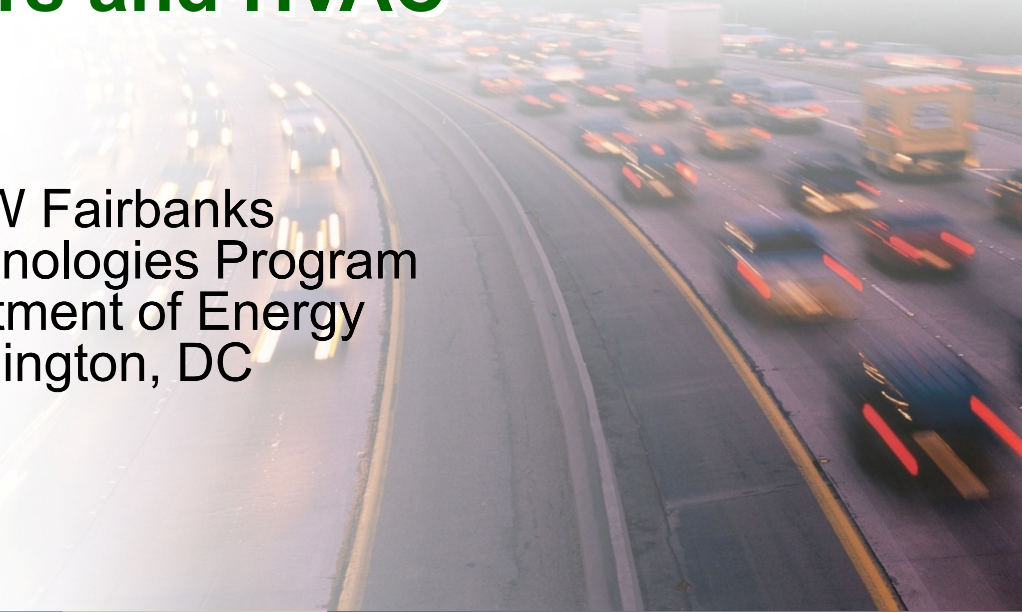
Automotive Thermoelectric Generators and HVAC

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



2012 Annual Merit Review
DOE Vehicle Technologies Program and Hydrogen and Fuel Cells Program

Washington, DC
May 14 - 18, 2012

Vehicle Technologies Program Mission

To develop more energy efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.

Steven Chu - Secretary of Energy
Nobel Laureate, Physicist

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"Our country needs to act quickly with fiscal and regulatory policies to ensure widespread deployment of effective technologies that **maximize energy efficiency and minimize carbon emission.**"

Steven Chu

Opportunities for Low Grade Heat Harvesting Using Thermoelectrics

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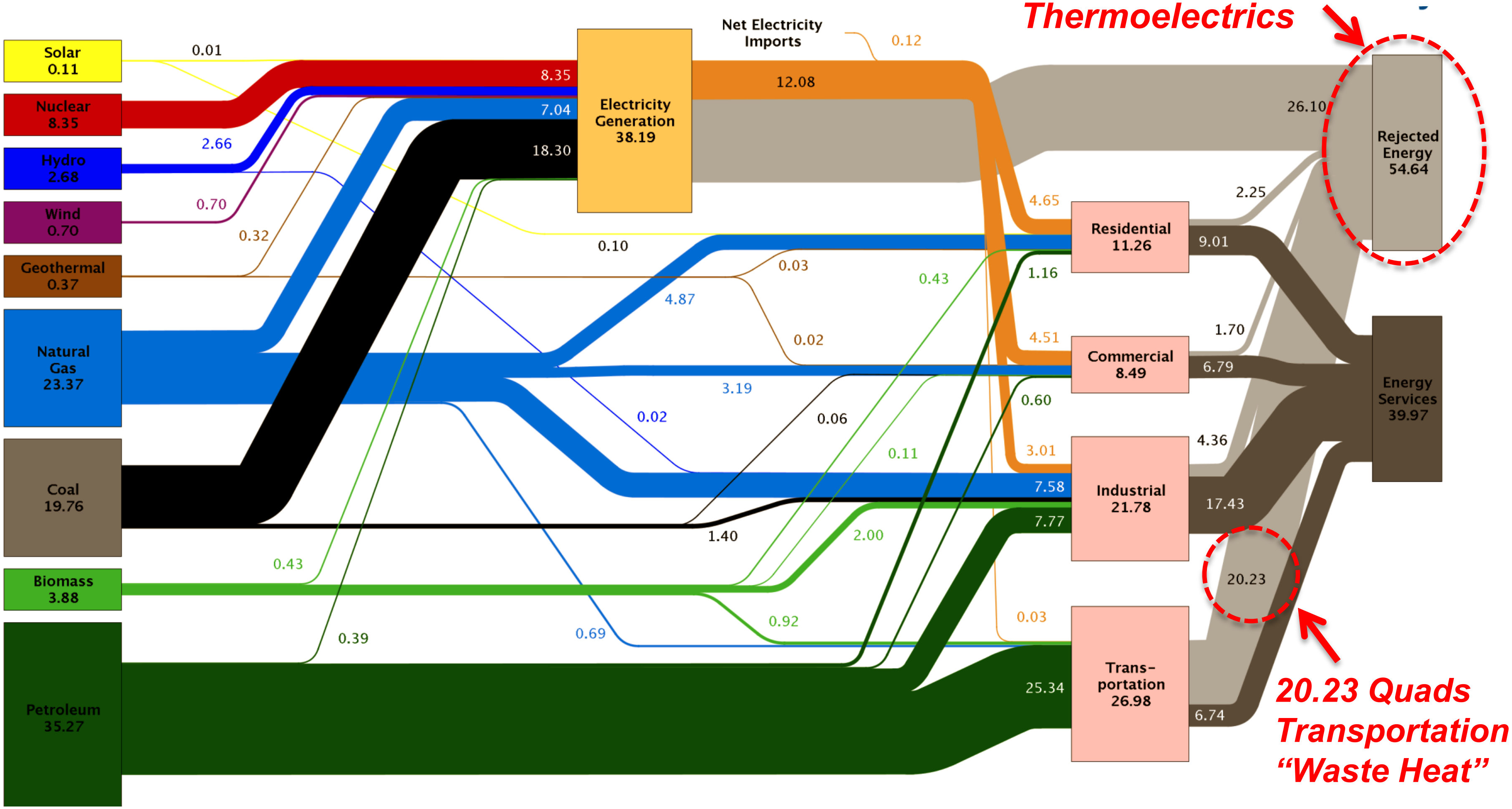
Estimated U.S. Energy Use in 2009 ~ 94.6 Quads

