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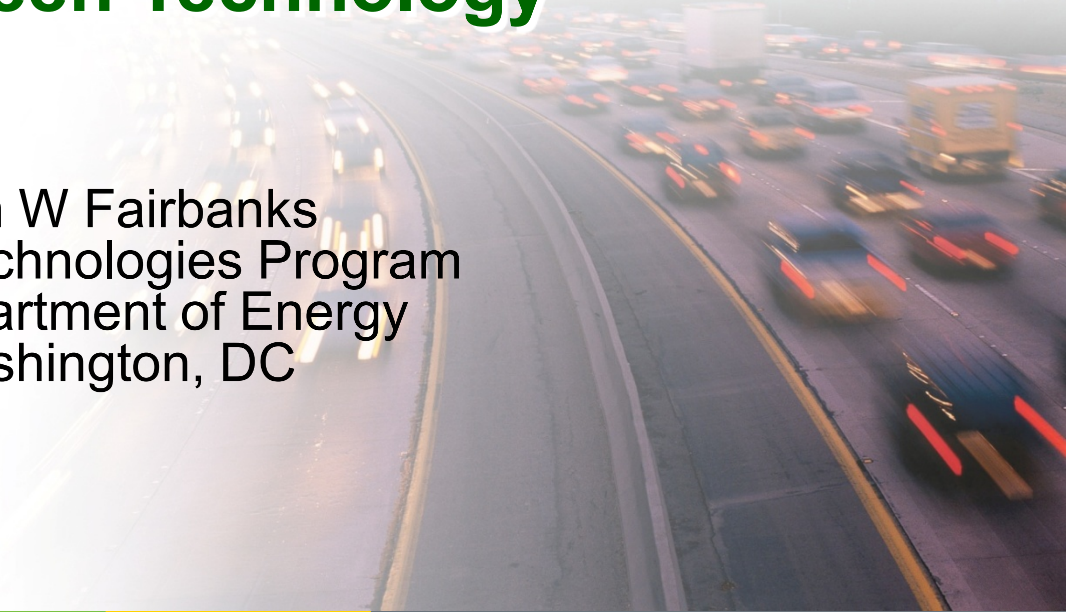
Vehicular Thermoelectrics: A New Green Technology

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



Presented at
DEER 2011
October 5, 2011
Detroit, Michigan

Steven Chu - Secretary of Energy
Nobel Laureate, Physicist

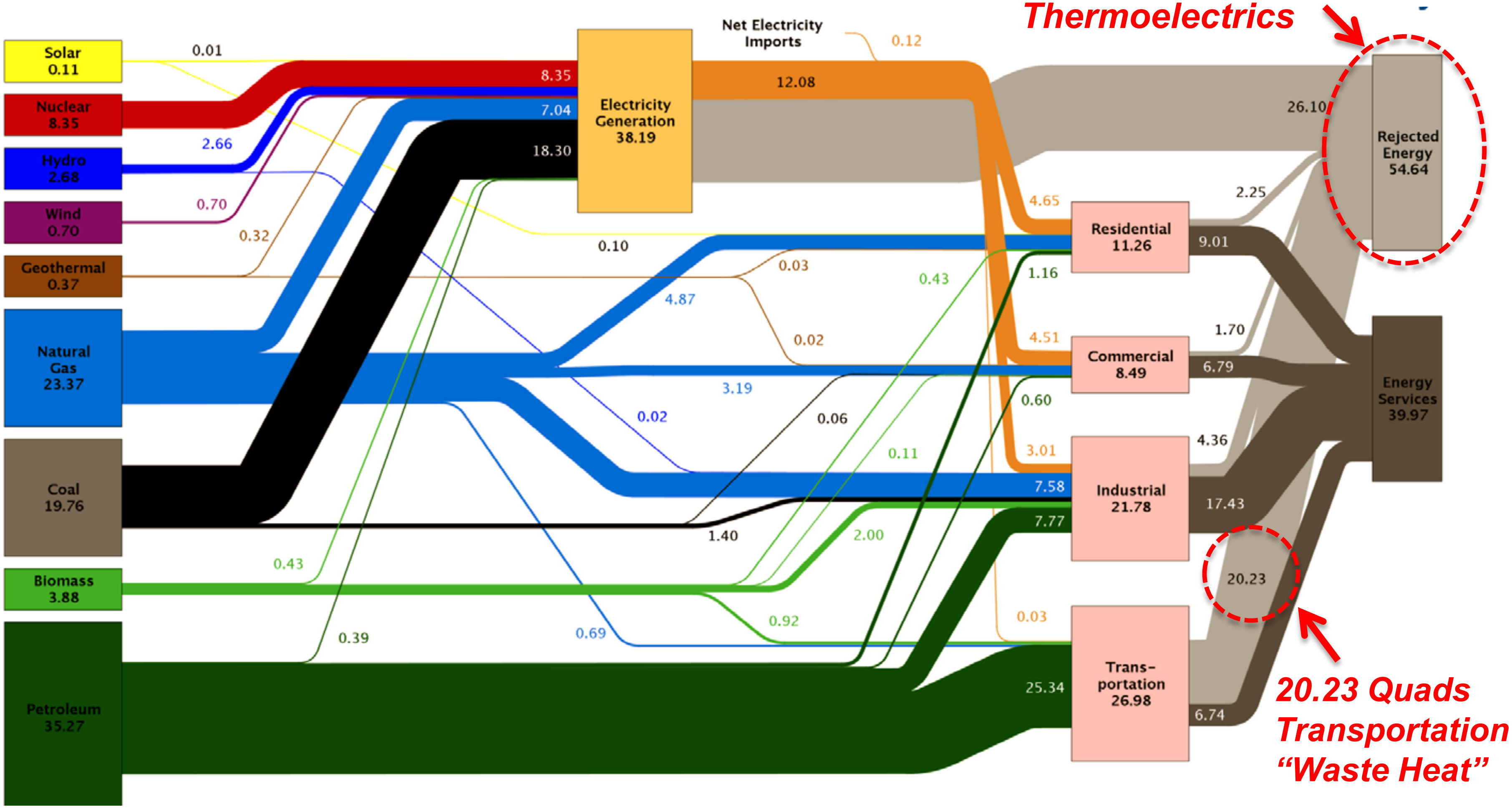
"Our country needs to act quickly with fiscal and regulatory policies to ensure widespread deployment of effective technologies that **maximize energy efficiency and minimize carbon emission.**"

Steven Chu

Opportunities for Low Grade Heat Harvesting Using Thermoelectrics

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 Influencing Thermoelectrics

- 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?

Vehicular Thermoelectric Applications

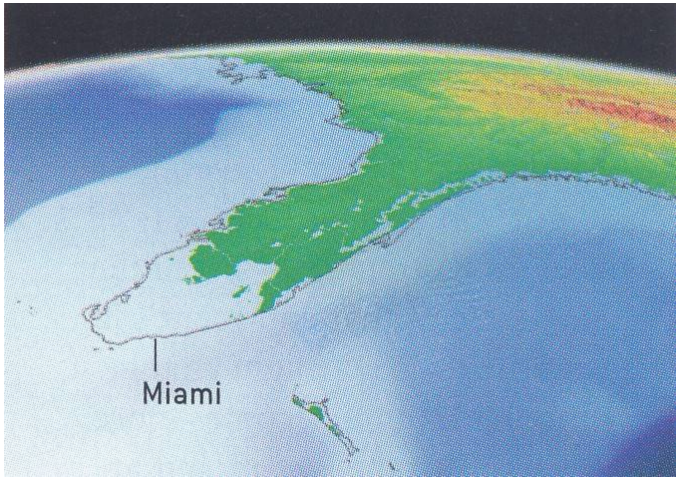
- Engine Waste Heat Generator (TEG)
- Air Conditioner / Heater (TE HVAC)

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

Heating Up… Melting Down…

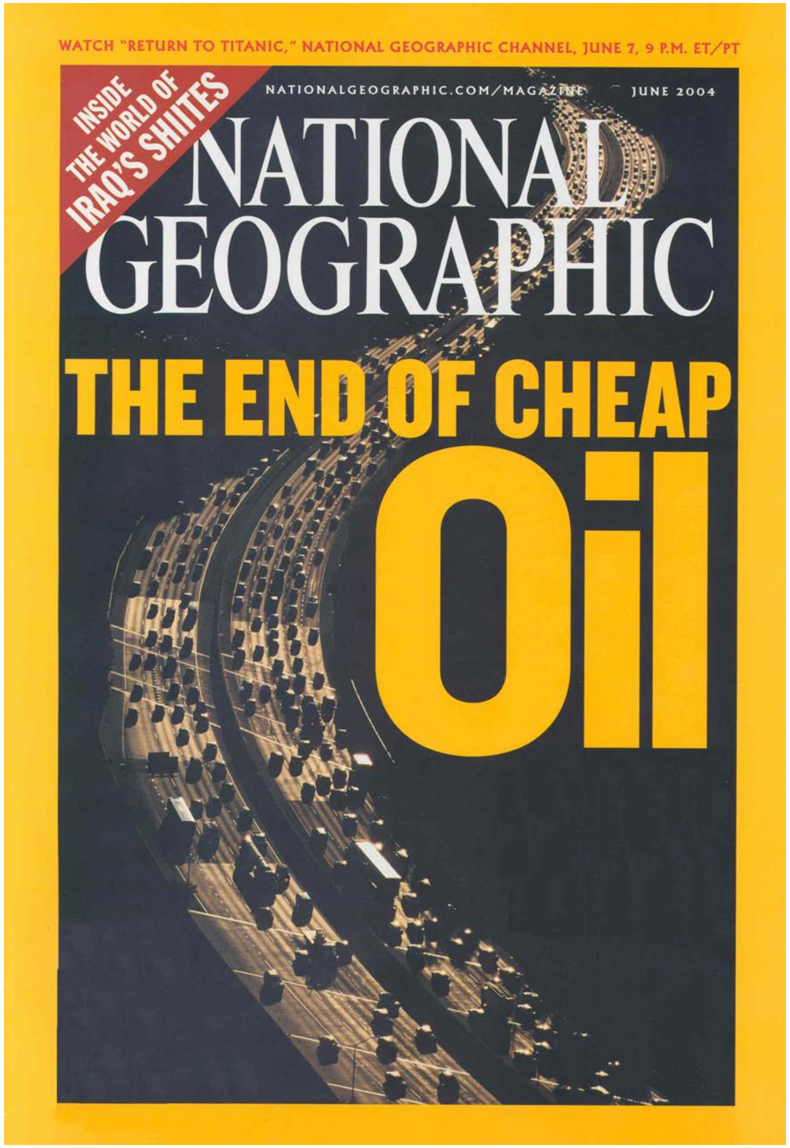
Global Climate Change Enigma

- Global Climate Change is Happening
  - Is there a man-made contribution?

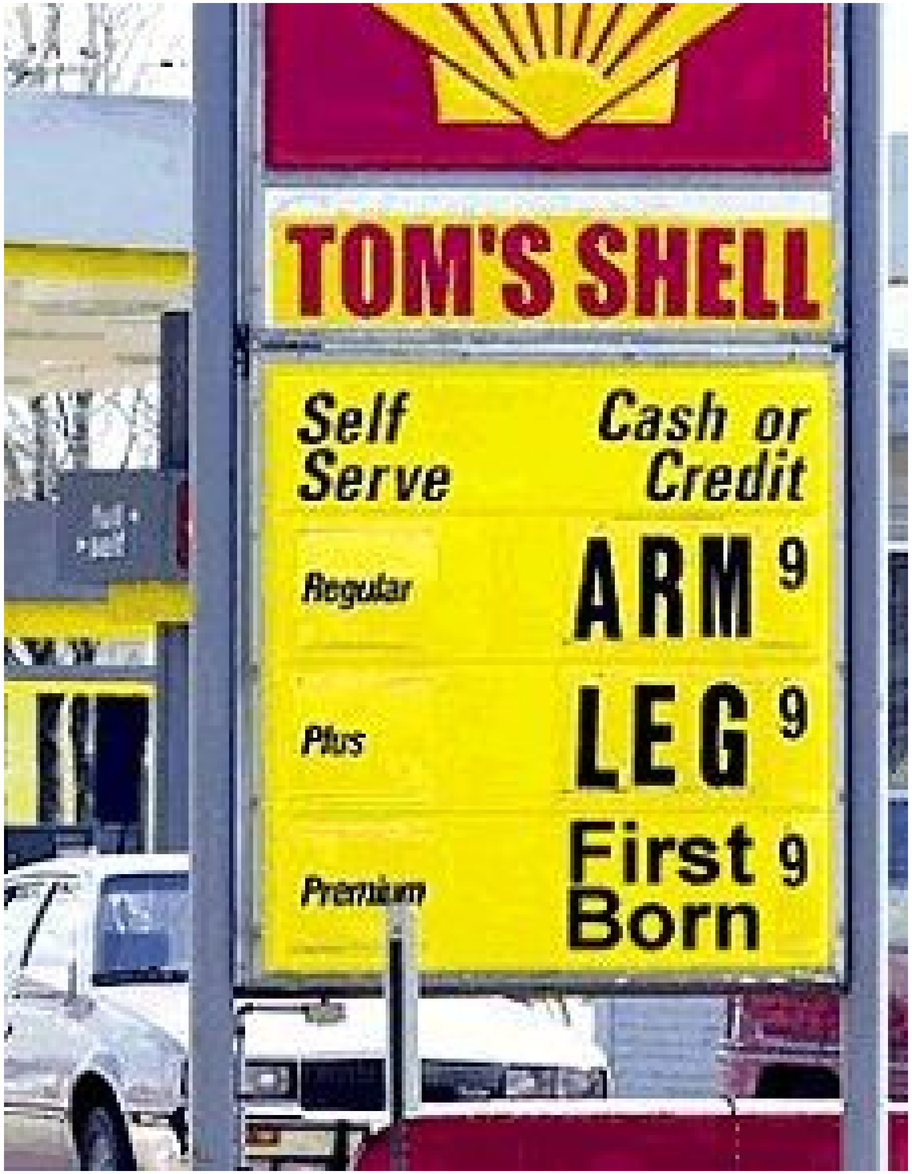


- NASA's Carbon Observatory Satellite Program should provide relevant data

- **Prudent approach: limit "Greenhouse Gas Emissions" with economic considerations until issue is settled**


