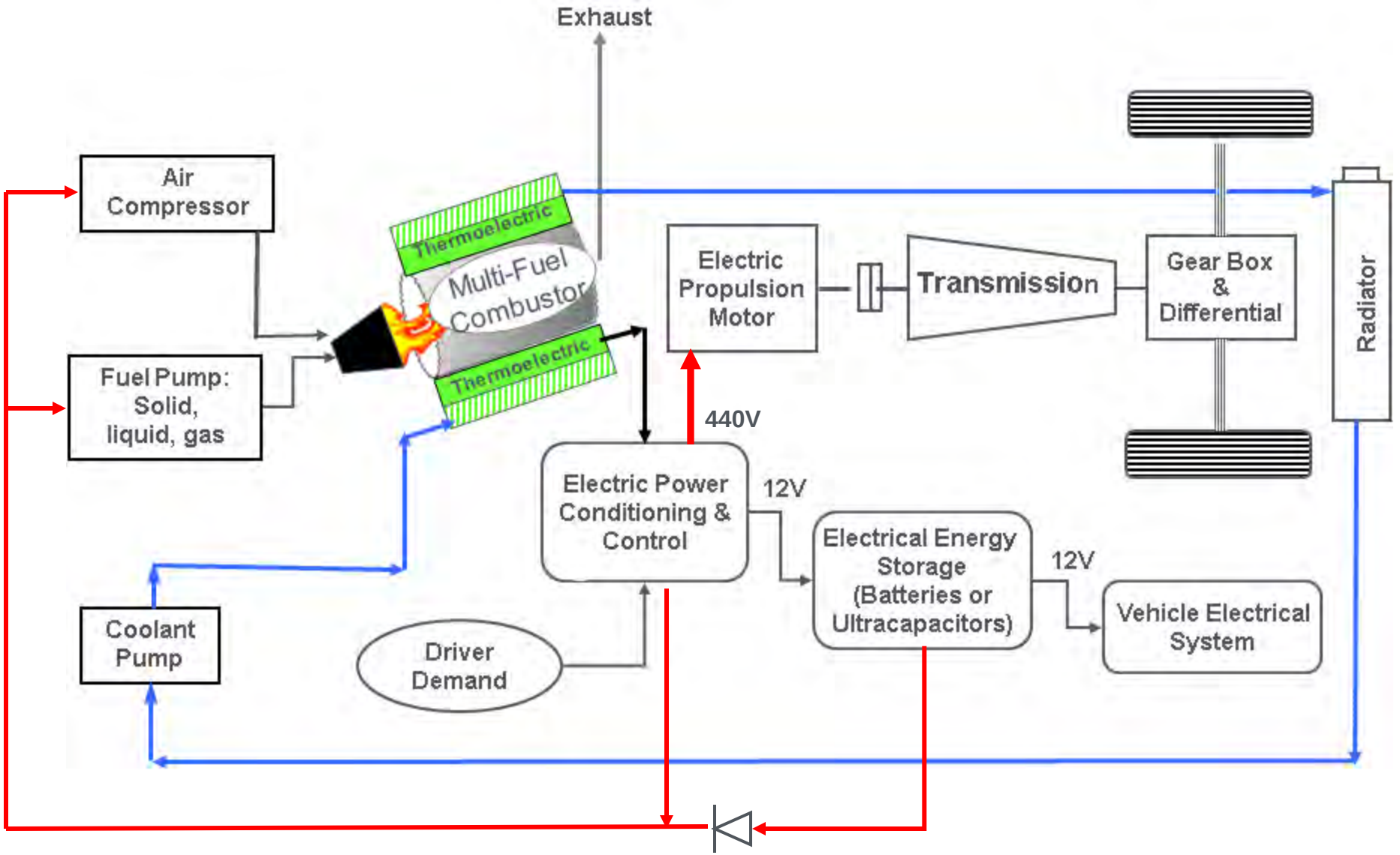
Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost

Maine Maritime Academy

Seawater Cooled Exhaust Stack TE Generator



Vehicular Thermoelectric Hybrid Electric Powertrain Replacing the ICE



Market Factors Involving Thermoelectrics for Automotive Applications

- **Dramatic Increase in Demand for Large Quantity Thermoelectric Materials**
- **Historically Semiconductor Costs Decrease with Volume Thermoelectrics Should Follow this Trend**
- **Automotive Industry Continually Wants "New and Improved" Technology**
- **Ever Increasing Gasoline/Diesel Prices**
- **Fuel Economy Requirements and Emissions Regulations**
- **Should Stimulate Waste Heat Energy Harvesting Applications**