54.64 Quads of "Waste Heat" Can Be Recovered Using Thermoelectrics



20.23 Quads Transportation "Waste Heat"

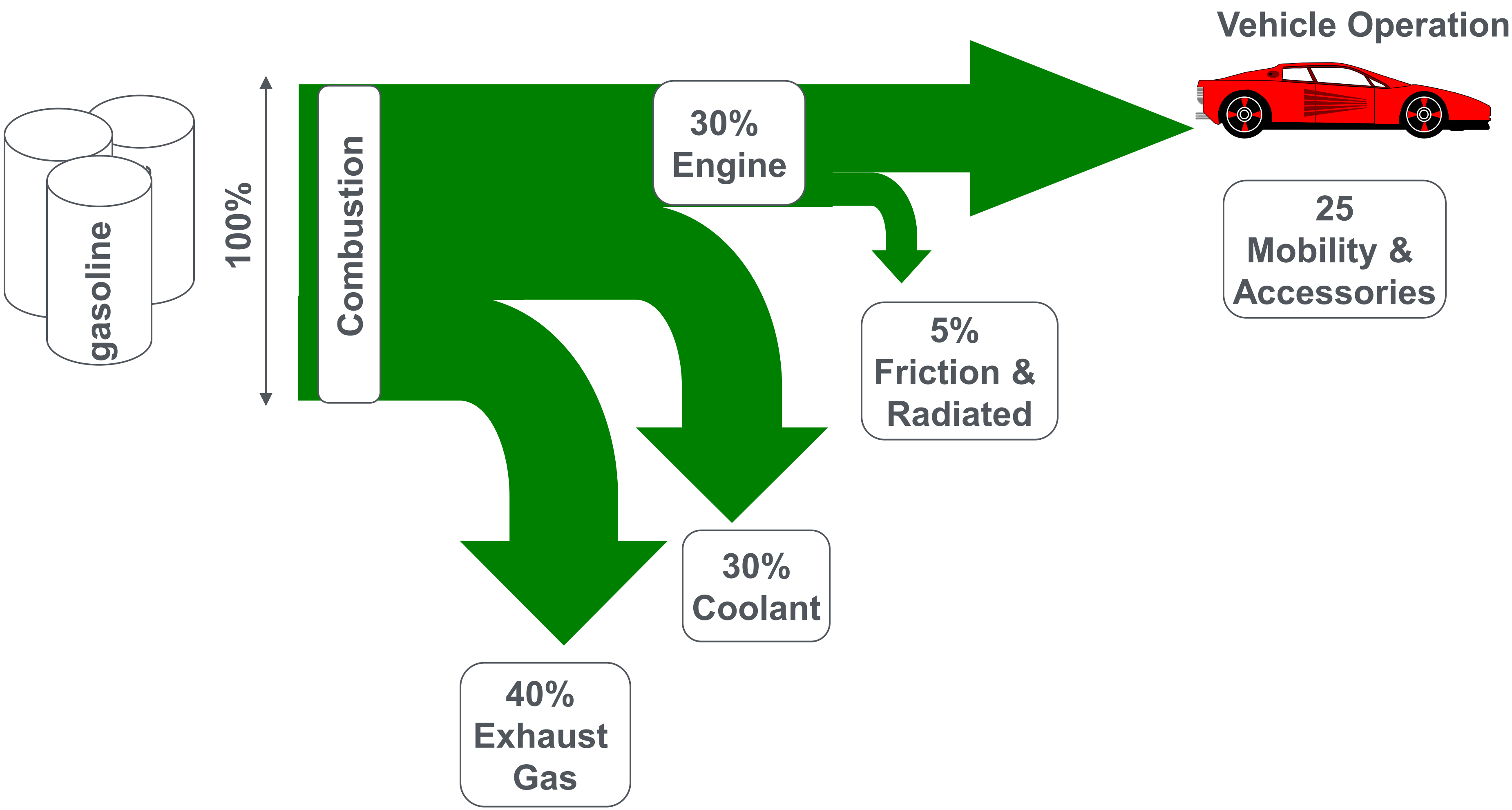
Source: LLNL 2010, data from DOE/EIA -0384 (2009), August 2010.

Lawrence Livermore National Laboratory

Energy Challenges

- The Supply and Demand for Petroleum is Accelerating Prices and Eventually Will Affect Availability
- Global Climate Change Issues
- How Do Thermoelectrics Contribute to Mitigating the Effects of These Challenges?

Typical Waste Heat from Gasoline Engine Mid-size Sedan



Vehicular Thermoelectric Applications

- Engine Waste Heat Generator (TEG)
- Air Conditioner / Heater (TE HVAC)

- Pre-start Engine Oil and Transmission Fluid warm up.
- Battery Thermal Management
- Beverage Cooler/Warmer
- Computer and Radar (Collision Avoidance) Cooling
- Regenerative Braking

Vehicular Thermoelectric Generators (TEG's)

- Generate Electricity without Introducing any Additional Carbon into the Atmosphere

Combustion of Hydrocarbon Fuels Releases Carbon

Gasoline C_7H_{16}

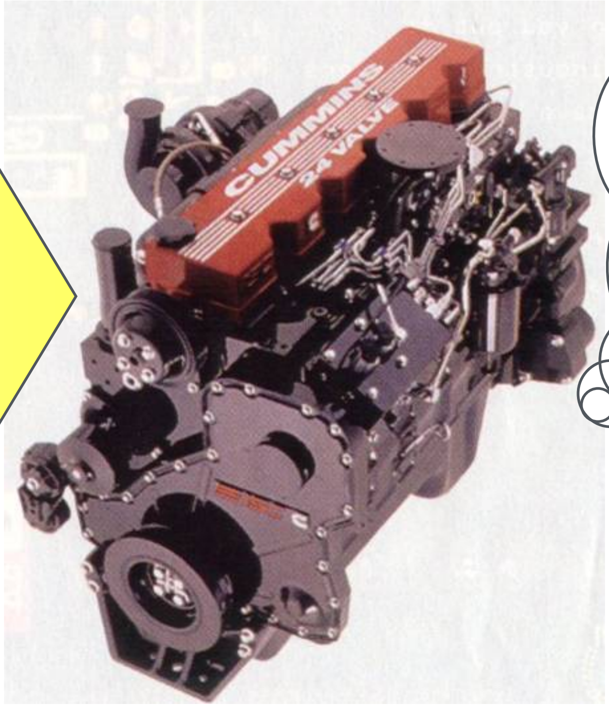
Diesel $C_{18}H_{30}$

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

European Emissions Targets

- Fleet Average Carbon Emission Regulations
  - 130 g CO_2/km in 2012
  - 95 g CO_2/km in 2020

- Fine 95€ per g CO_2/km per vehicle
  - Fines over $3,000/vehicle…… if enforced

New US Personal Vehicle Fuel Economy (CAFE) Requirements

- Corporate Average Fuel Economy (CAFE)

Vehicle Type	2010	2016
Passenger Cars (mpg)	27.5	37.8
Light trucks (mpg)	23.5	28.8

- Penalty: $5.50 per 0.10 mpg under standard multiplied by manufacturers total production for US market
- White House announced an agreement with 13 major automakers for car and light truck fuel economy average 54.5 mpg by 2025
  - Agreed upon by Ford, GM, Chrysler, BMW, Honda, Hyundai, Jaguar/Land Rover, Kia, Mazda, Mitsubishi, Nissan, Toyota, and Volvo

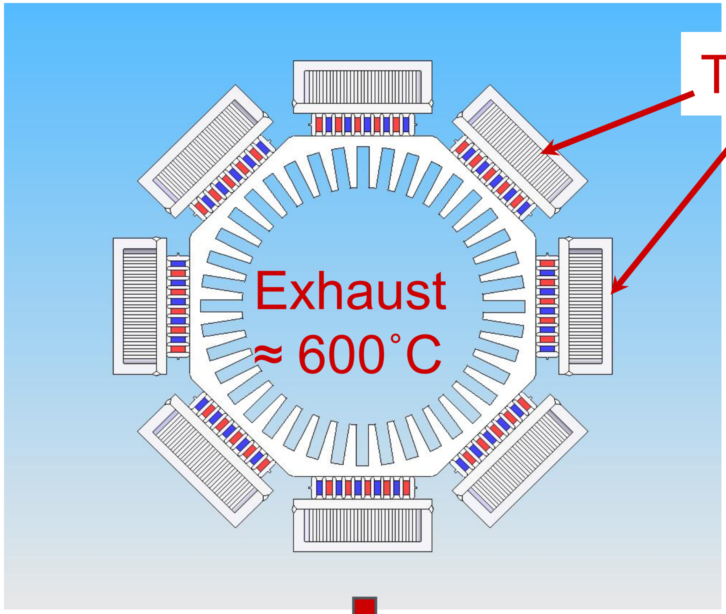
TEG Direct Conversion of Engine Waste Heat to Electricity

Heat Rejection

Waste Heat > 60%

$T_H \approx 600^\circ C$

$T_C \approx 110^\circ C$



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 > 5% Increase in Fuel Economy

With 1st Generation Thermoelectric Generators

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

Electrical conductivity

Seebeck coefficient or thermopower (ΔV/ΔT)