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

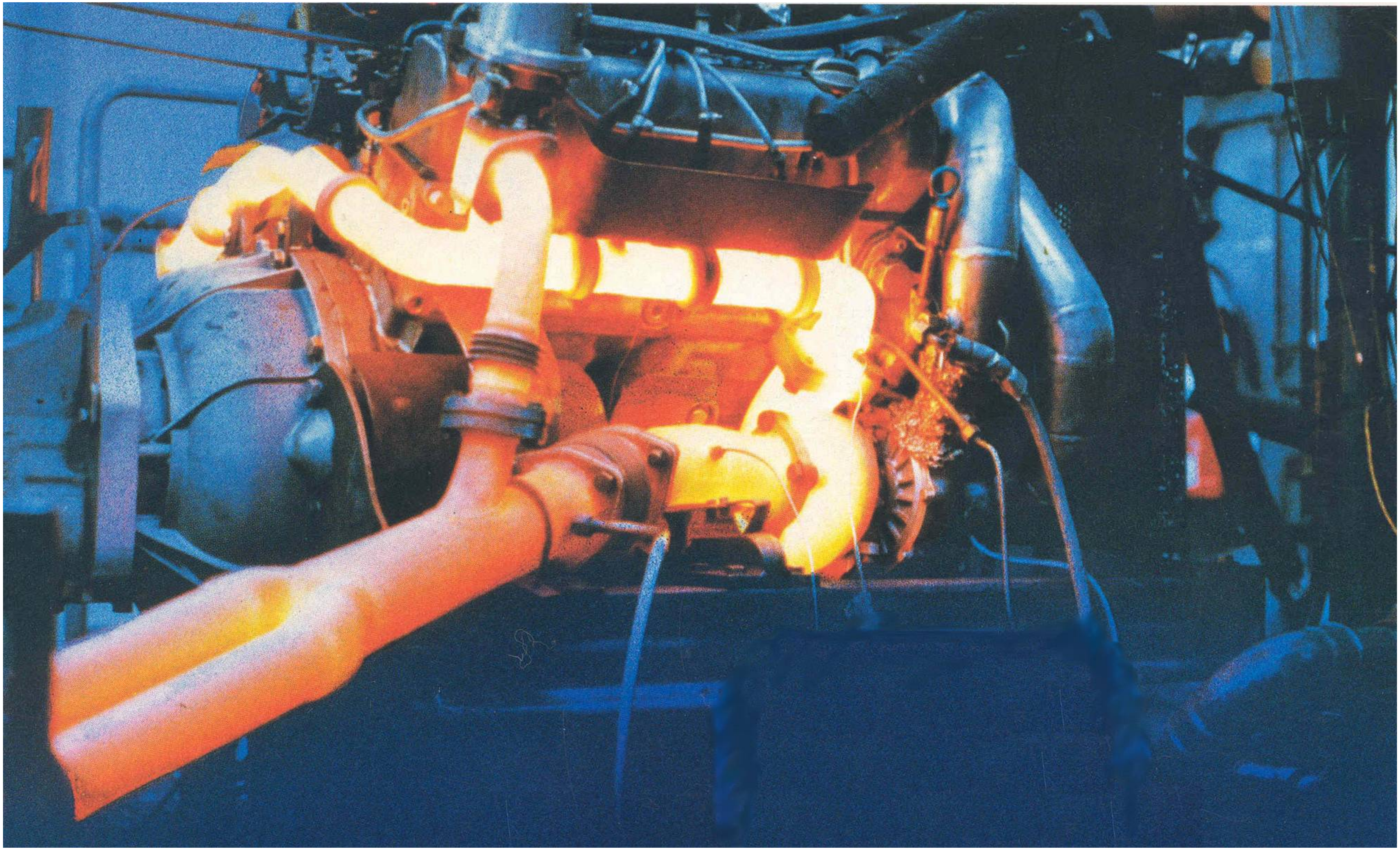
Gasoline Prices 201X…



Gasoline Prices 201X…

- Generate Electricity without Introducing any Additional Carbon into the Atmosphere

Automotive Internal Combustion Engine Waste Heat Energy



Typical Waste Heat from Gasoline Engine Mid Size Sedan

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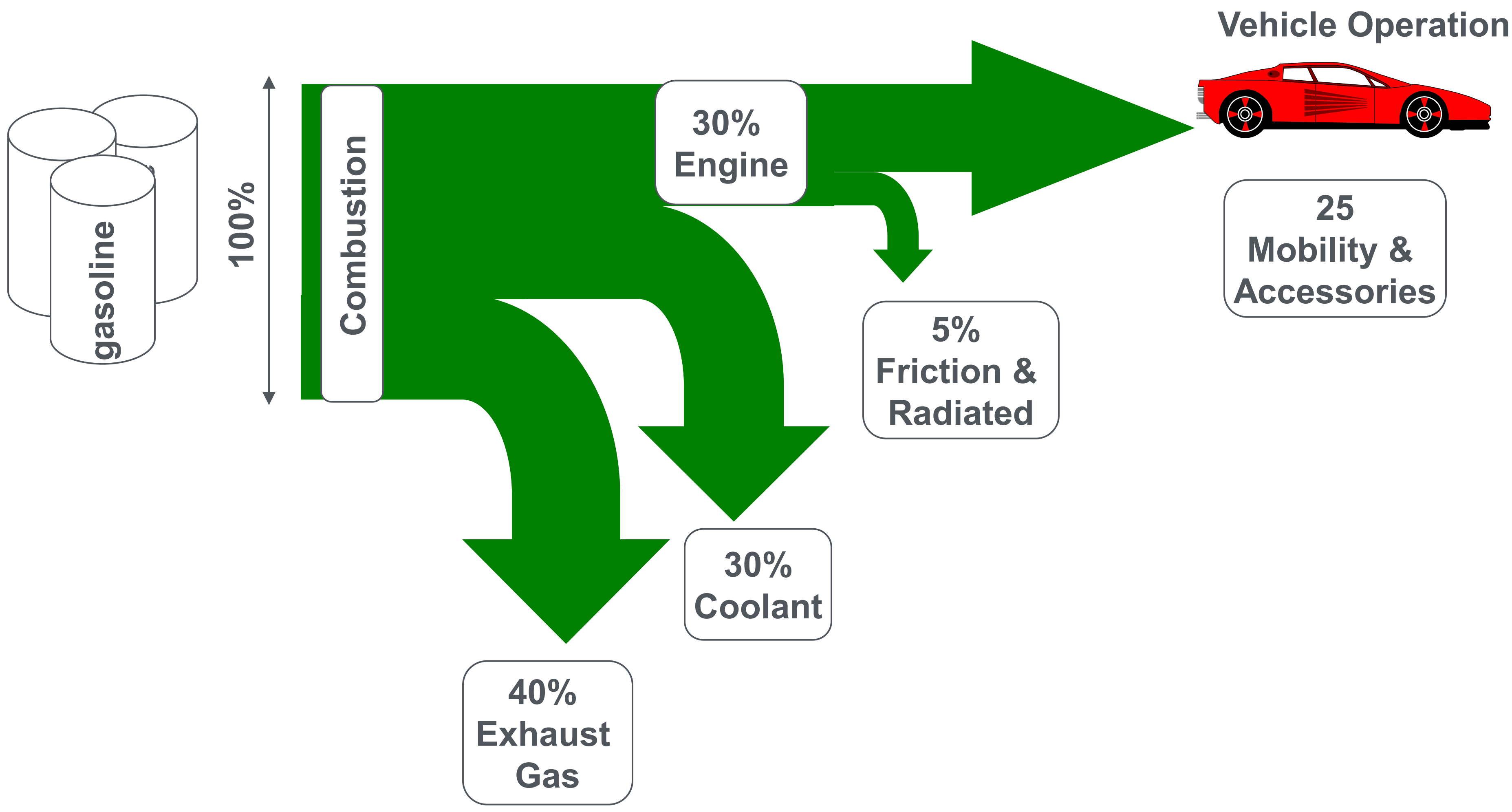


Combustion of Hydrocarbon Fuels Releases Carbon

Gasoline C_7H_{16}

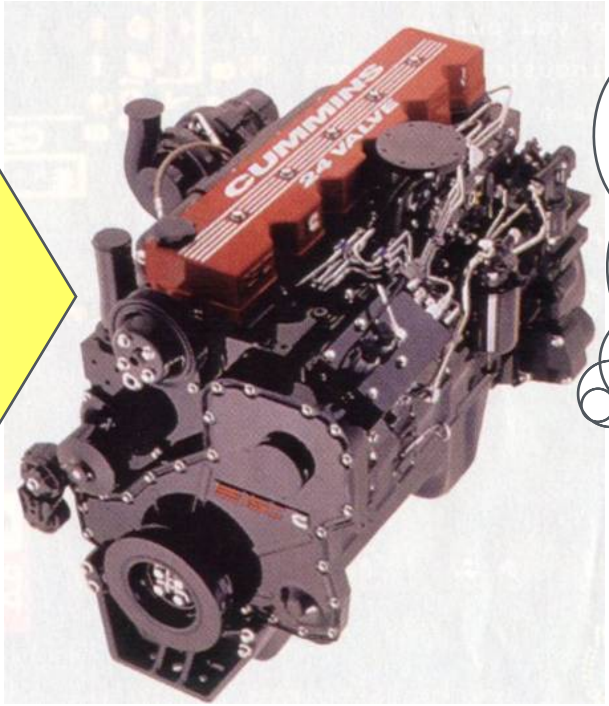
Diesel $C_{18}H_{30}$

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 could be over $3,000/vehicle if enforced

New US Personal Vehicle Fuel Economy Requirements (CAFE)

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- Corporate Average Fuel Economy (CAFE)

	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
- The White House announced an agreement with thirteen 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
  - Together account for over 90% of all vehicles sold in the United States

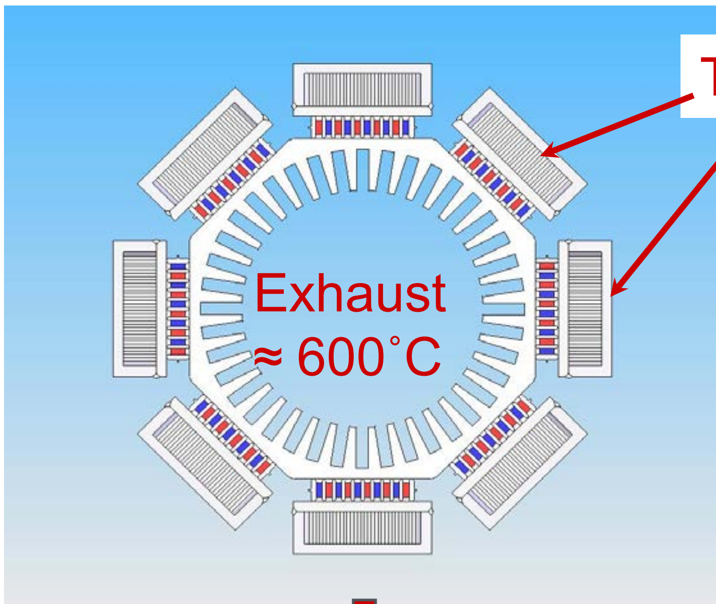
TEG Direct Conversion of Automotive Gasoline Engine Waste Heat to Electricity

Heat Rejection
Waste Heat > 60%

$T_H \approx 600^\circ C$

$T_C \approx 110^\circ C$

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 > 5% Increase in Fuel Economy

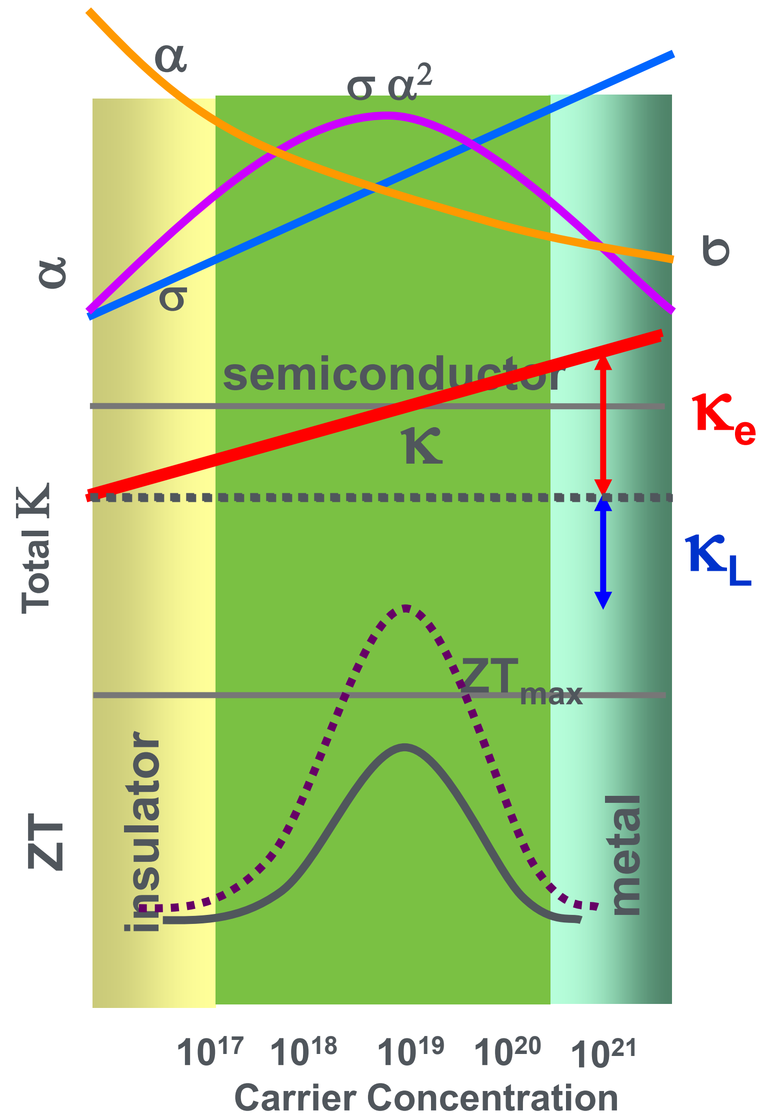
TE Materials Performance: Figure of Merit (ZT) *[Oregon State]*

Electrical conductivity

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

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

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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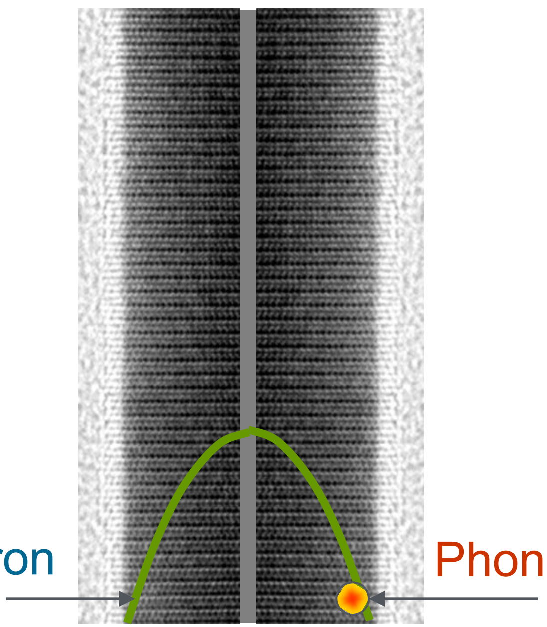
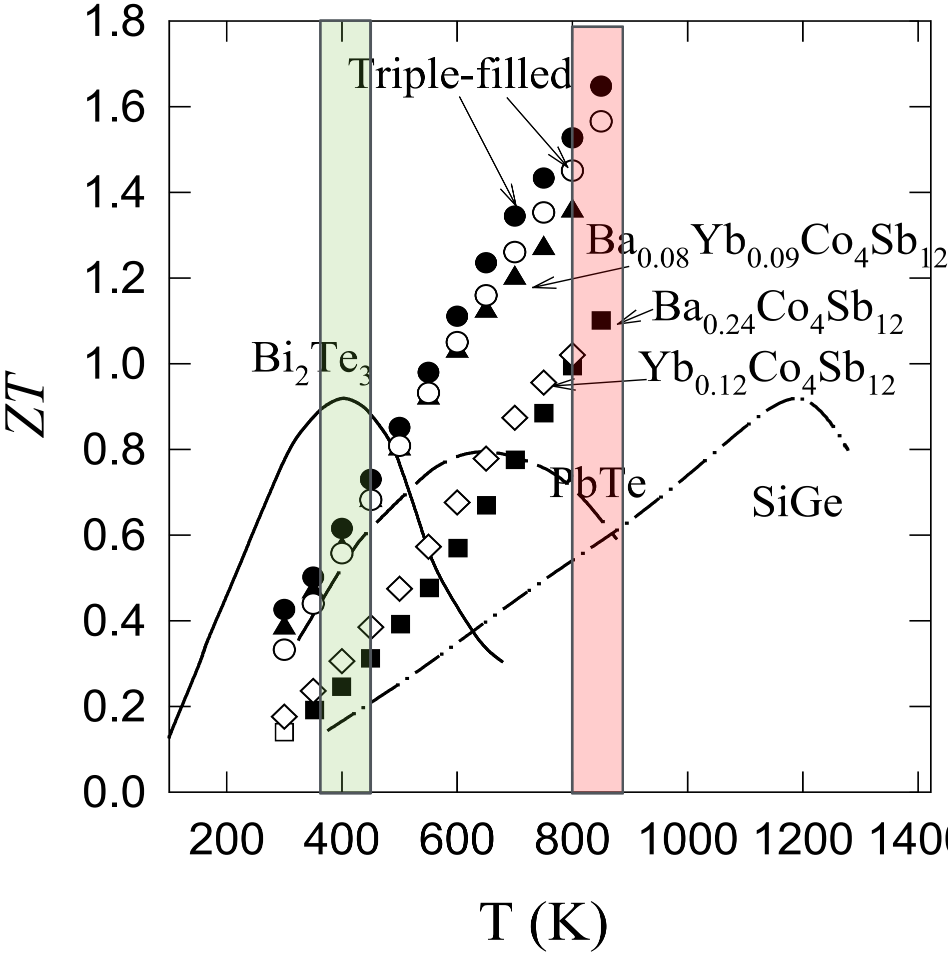
Interfaces that Scatter Phonons but not Electrons

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

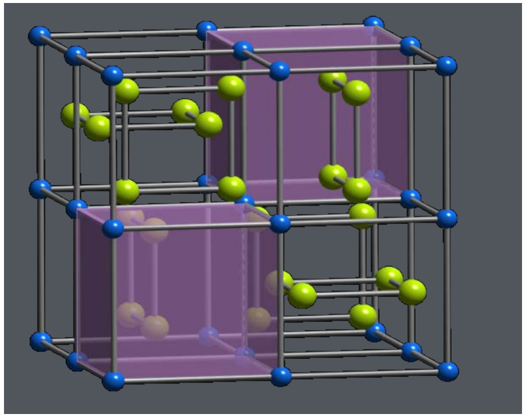


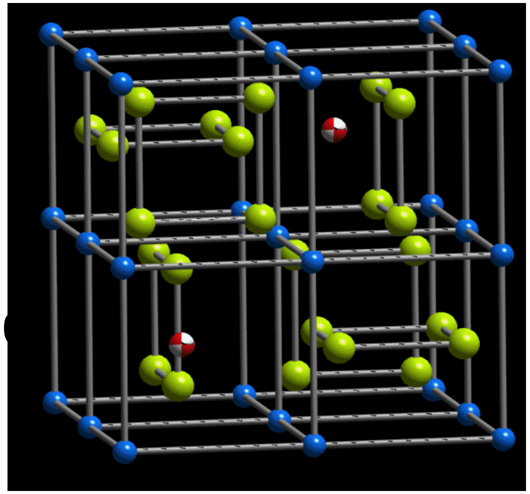
Highest ZT Achieved with Triple-filled Skutterudites (GM and U of Michigan)



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

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



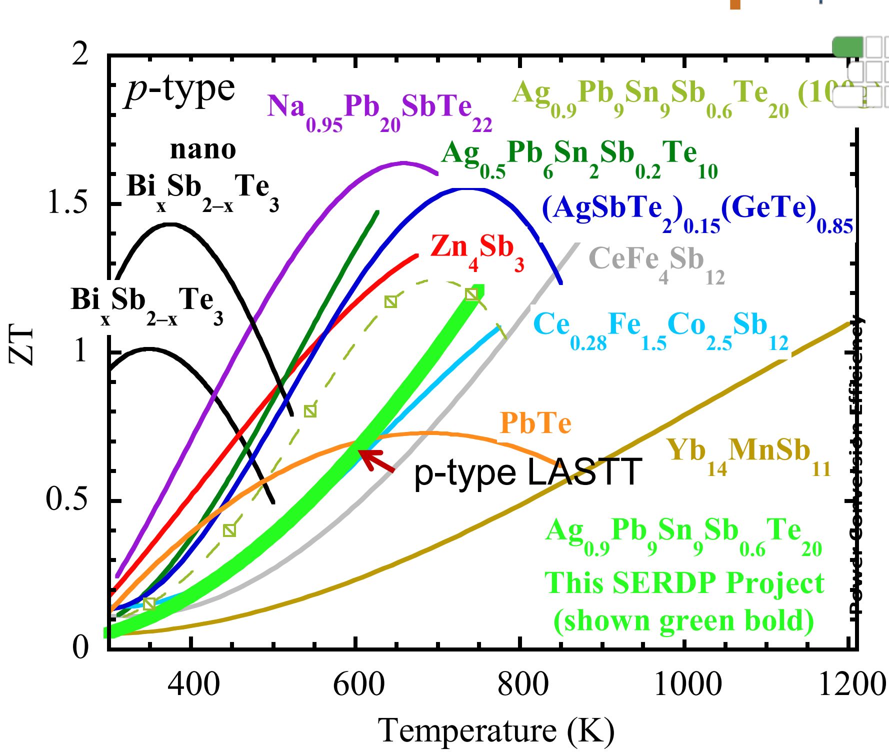


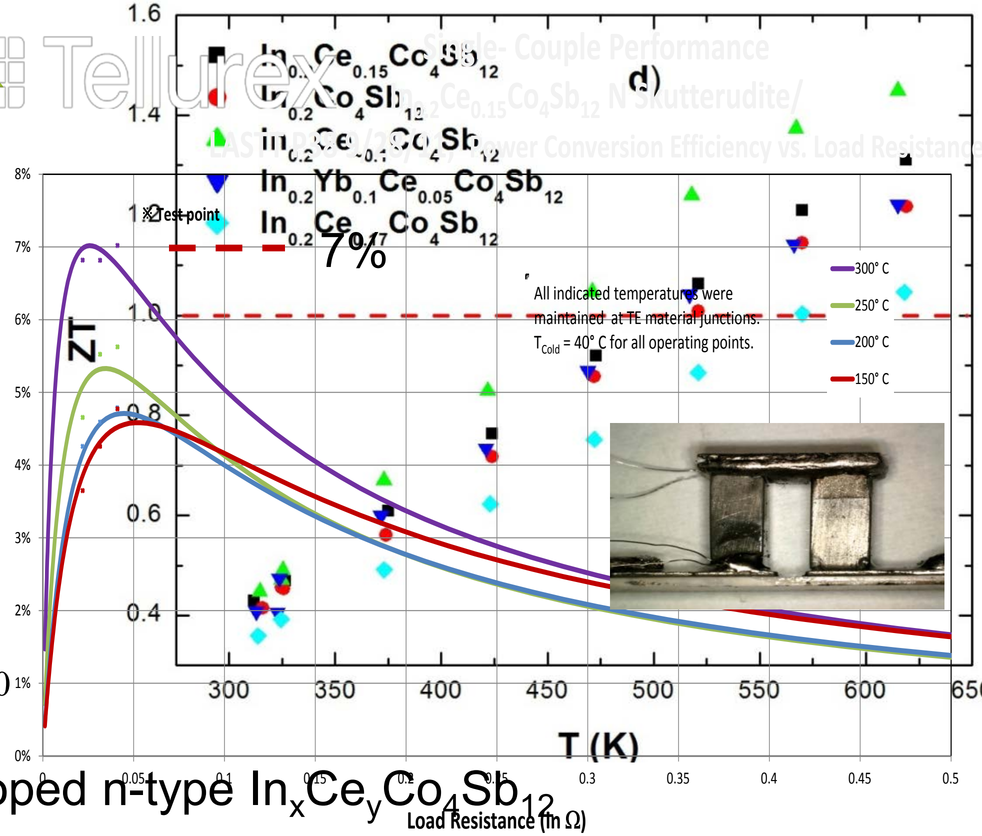
Atoms can be inserted into empty sites. Atoms can "rattle" in these sites – scatter phonons and lower the lattice thermal conductivity.