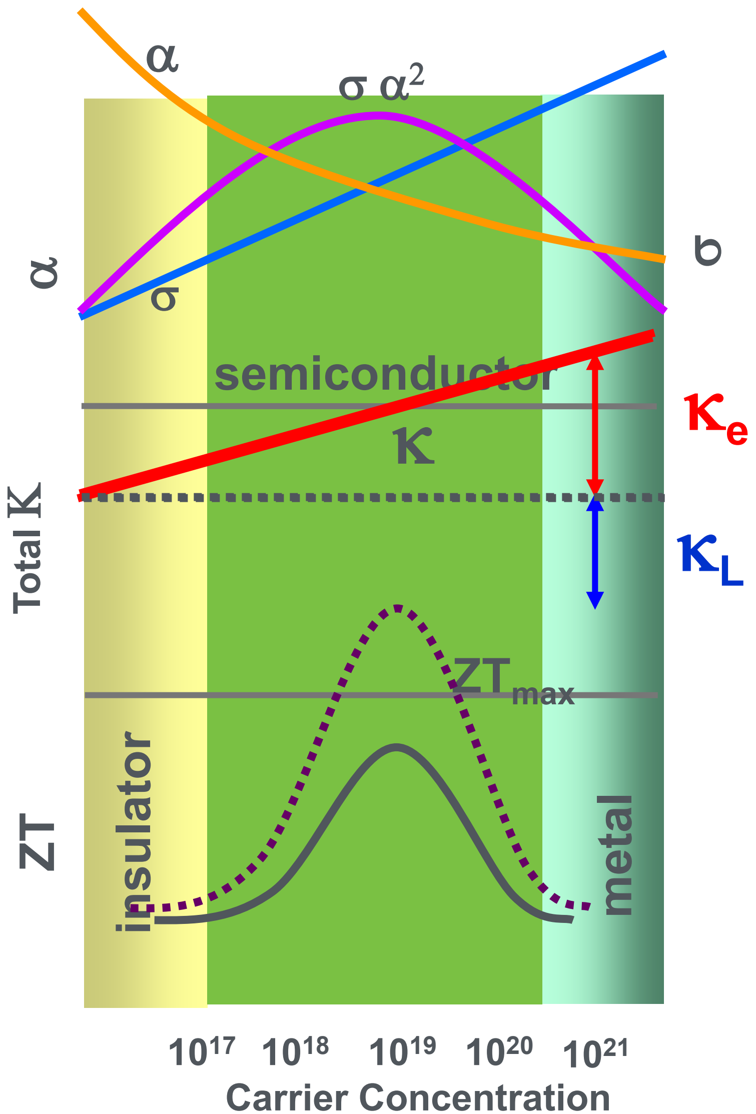
$$ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \cdot T$$

Total thermal conductivity

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

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

$\rho =$ **electrical resistivity**



Nanoscale Effects for Thermoelectrics (courtesy of Millie Dresselhaus, MIT)

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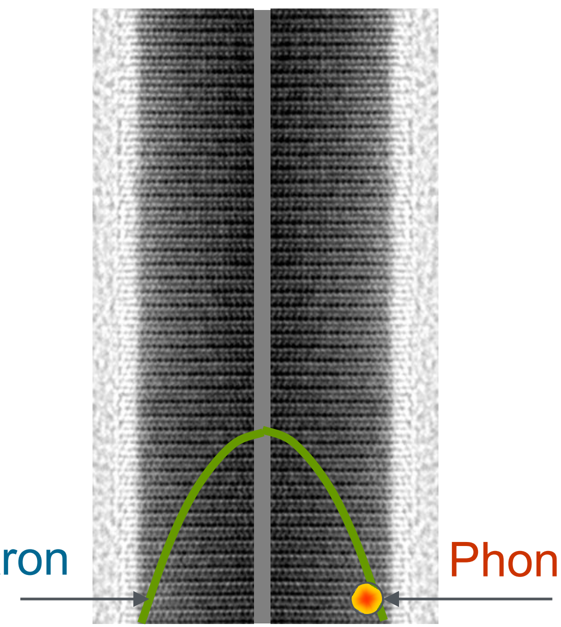
Interfaces that Scatter Phonons but not Electrons

	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)

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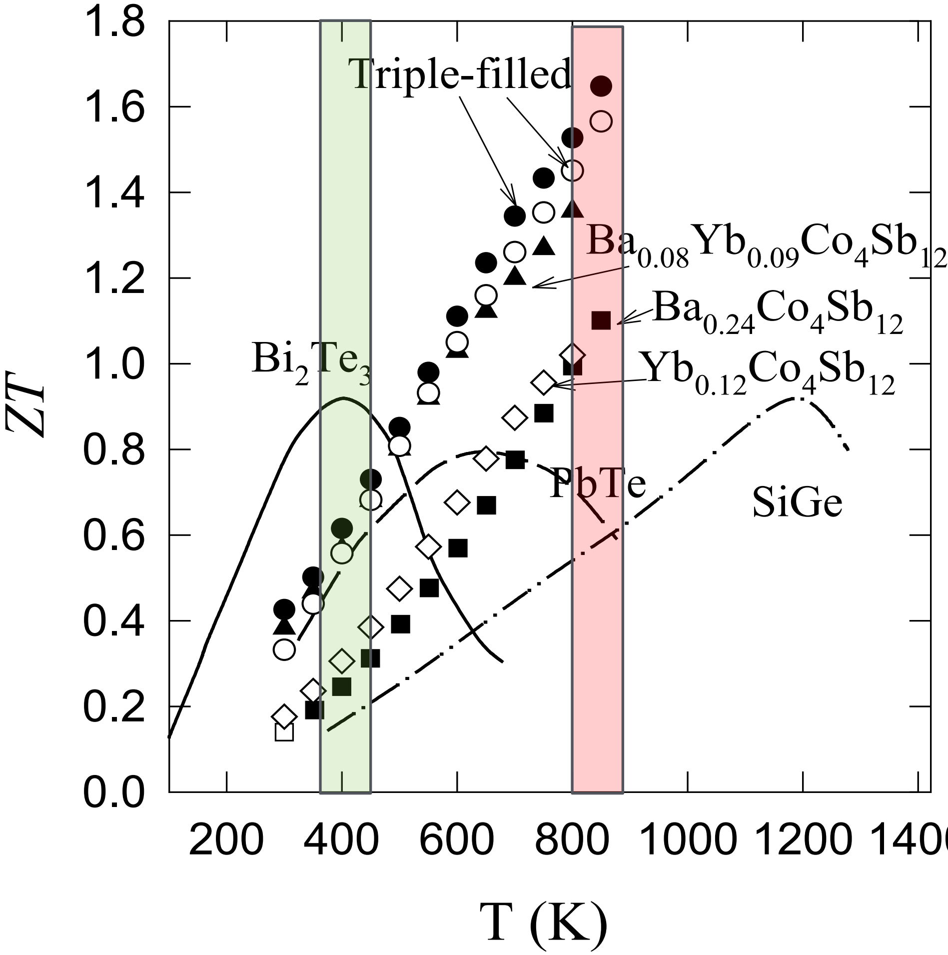
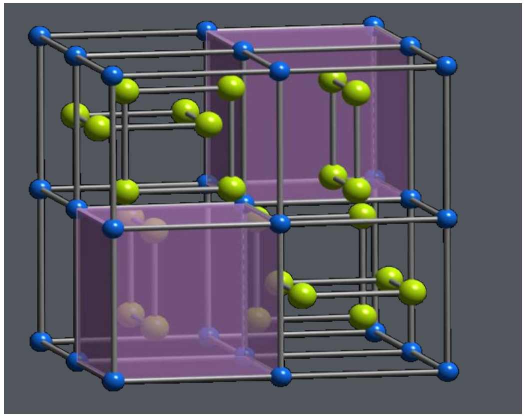
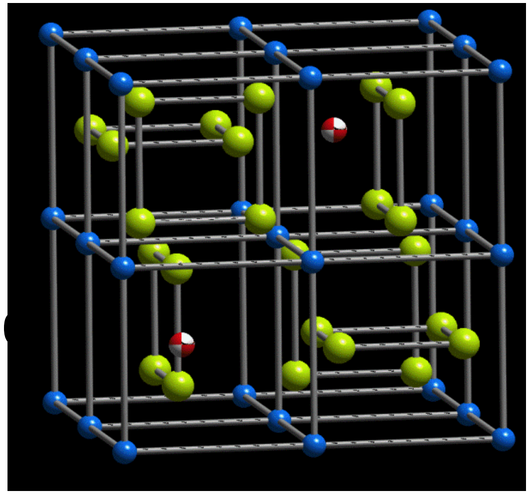
- $Ba_{0.08}La_{0.05}Yb_{0.04}Co_4Sb_{12.05}$