R_xCoSb_3

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

PNNL/Tellurex/OSU – Latest Excellent n-type Skutterudite TE Couple Results

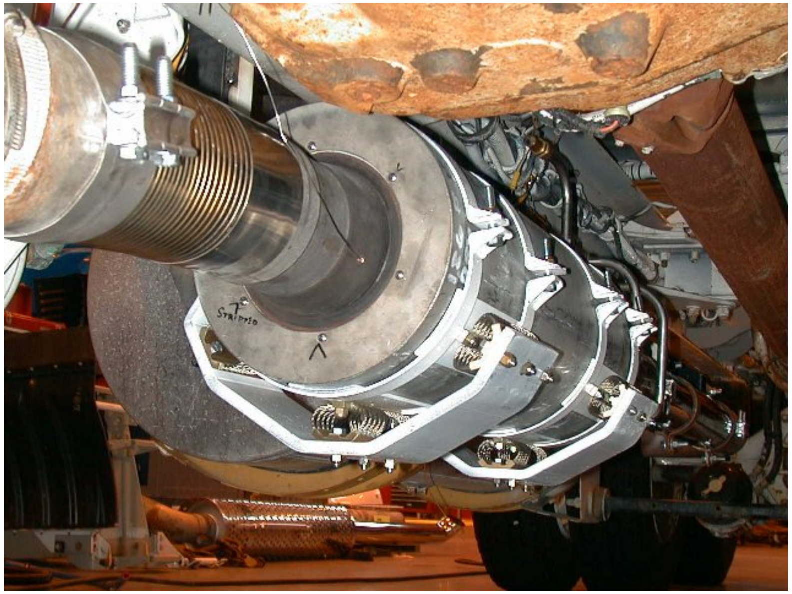




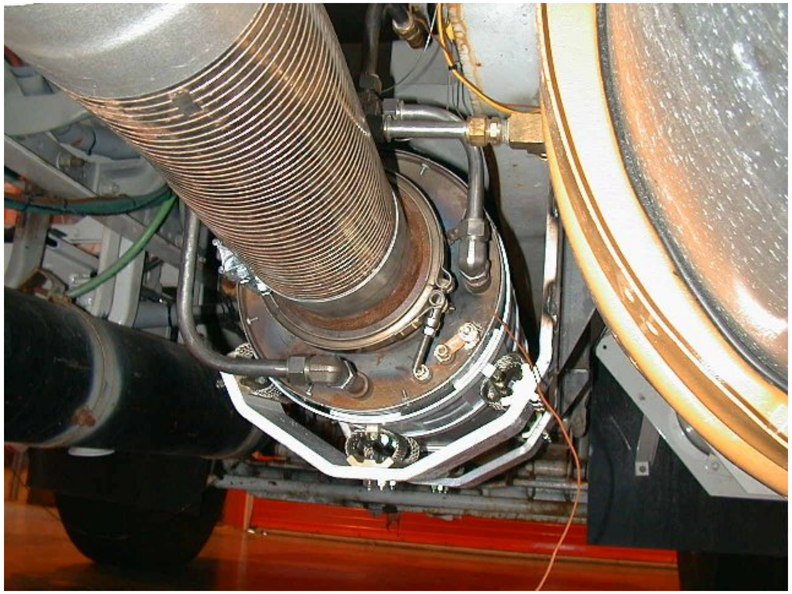
- PNNL, Tellurex, & Oregon State Developed n-type $In_xCe_yCo_4Sb_{12}$
  - TE Properties Characterized
  - Structural Properties Characterized
  - Thermal Cycling Enhancement Effects Discovered and Quantified
- New TE Couples Fabricated and Tested (p-type LASTT/n-type $In_{0.2}Ce_{0.15}Co_4Sb_{12}$)
- Test Results: 7% TE Couple Conversion Efficiency at T_h = 573 K & T_c = 313 K
  - New TE Couple Capable of T_h = 673 to 723 K

Contact: Dr. Terry Hendricks, PNNL,
E-mail: terry.hendricks@pnnl.gov

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 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 etc.)
- Reduce size of alternator (target: 1/3rd reduction in size)
- Improve fuel economy (targets: 5% to 6%)
- Reduce Regulated Emissions and Greenhouse Gases

DOE/NETL Vehicular Thermoelectric Generator Projects

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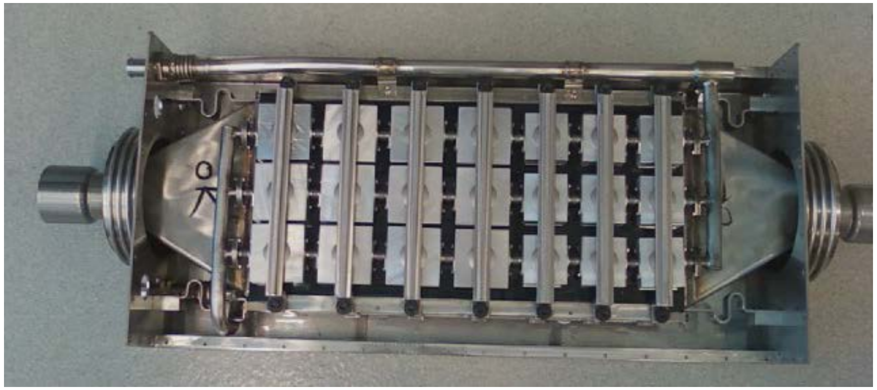
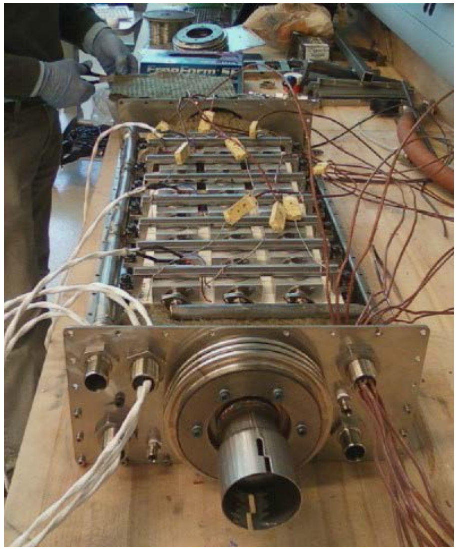
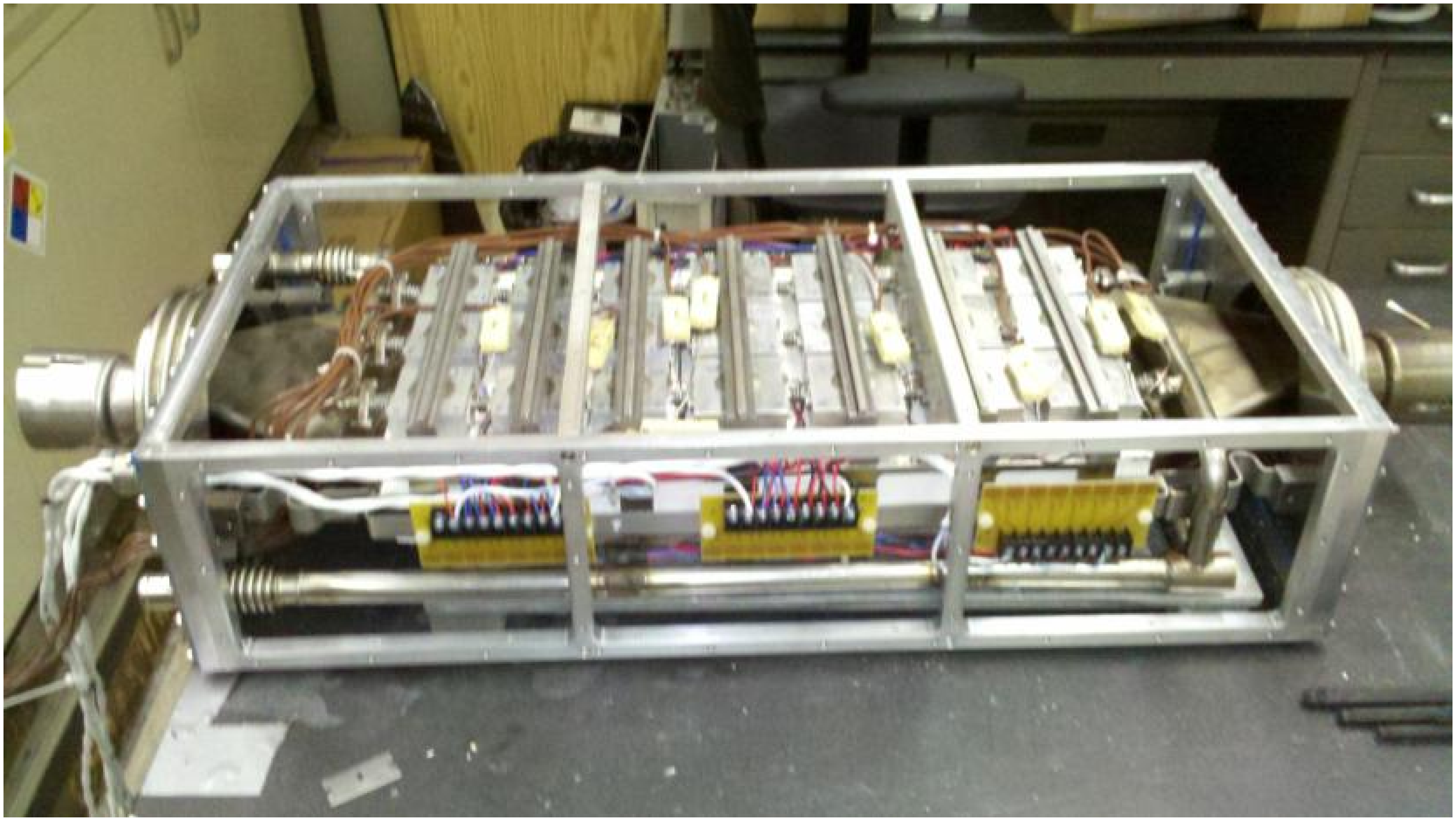
Awardees	Team Members
General Motors and General Electric	University of Michigan, University of South Florida, Oak Ridge National Laboratory, Marlow Industries
BSST, LLC	Visteon, BMW-NA, Ford, ZT Plus, Faurecia
Michigan State University	NASA Jet Propulsion Laboratory, Cummins Engine Company, Tellurex,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

GM Prototype TEG Fabrication

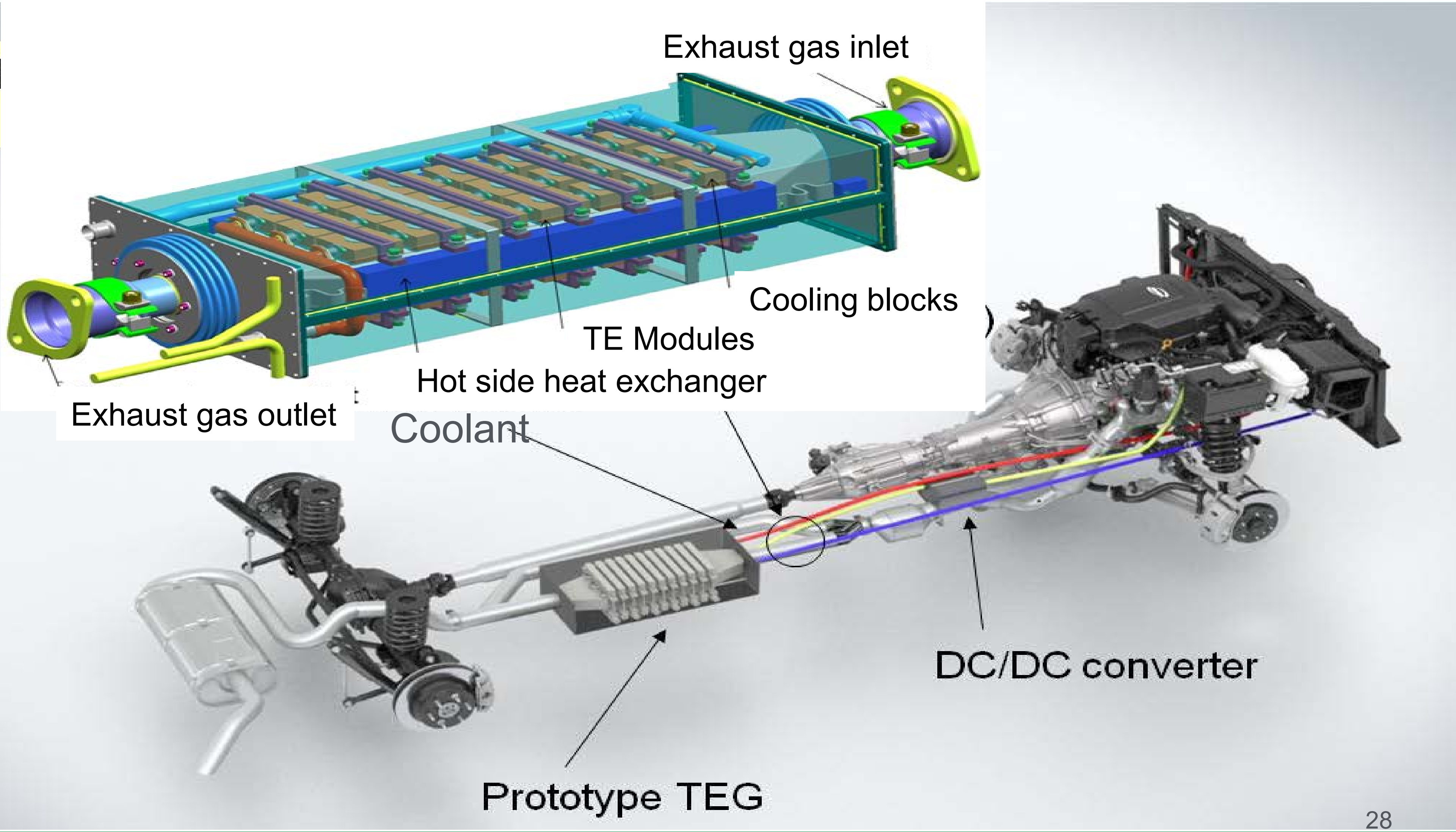




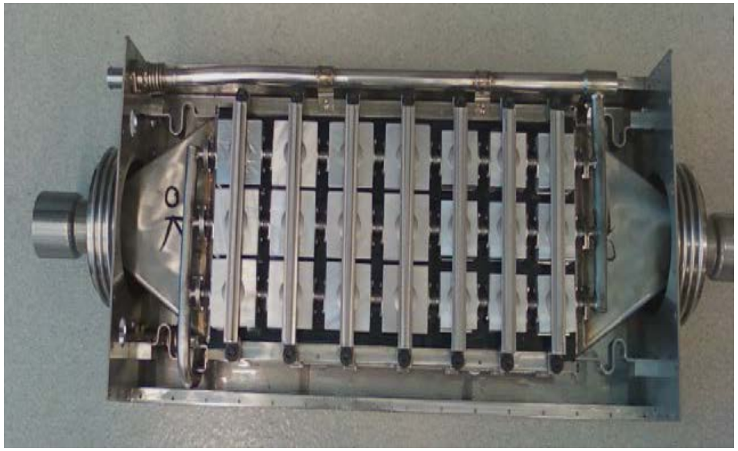
TEG #3
Skutterudite + Bi-Te modules

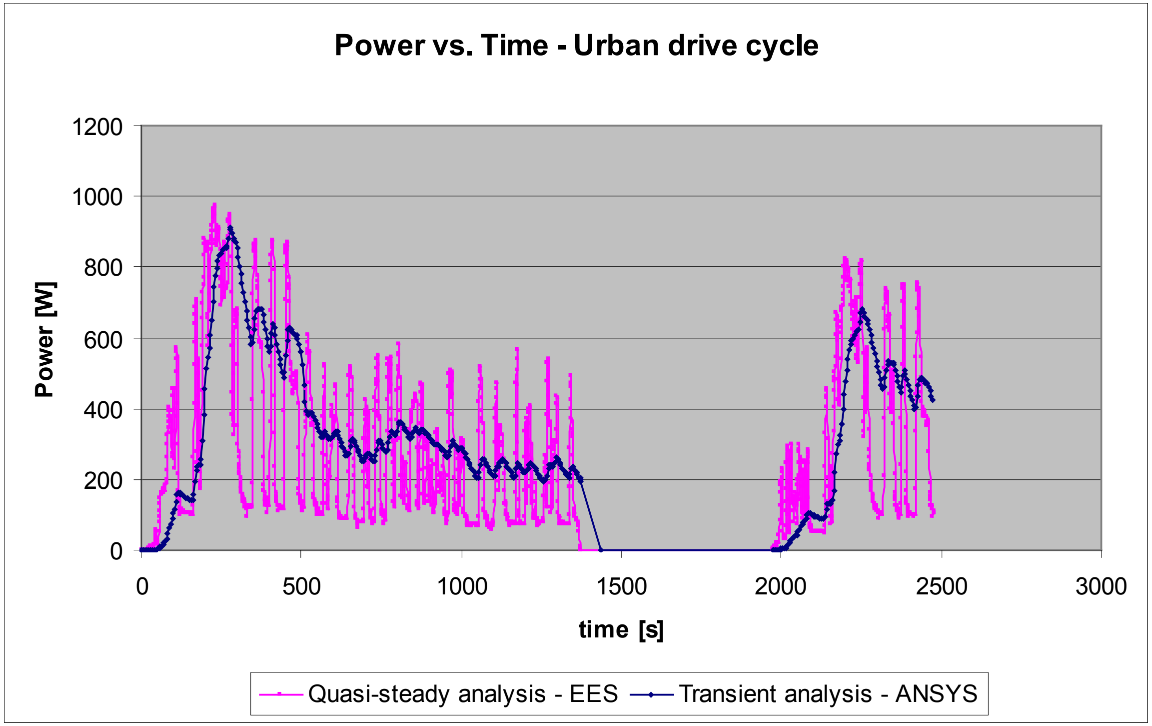


GM Prototype TEG Installation in a Chevy Suburban Chassis



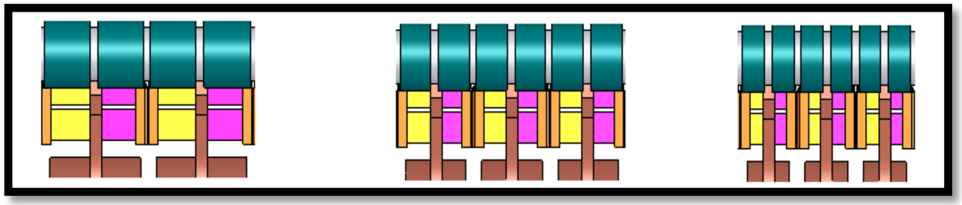
GM TEG Performance in Chevy Suburban



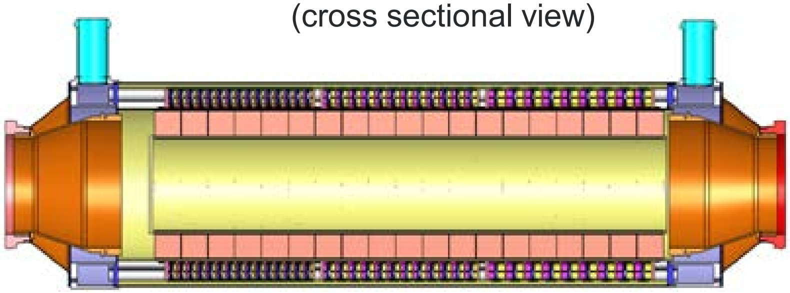


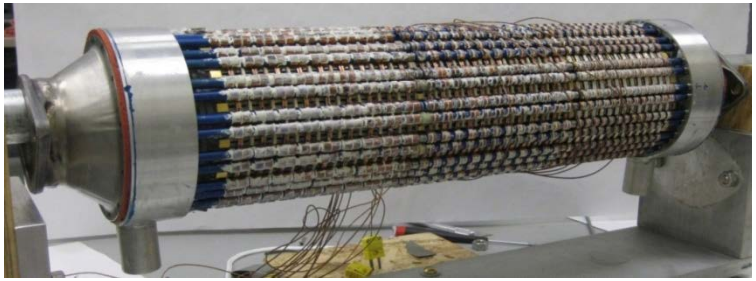
- ~ 1 mpg (~ 5 %) fuel economy improvement on FTP Driving Cycle
  - > 350 Watts City
  - > 600 Watts Highway

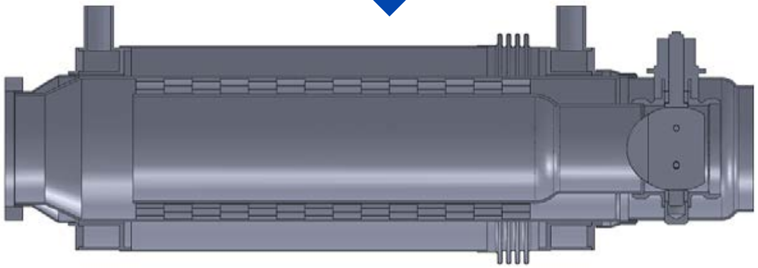
TEG for Ford Lincoln MKT and BMW X6



Pre-production Waste Heat Recovery TEG (cross sectional view)

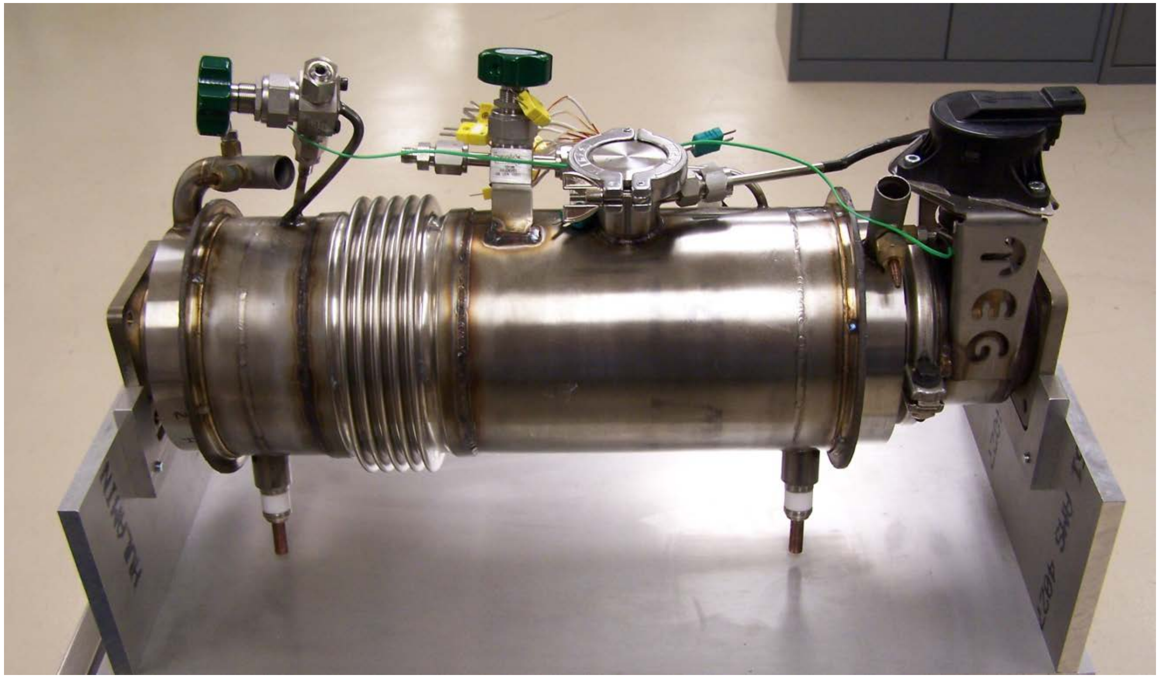






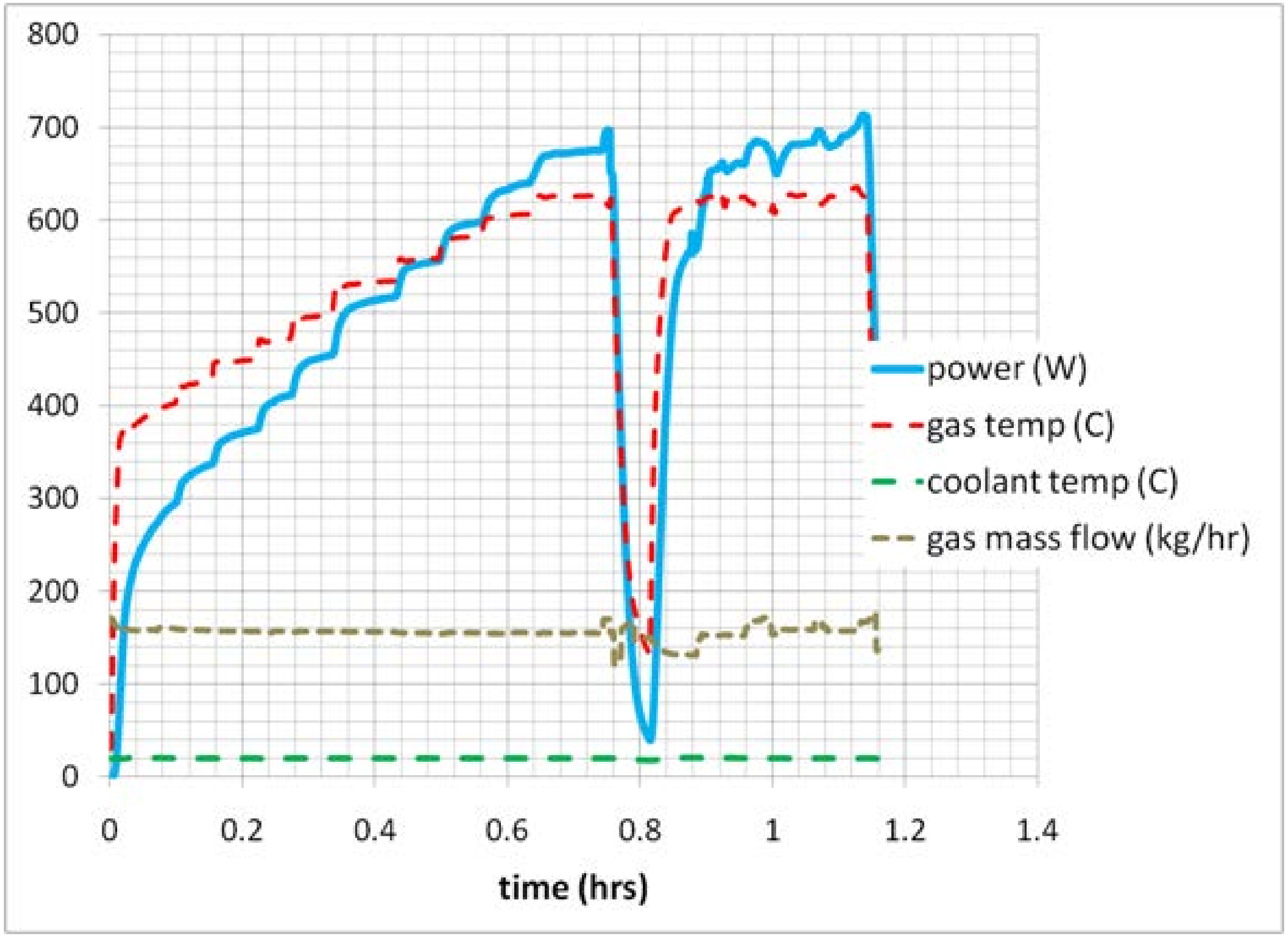
- Designed for 500 watt output driving at 75 mph (120 kph)
- Weights 22.4 lbs (10.2 kg)
- 5 percent improvement in fuel economy on-highway
- Improved performance anticipated with technologies in development