o $Ba_{0.10}La_{0.05}Yb_{0.07}Co_4Sb_{12.16}$





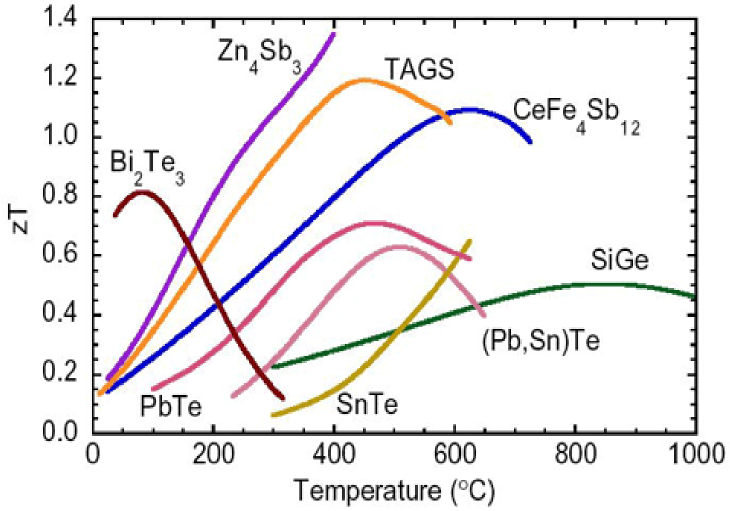


Atoms can be inserted into empty sites. Atoms can "rattle" in these sites – scatter phonons and lower the lattice thermal conductivity.