Bench Test of Amerigon's Cylindrical TEG for Ford and BMW



- Exceeds 700W power generation.
  Hot Air 620° C Cold side 20° C

Amerigon's Cylindrical TEG Bench Test



TEG & Exhaust System in Lincoln MKT

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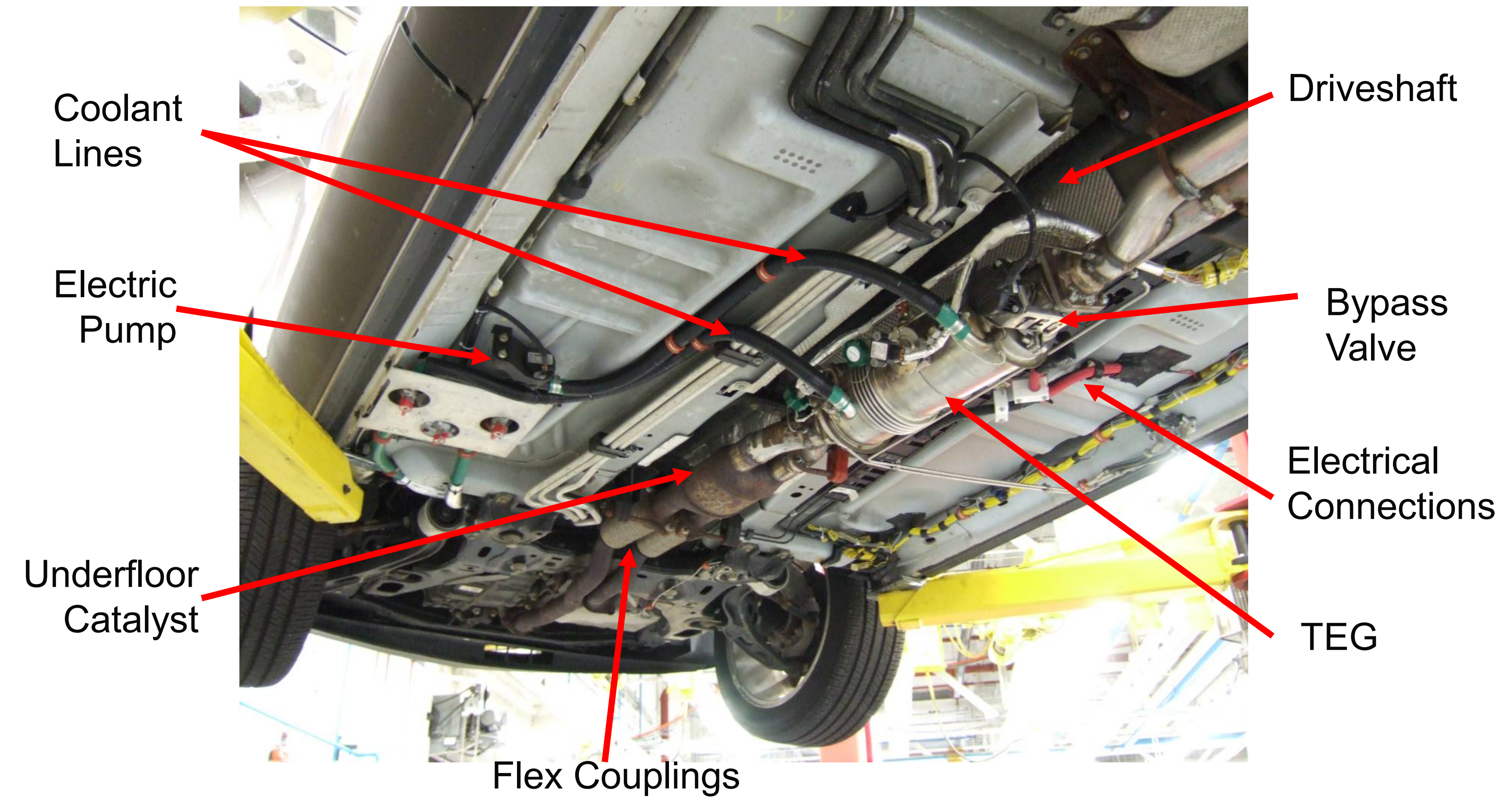

Prototype TEG's In Ford Lincoln MKT, BMW X6 and Chevy Suburban- DOE Programs

Thermoelectric Power Generation – Analytical Projections for BMW Sedans

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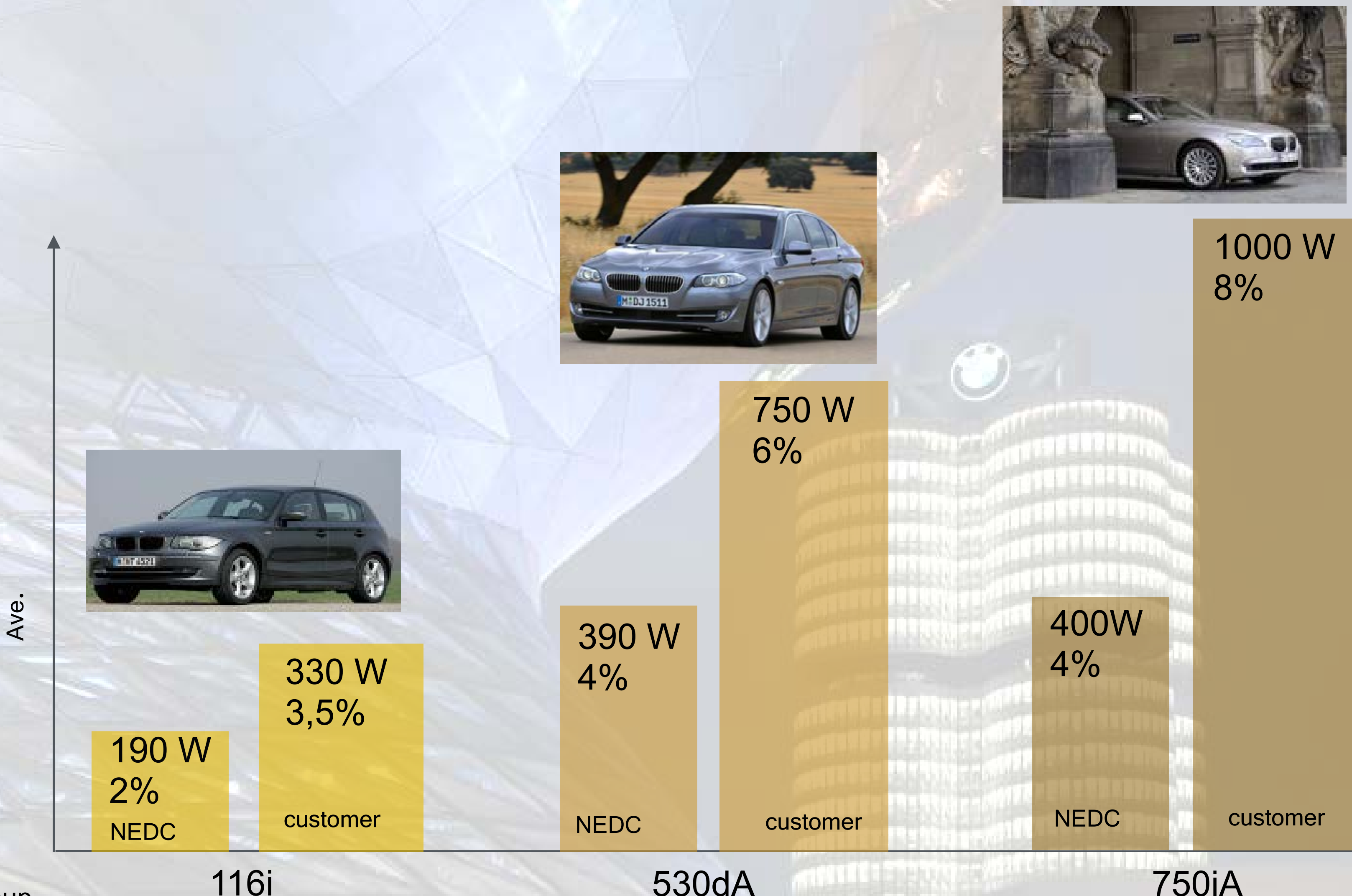

Source: BMW Group

TE Materials Performance Objective

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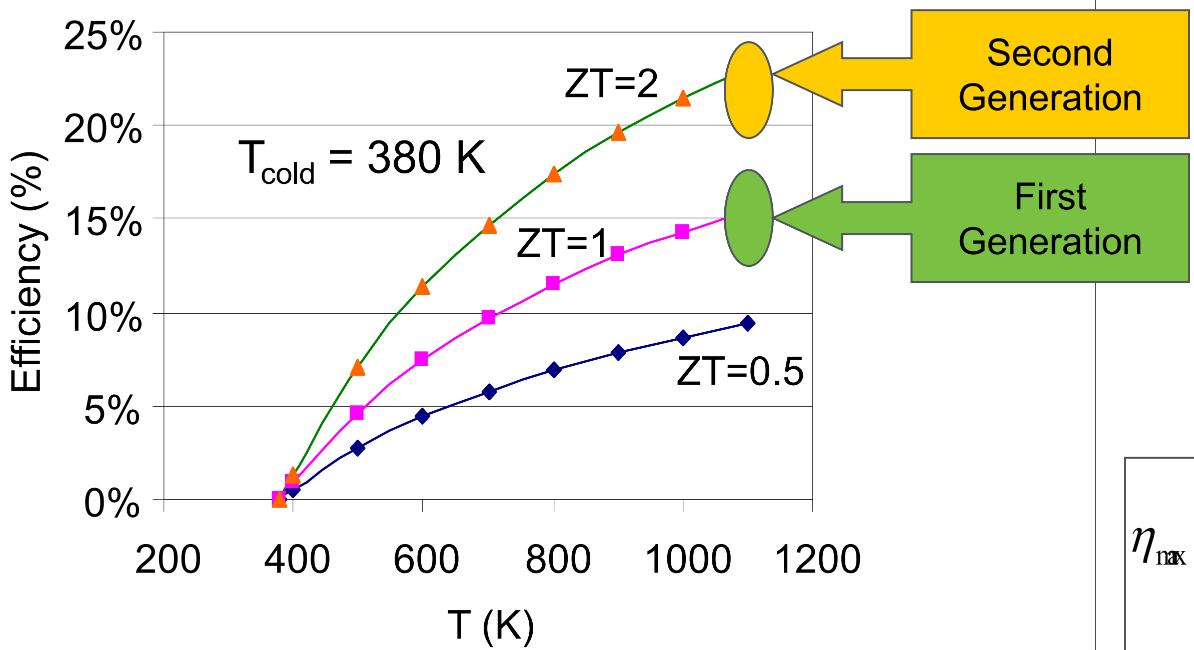
TE conversion efficiency as a function of hot junction temperature and ZT



TE Materials for Vehicular TE Generators

$$\eta_{max} = \underbrace{\frac{T_{hot} - T_{cold}}{T_{hot}}}_{\text{Carnot}} \; \underbrace{\frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{cold}}{T_{hot}}}}_{\text{TE Materials}}$$

DOE's Objectives: Second Generation Automotive TEG's

- Commercially viable thermoelectric modules
  - $ZT_{avg} = 1.6$
  - Temperature range 350 - 900K
- Eliminate the alternator
- Large volume commercial introduction in vehicles

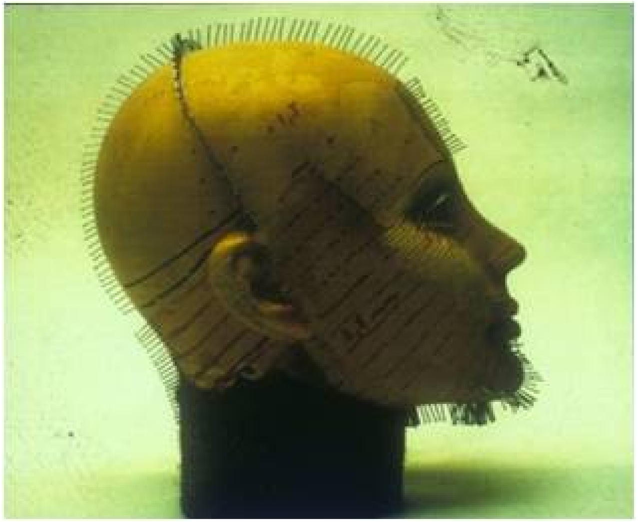
Concept of Zonal Thermoelectric Air Conditioner/Heater (HVAC)

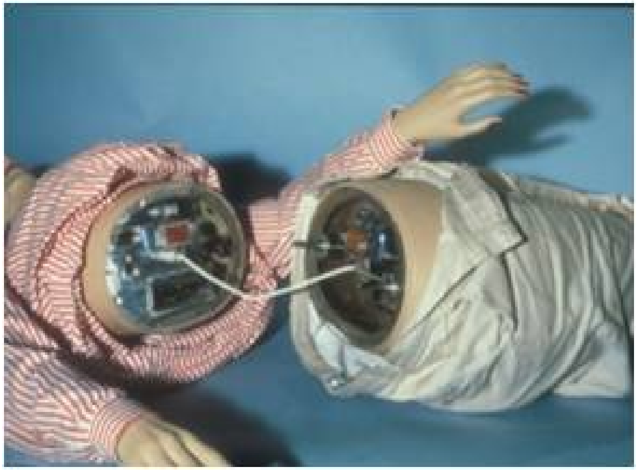
Zonal TE units located in dashboard, headliner, A&B pillars and seats/seatbacks

- Energy Requirements (Analytical):
  - Zonal Concept cools/heats each occupant independently
  - **630** Watts to cool single occupant
  - Current A/C's **3,500 to 4,500** Watts cool entire cabin

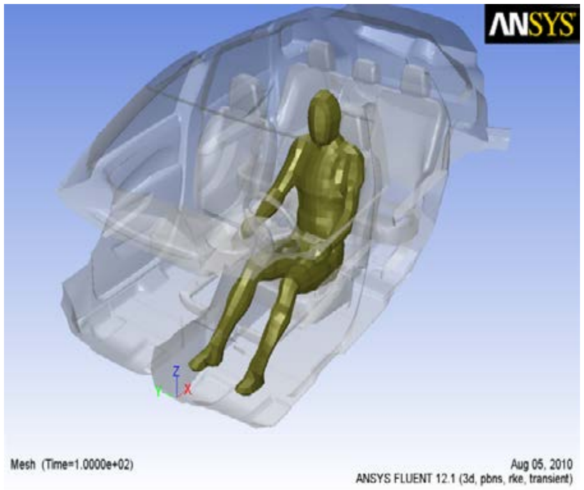
Defining Vehicle Occupant Comfort

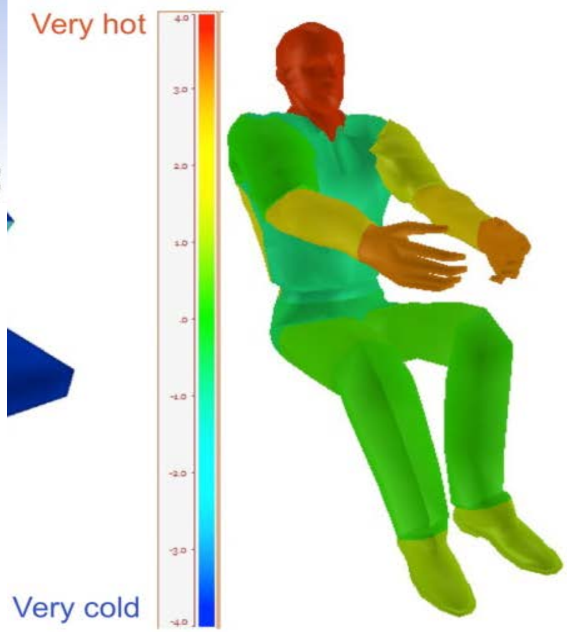
UC Berkeley Thermal Mannequin Evaluation
Detailed Localized Comfort Measurements