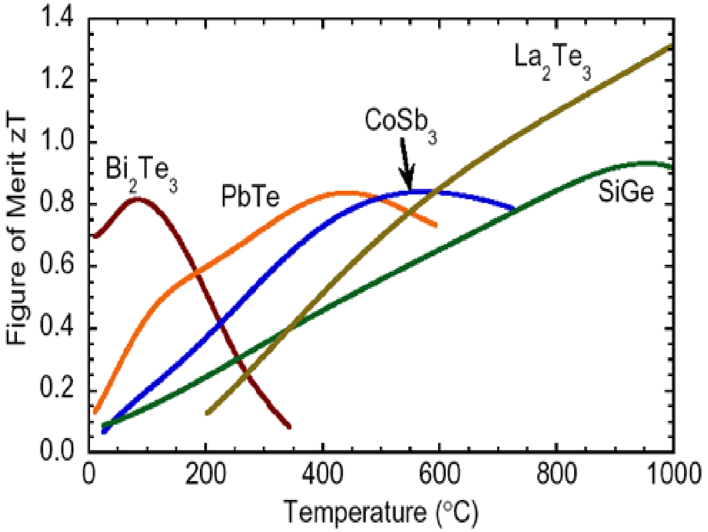
R_xCoSb_3

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

Current TE Materials



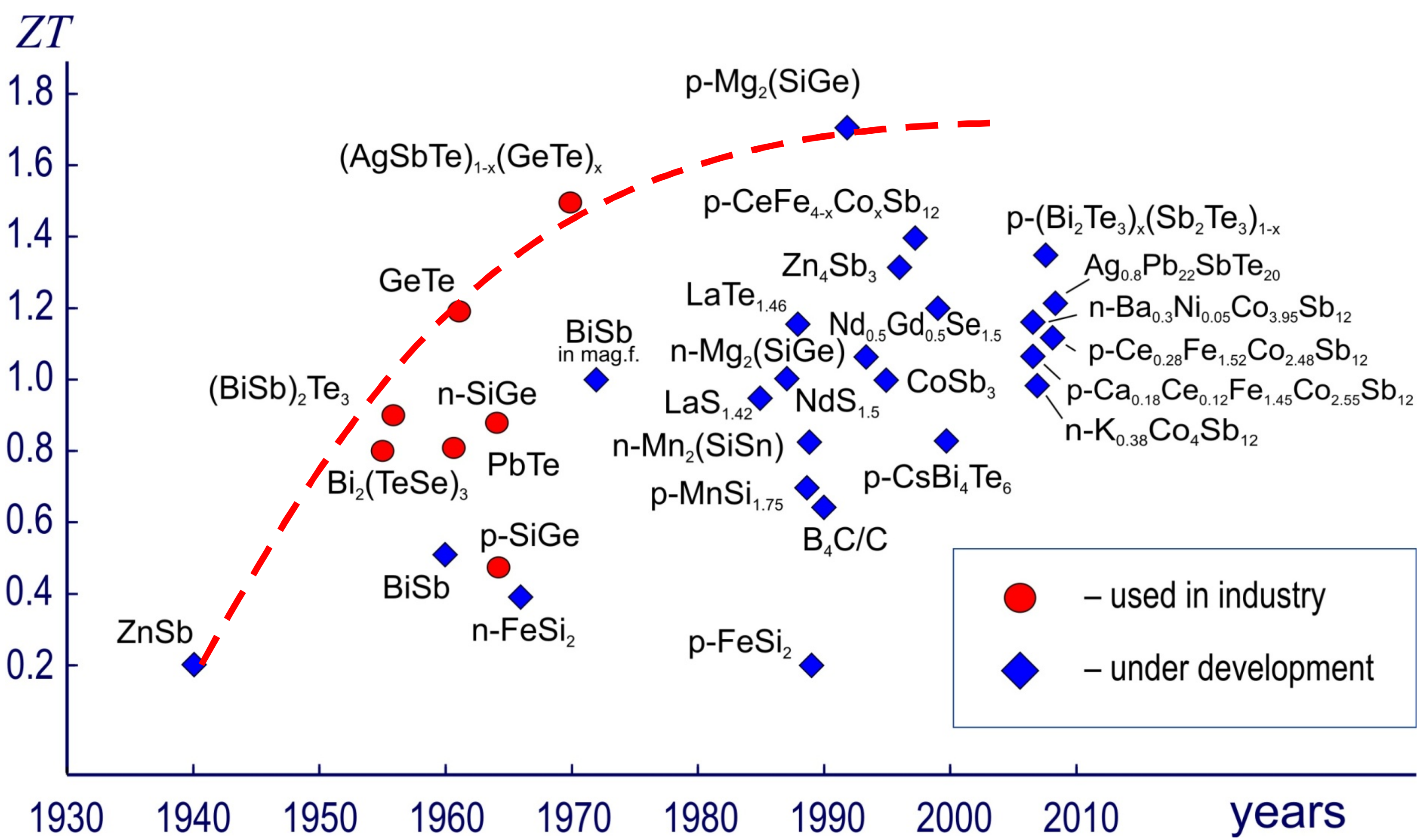
P-type TE material



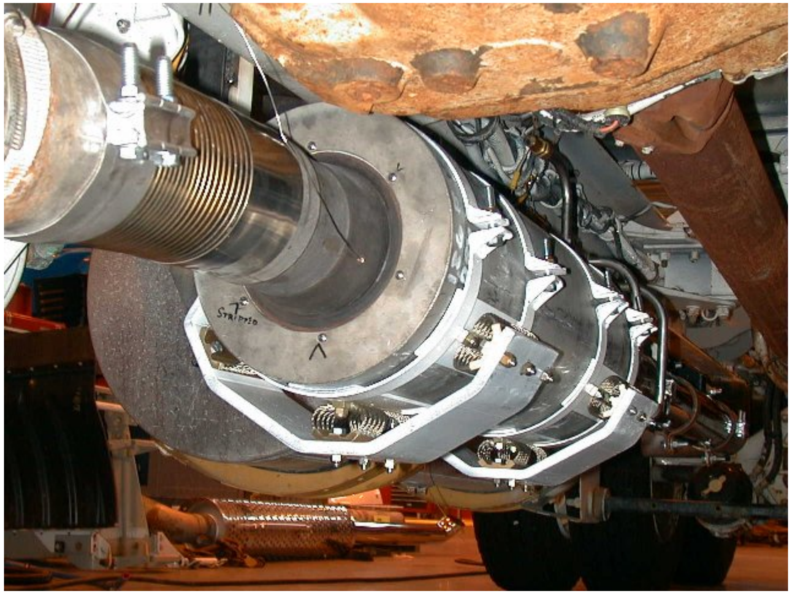
N-type TE material

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

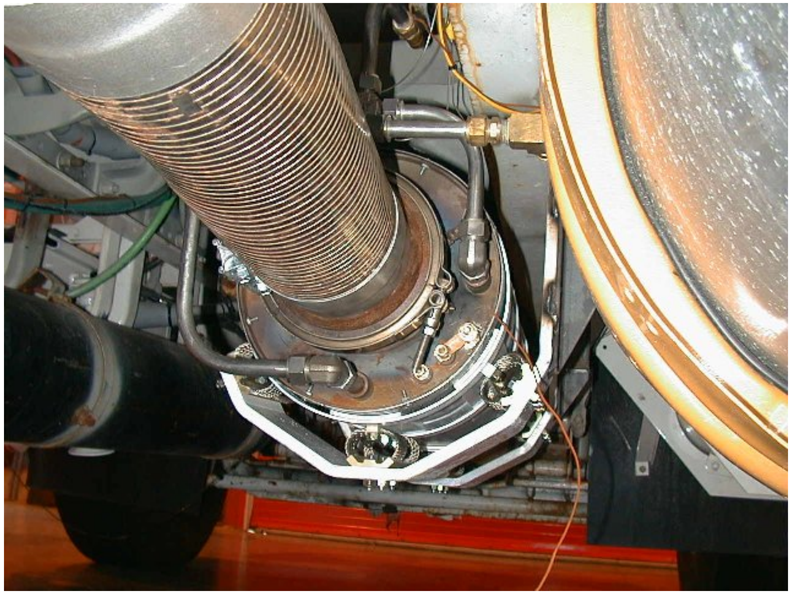
Increase in the Figure of Merit of Thermoelectric Materials



First Thermoelectric Generator Test on Vehicle (DOE/VT, Hi-Z/Paccar, 1994)



Front View



Rear View

550 HP Heavy-Duty Truck Equipped with TEG (1994)

Engine – Caterpillar 3406E, 550 HP
PACCAR's 50 to 1 test track
(Note speed bumps and hill)
Standard test protocols used for each evaluation
Heavy loaded (over 75,000 lbs)
TEG installed under the cabin

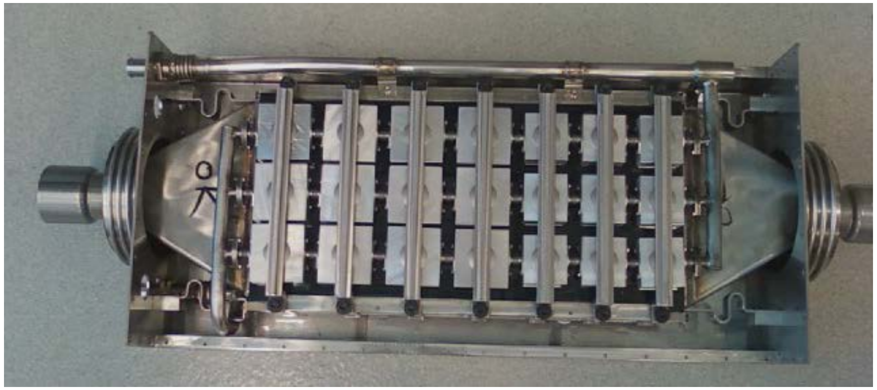
Results, together with advances in thermoelectric materials, provided impetus for further development for vehicle applications

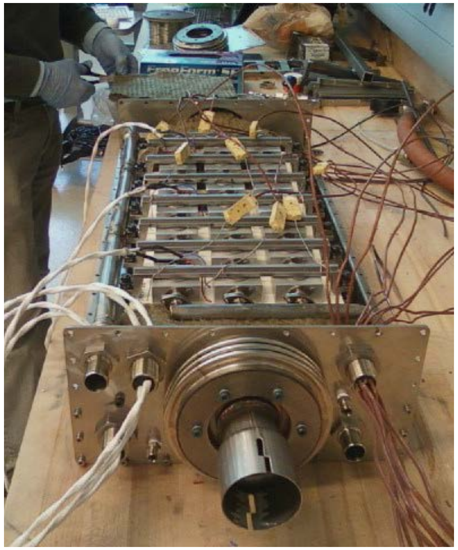
DOE's 1st Generation Vehicular Thermoelectric Generators (TEGs)

Objectives:

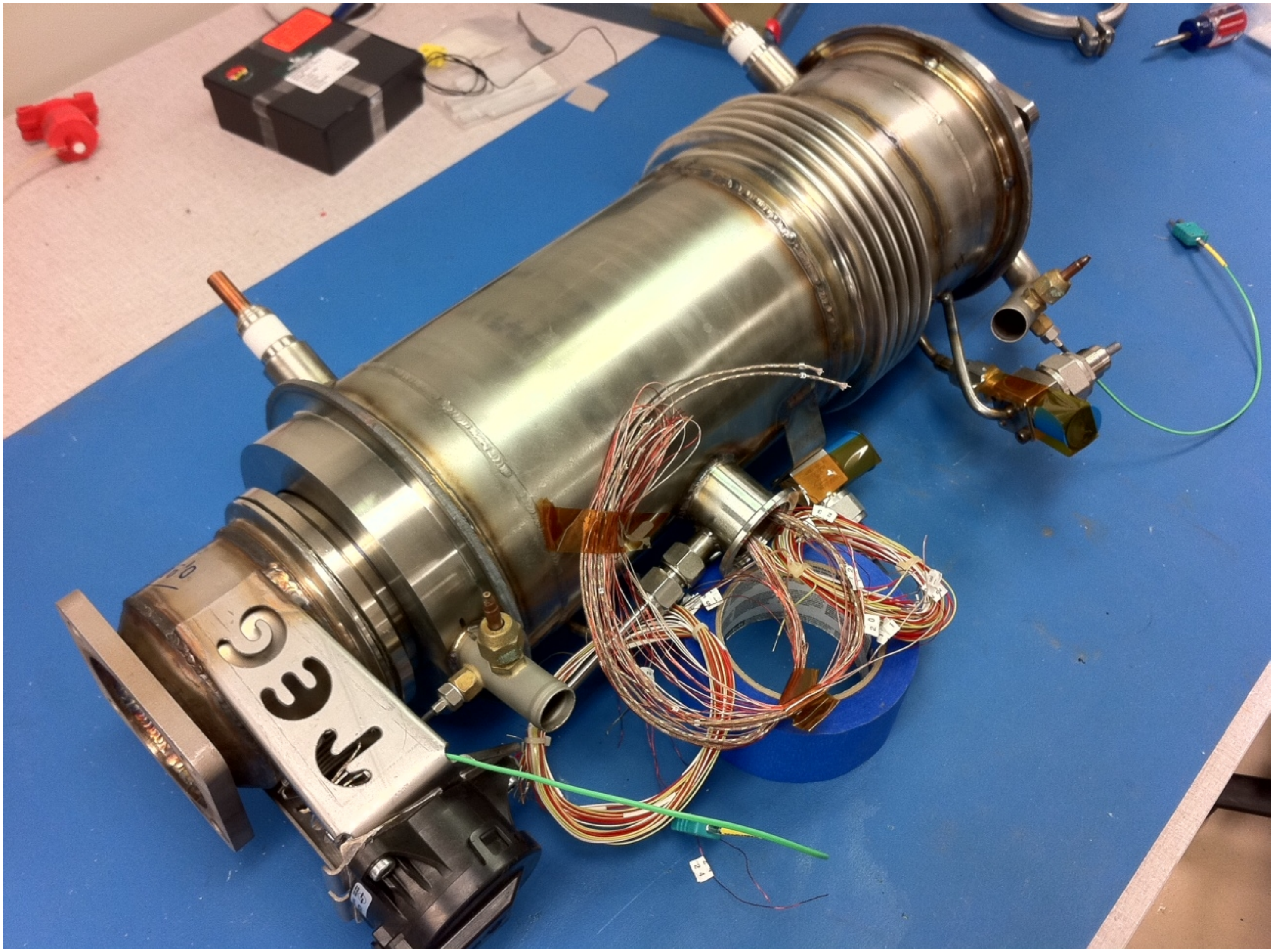
- Use Thermoelectrics to generate electricity for powering auto components
  - (lights, pumps, occupant comfort, stability control, computer systems, electronic braking, drive by wire, radiator fan, GPS, audio and video systems etc.)
- Reduce size of alternator (target: 1/3rd reduction in size)
- Improve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

GM Prototype TEG

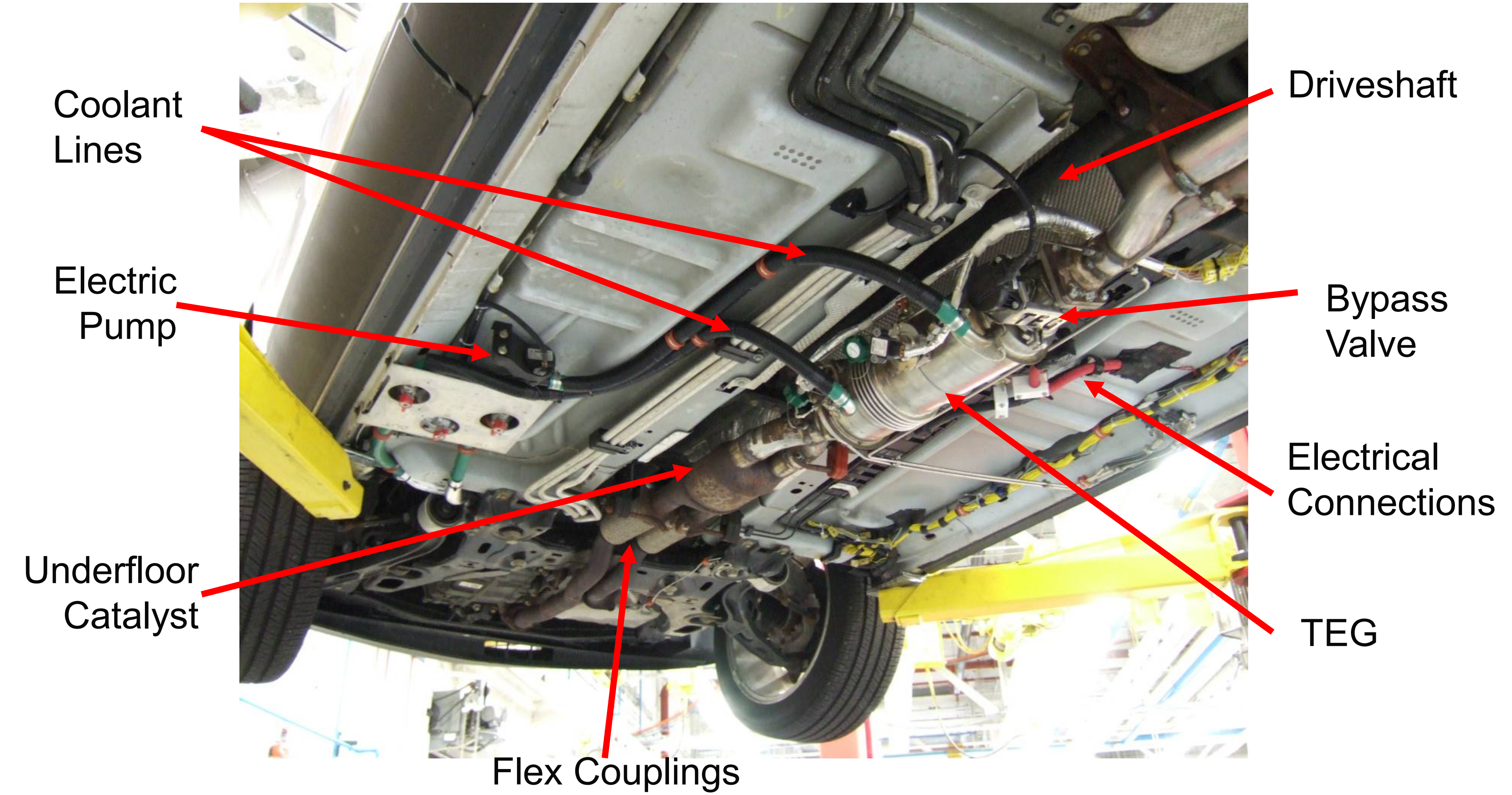




Amerigon TEG for Ford Lincoln MKT and BMW X6



TEG & Exhaust System in Lincoln MKT



Prototype TEGs Developed in DOE/Vehicle Technologies Program

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Ford Lincoln MKT

Chevy Suburban

BMW X6

- Amerigon TEG’s Developed for Ford and BMW, and GM’s Production Prototype TEG to Provide 5% Improvement in Fuel Economy
- Amerigon TEG Bench Test Peak output was 608 Watts with 620^{0}C inlet air and 20^{o}C cold side temperatures
- TEG tested in a BMW X6 in Munich
- A second TEG is being tested in a Ford Lincoln MKT in Dearborn
- GM installed their TEG in Chevy Suburban and is undergoing similar testing