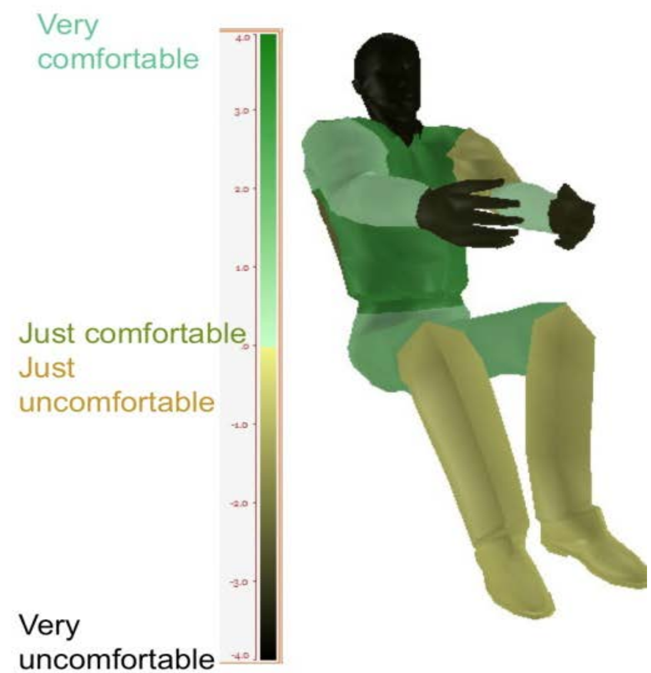




Human Thermal Comfort Model for Localized Cooling and Heating



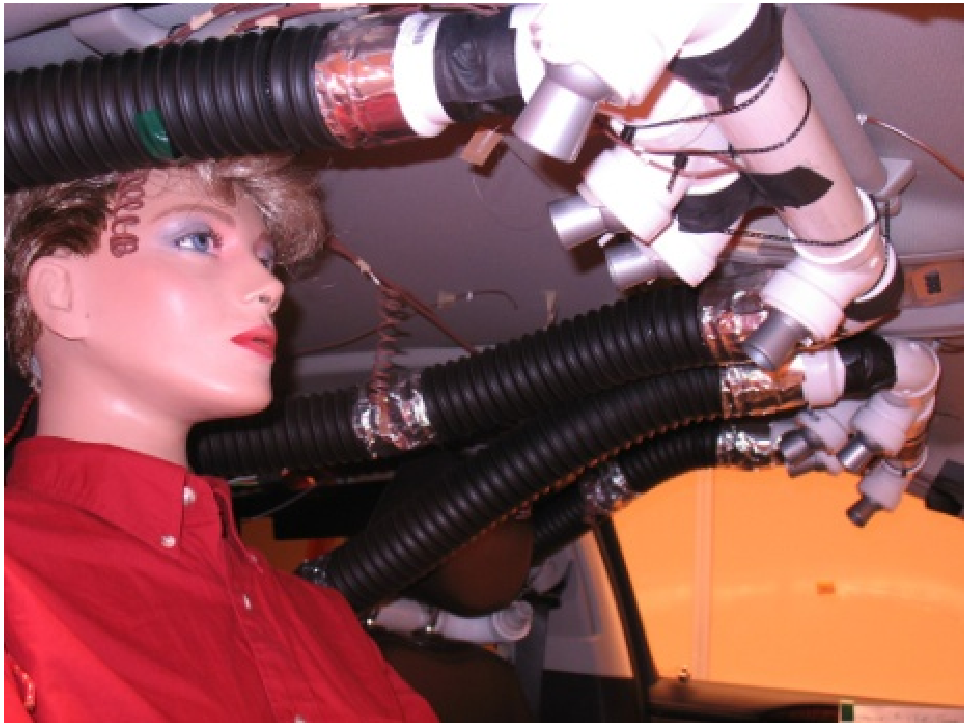


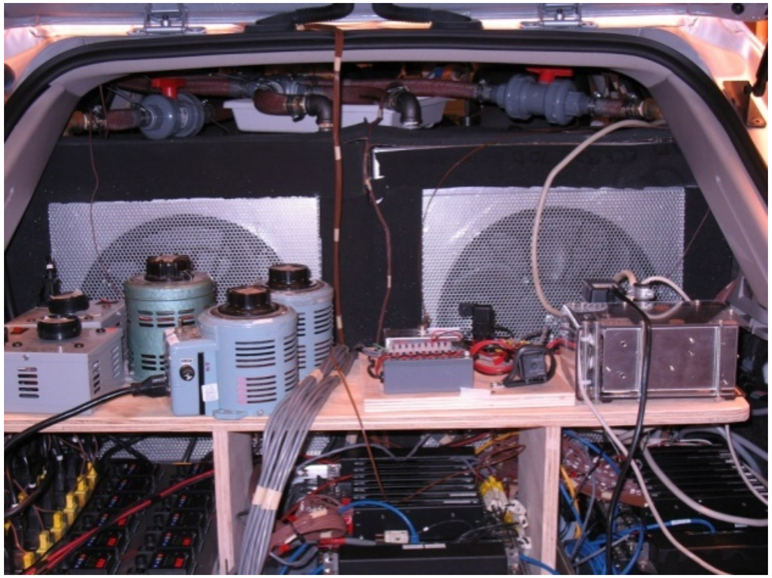


- Correlates well with 16 segment thermal mannequin vehicle evaluations

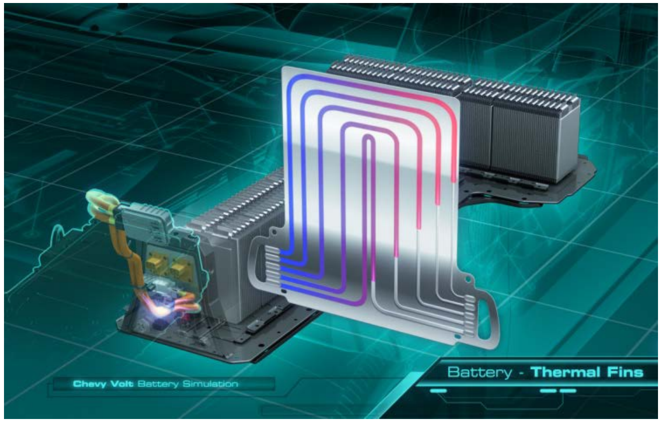
Delphi's Climatic Wind Tunnel Testing to Emulate Local Spot Cooling

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





Chevy Volt Battery Temperature Impacts Performance and Service Life ……24/7



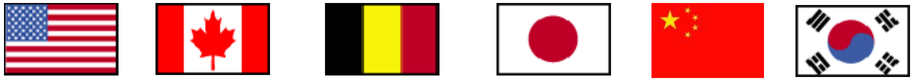
Battery temperature impacts vehicle performance, reliability, safety, and life cycle cost

Main HTML functions in thermoelectric research

- Transport properties measurements
- Thermomechanical properties and reliability
- Advanced materials characterizations:
  - **Atomic resolution microscopy (STEM)**
  - **X-ray and neutron scattering**
- HTML is leading a thermoelectric characterization program via the International Energy Agency (IEA) – Advanced materials for Transportation (AMT)

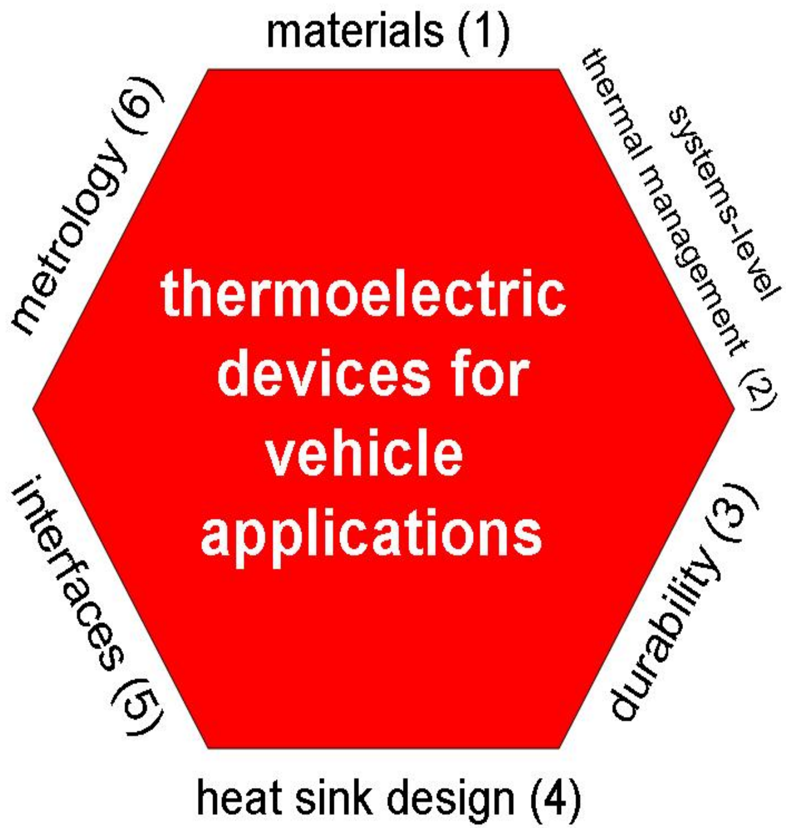
  Annex VIII on thermoelectrics led by ORNL
  - **Participating countries: USA, Canada, Germany, Japan, China and South Korea**
  - **Participating labs: more than 10**

iea International Energy Agency



DOE/NSF Partnership in Thermoelectric R&D

University/industry collaboration, $9M/yr over 3 years



2010 NSF/DOE Partnership - Thermoelectric Devices for Vehicle Applications

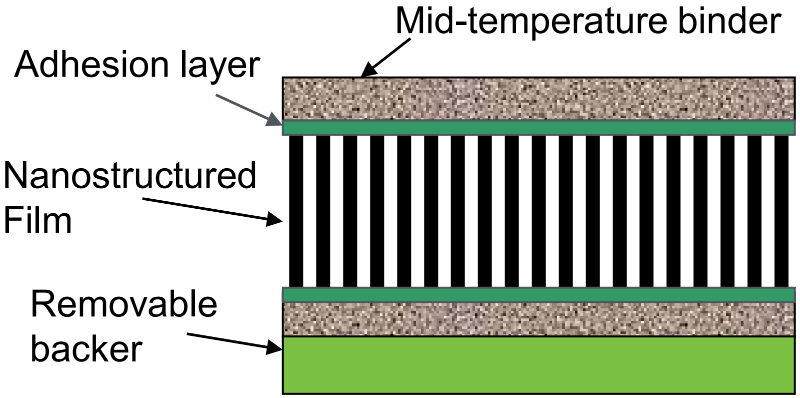
- An integrated approach towards efficient, scalable, and low cost thermoelectric waste heat recovery devices for vehicle - Scott T Huxtable (VT)
- Automotive Thermoelectric Modules with Scalable Thermo- and Electro-Mechanical Interfaces - Kenneth E Goodson (Stanford)
- High-Performance Thermoelectric 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 - Yongho 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), Mercouri Kanatzidis (Northwestern)
- Thermoelectrics for Automotive Waste Heat Recovery - Xianfan Xu (Purdue)
- Integrated Design and Manufacturing of Cost Effective and Industrial-Scalable TEG for Vehicle Applications - Lei Zuo, SUNY-Stony Brook

NSF-DOE TE Partnership: Automotive TE Modules with Scalable Thermo- and Electro-Mechanical Interfaces (Stanford, Univ. South Florida, Bosch)

Objectives

- Develop, and assess the impact of, novel interface and material solutions for TEG systems of particular interest for Bosch.
- Explore and integrate promising technologies including nanostructured interfaces, filled skutterudites, cold-side microfluidics.
- Practical TE characterization including interface effects and thermal cycling.