Thermoelectric Power Generation – Analytical Projections for BMW Sedans

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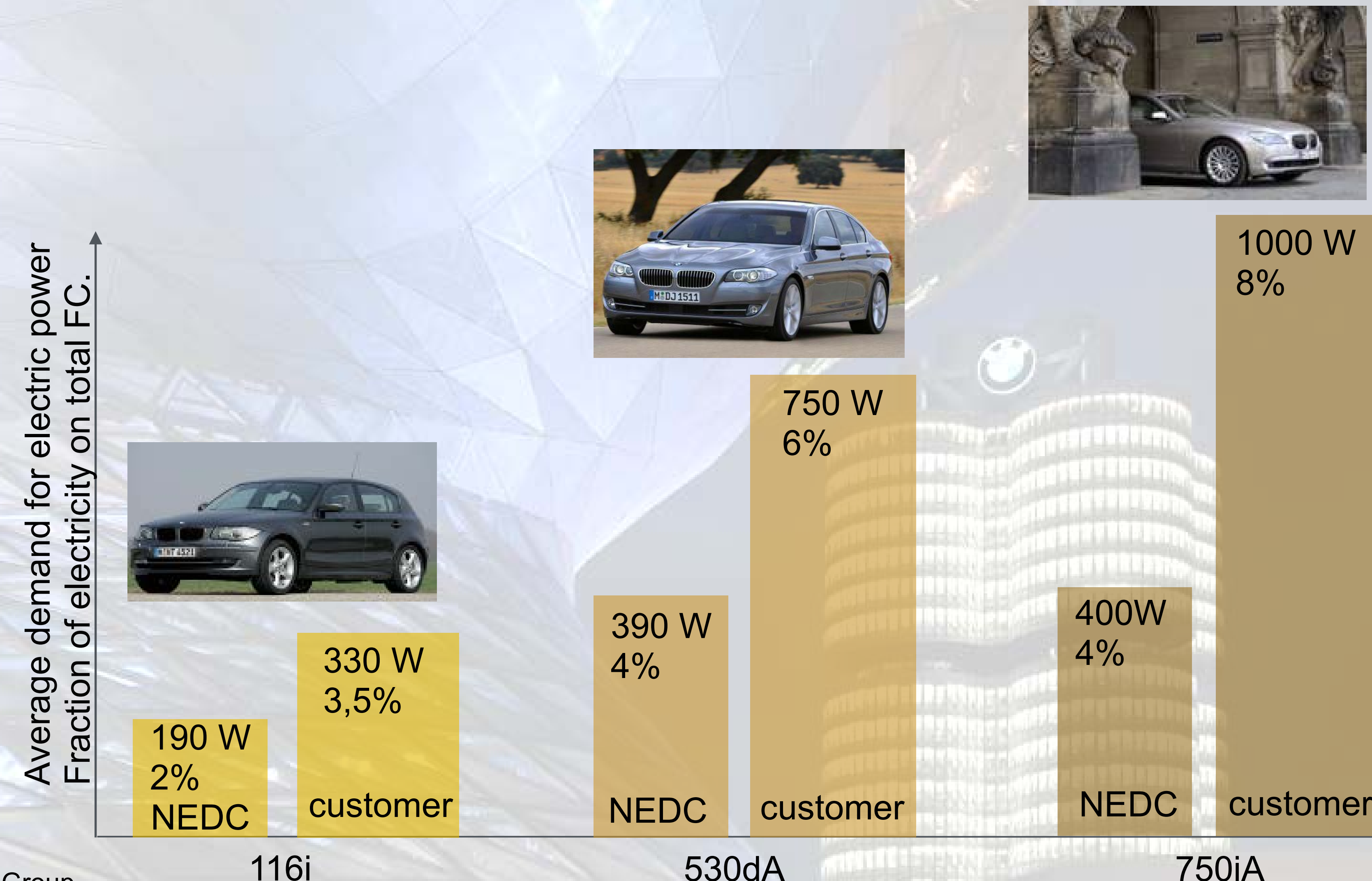

Source: BMW Group

DOE's Second Generation Automotive TEG's: Objectives

- Commercially viable thermoelectric modules
  - $ZT_{avg} = 1.6$
  - Temperature range 350º - 900ºK
- Eliminate the alternator
- Large volume commercial introduction in vehicles
- Competitively selected cost-shared project awardees
  - Amerigon
  - GM
  - GMZ Energy

Vehicular Thermoelectric HVAC Zonal Concept

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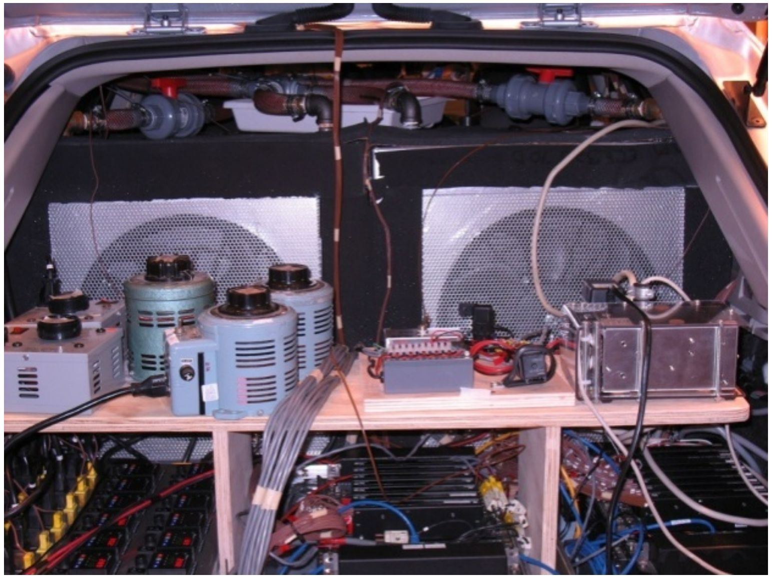
Energy Requirements (Analytical)

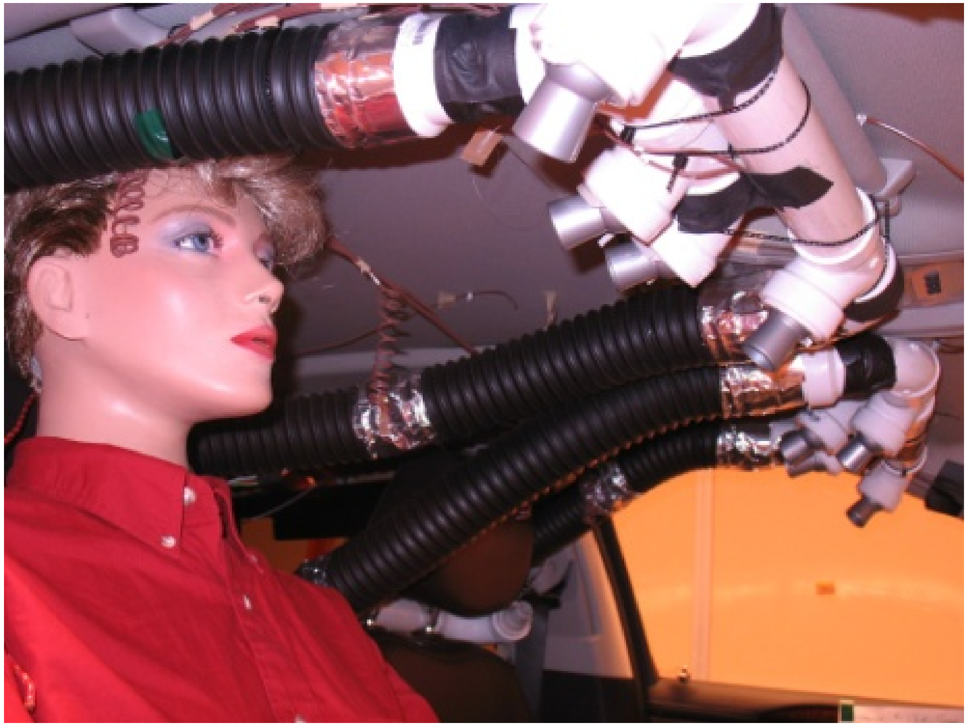
- **Zonal Concept**: cool/heat each occupant independently
- **630** Watts to cool a single occupant
- Current A/Cs: **3,500 to 4,500** Watts to cool the entire cabin

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

Delphi's Climatic Wind Tunnel Testing to Emulate Local Spot Cooling



UC-B thermal mannequin and human subjects used to evaluate spot cooling



NSF/DOE Partnership in Thermoelectrics R&D

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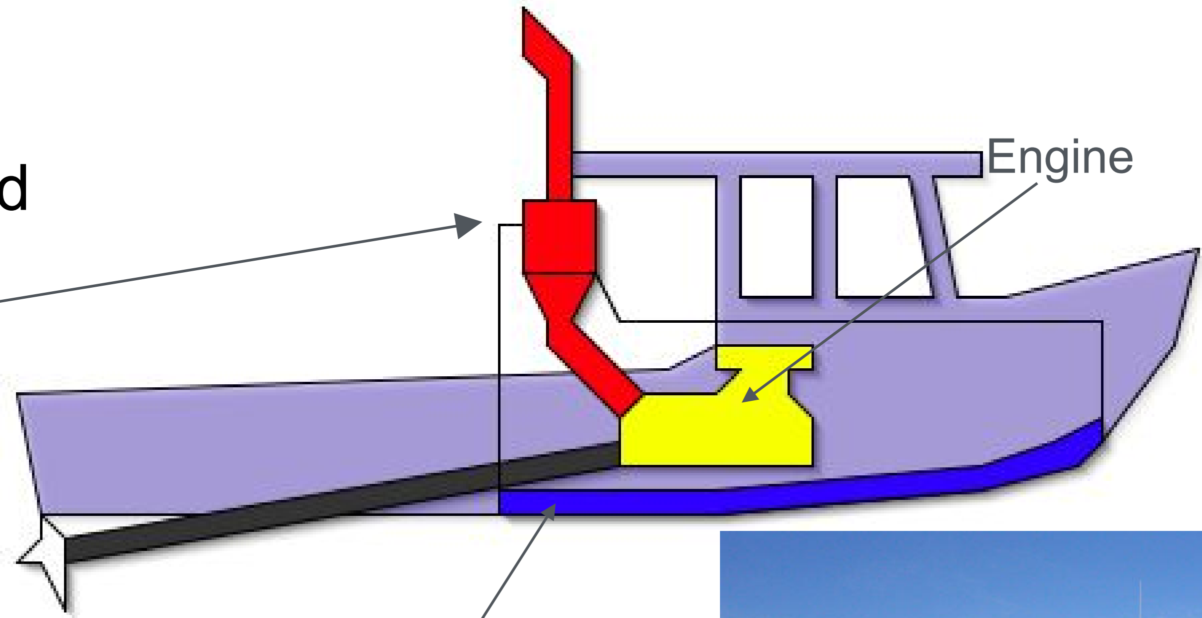
DOE/NSF funded university/industry/national lab collaboration in Thermoelectric Devices for Vehicle Applications

- An integrated approach towards efficient, scalable, and low cost thermoelectric waste heat recovery devices for vehicle – S. Huxtable (VT)
- Automotive Thermoelectric Modules with Scalable Thermo- and Electro-Mechanical Interfaces - Kenneth E Goodson (Stanford)
- High-Performance Thermoelectric Devices Based on Abundant Silicide Materials for Waste Heat Recovery - Li Shi (UT-Austin)
- Inorganic-Organic Hybrid Thermoelectrics - Sreeram Vaddiraju (TAMU)
- Integration of Advanced Materials, Interfaces, and Heat Transfer Augmentation Methods for Affordable and Durable Devices – Y. Ju (UCLA)
- High Performance Thermoelectric Waste Heat Recovery System Based on Zintl Phase Materials with Embedded Nanoparticles - Ali Shakouri (UCSC)
- Project SEEBECK-Saving Energy Effectively by Engaging in Collaborative research and sharing Knowledge - Joseph Heremans (Ohio State)
- Thermoelectrics for Automotive Waste Heat Recovery – X. Xu (Purdue)
- Integrated Design and Manufacturing of Cost Effective and Industrial-Scalable TEG for Vehicle Applications - Lei Zuo, SUNY-Stony Brook

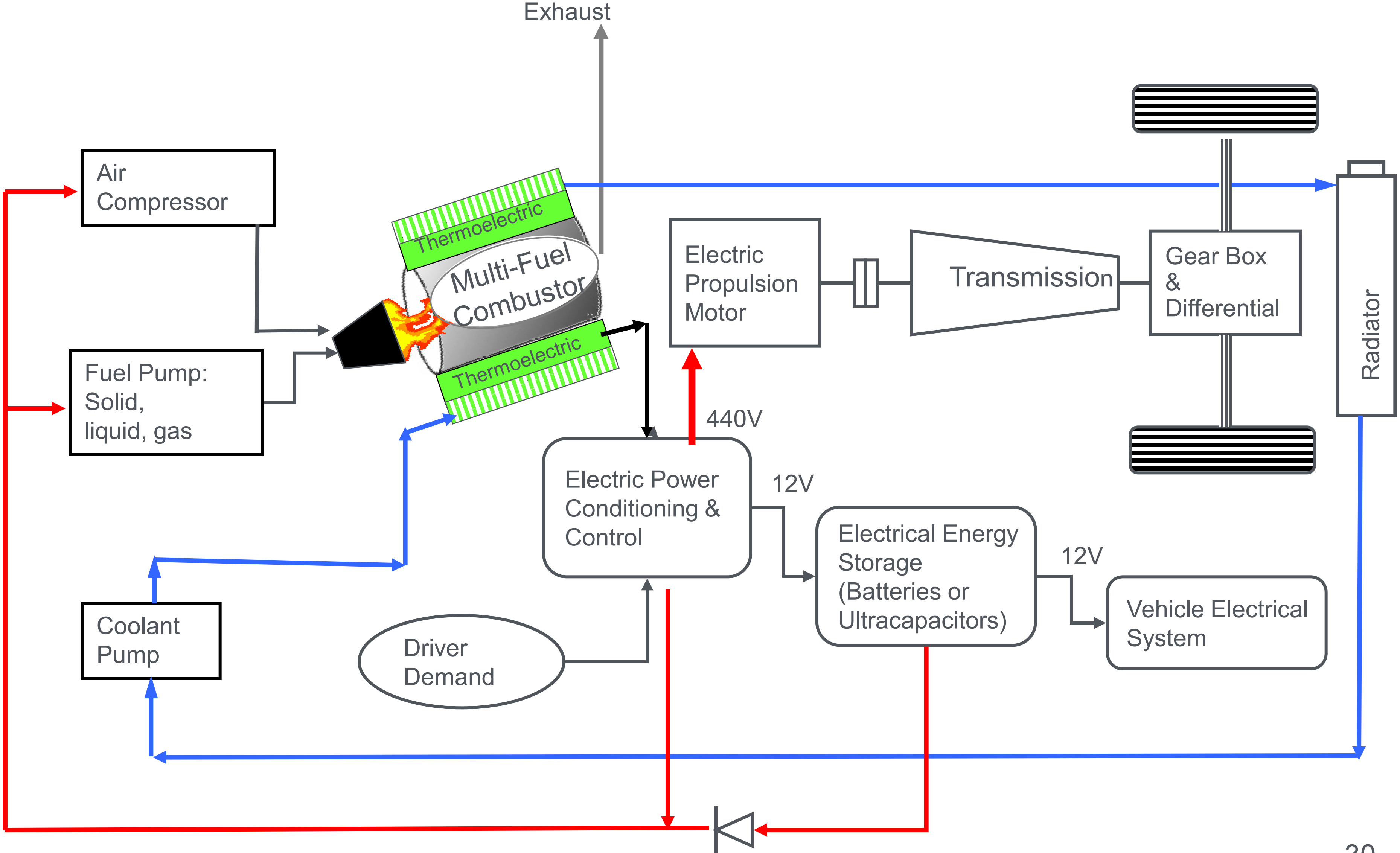
Maine Maritime Academy

Seawater Cooled
Exhaust Stack
TE Generator



Keel Coolers

Vehicular Thermoelectric Hybrid Electric Powertrain Replacing the ICE



Market Factors Impacting Automotive Thermoelectric Applications

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- 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

Questions?


THERMOELECTRICS:
THE NEW GREEN
AUTOMOTIVE TECHNOLOGY
......AND MORE........

Typical Transportation Entering the 20th Century

- **Stage coach**
  - 6 Passengers
  - 4 Horsepower (quadrupeds)
  - Drive by Line
  - Fare $.06/Mile
- **Bio-Mass Derived Fuel**
  - Minimally processed
  - Fuel infrastructure in place
  - "Stable" Fuel Costs
- **Emissions**
  - Equine methane
  - Agglomeration of macro particles
    - Minimally airborne
    - Recyclable

Entering the 22nd Century?

All-electric vehicle

- Advanced batteries
- Fast Inductive-charging
- Lightweight materials
- No emissions

Thermoelectrics

- TE AC/heater
- TE thermal management of batteries
- TE-cooled collision avoidance system and computers
- TE-cooled/heated beverage holders
- TE-regenerative braking