Prototype TEG in exhaust system



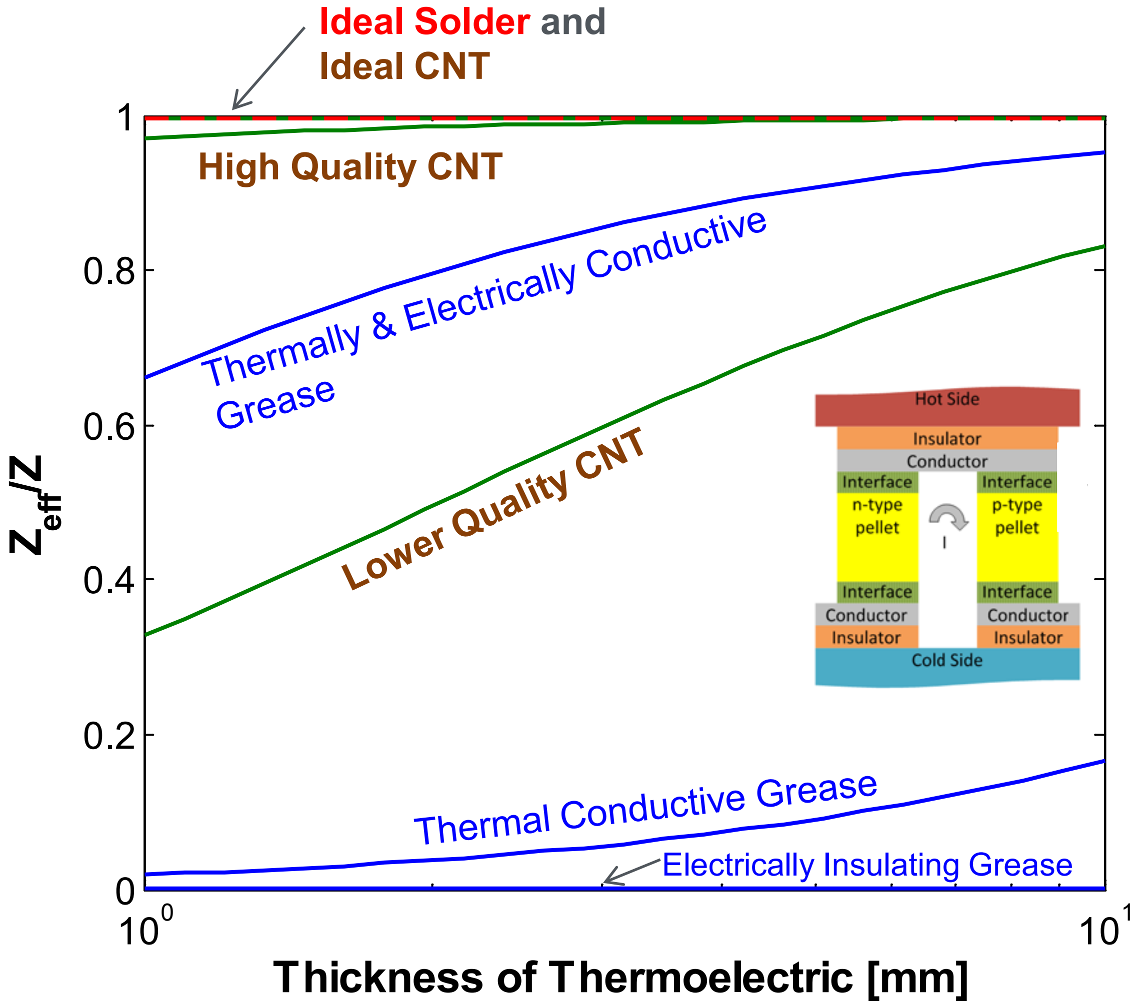
Panzer, Goodson, et al., Patent Pending (2007)

Approach

- Multiphysics simulations ranging from atomic to system scale.
- Photothermal metrology including pico/nanosecond, cross-sectional IR.
- MEMS-based mechanical characterization.
- System design optimization by combining all thermal, fluidics, stress, electrical and thermoelectric components.

NOVEL MATERIALS LABORATORY
UNIVERSITY OF SOUTH FLORIDA
BOSCH

Effect of Interface Resistances on Thermoelectric Device Properties

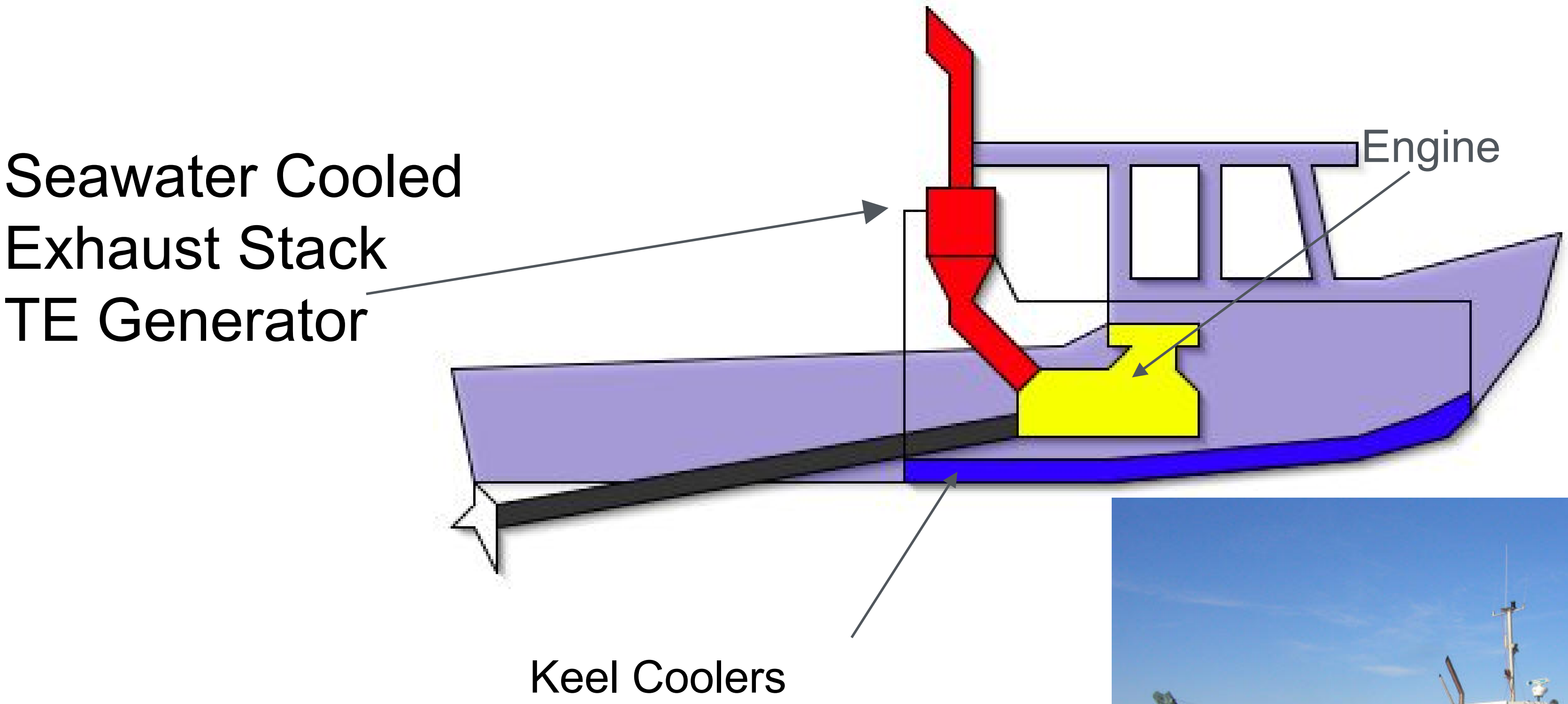


Using model of Xuan, *et al.* International Journal of Heat and Mass Transfer 45 (2002).

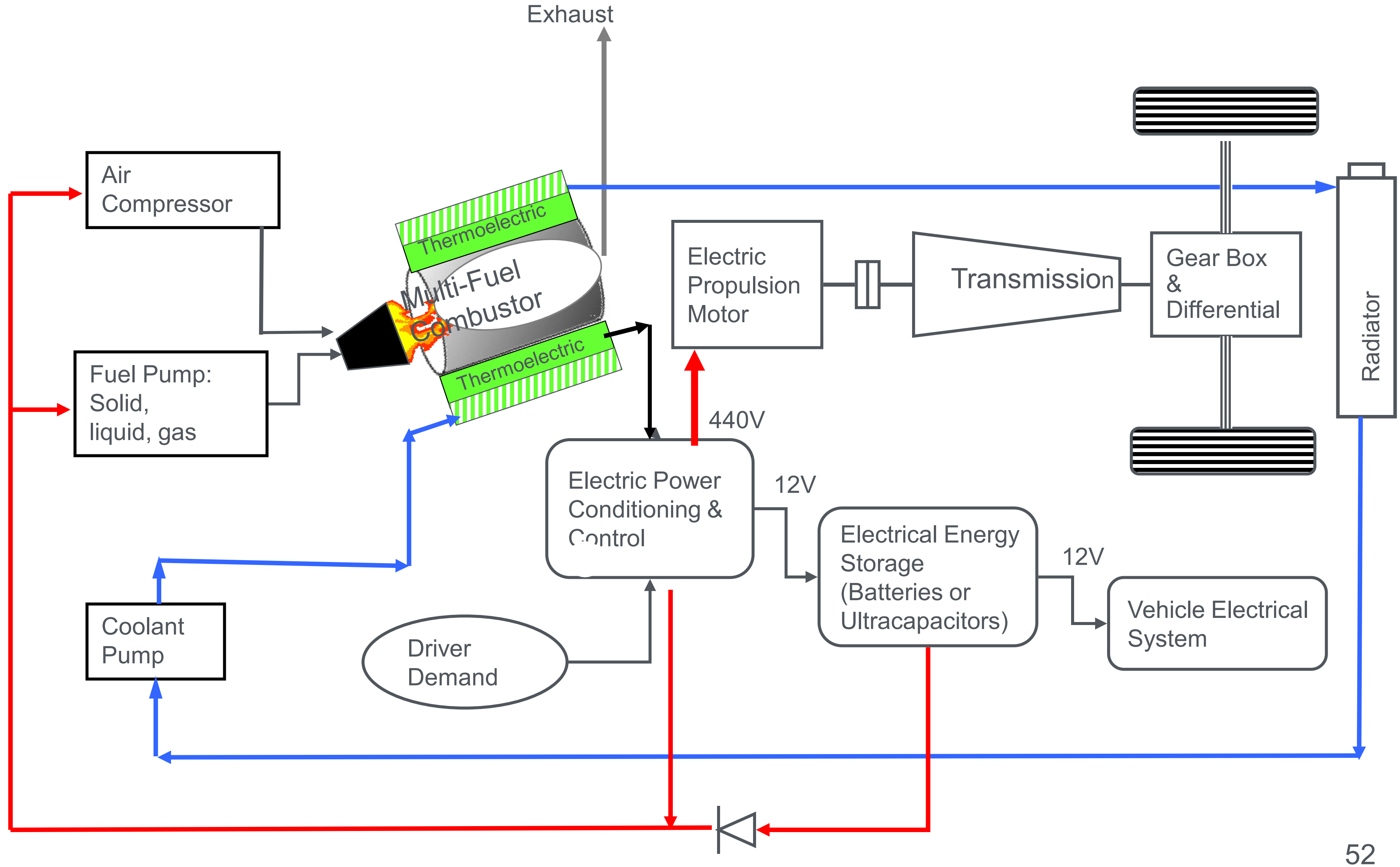
Interface Material	R''$_{th}$ [W/m^2/K]	R''$_e$ [Ω m^2]
Solders And Ideal CNT	~10^{-7}	~10^{-12}
High Quality CNT	~10^{-6}	~10^{-10}
Lower Quality CNT	~10^{-5}	~10^{-8}
Thermally & Electrically Conductive Grease	~$3x10^{-6}$	~$3x10^{-9}$
Thermal Conductive Grease	~$8x10^{-6}$	~$3x10^{-7}$
Electrically Insulating Grease	~$8x10^{-6}$	>10^{-5}

- Where: Annapolis, Maryland (Nearest airport: Baltimore/Washington International, BWI)
- When: January 18-20, 2012
- Cost: No Registration Fee
- Sponsors: Needed
- Abstracts: Submit Directly to: john.fairbanks@ee.doe.gov

Maine Maritime Academy



Vehicular Thermoelectric Hybrid Electric Powertrain Replacing the ICE



Market Factors Involving Automotive Thermoelectric Applications

- Fuel Economy Requirements and Emissions Regulations
- Increasing Gasoline/Diesel Prices
- Automotive Industry Continually Wants “New and Improved” Technology
- Dramatic Increase in Demand for Large Quantity Thermoelectric Materials
- Historically Semiconductor Costs Decrease with Volume
  - Thermoelectrics Should Follow this Trend

Russian Automotive Market

- Automakers in Russia
  - GM, Ford, VW, Fiat, Mercedes-Benz, Suzuki, BMW, Renault-Nissan, Toyota, AvtoVAZ/Magna
- Under decree 166, OEM's Must:

  Achieve 60% local content within 6 years
- Equip > 30% of vehicles with locally-sourced engines and/or transmissions
- Rusnano (government) and a VC built and equipped thermoelectric clean room manufacturing facility
  - Currently 149 workers, projected → 333 by 2015

Thermoelectrics Production: Russia

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

Thermoelectrics Production: Russia

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

Typical Transportation Entering The 20th Century

- Stage coach
  - 6 Passengers
  - 4 Horsepower (quadrupeds)
  - Drive by Line
  - Fare - 6¢/mile
- Bio-mass derived fuel
  - Minimally processed
  - Stable fuel cost
  - Fuel infrastructure in place
- Emissions
  - Equine methane
  - Agglomeration of macro particles
    - Minimally airborne
    - Recyclable

Evolution of Personal Transport

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

1900 **2011**

Plan "B" Entering the 22nd Century?

- **From the 20th Century to the 22nd Century**
  - **Reduced fuel consumption and emissions by 75%**
- **Renewable bio-mass fuel**
  - **Stable fuel prices**
- **Velocity Enhanced Ambient Air Conditioning**
  - **Solar Heating**
- **Drive by Line**

Plan "C" Entering the 22 Century?

- **All-electric vehicle**
- **Advanced batteries**
- **Inductive-charging**
- **Lightweight materials**
- **No emissions**

- **Thermoelectrics**
- **TE Air Conditioner/heater**
- **TE thermal management of batteries**
- **TE-cooled collision avoidance system and computers**
- **TE-cooled/heated beverage holders**
- **TE-regenerative braking**

Thank You…………Questions?