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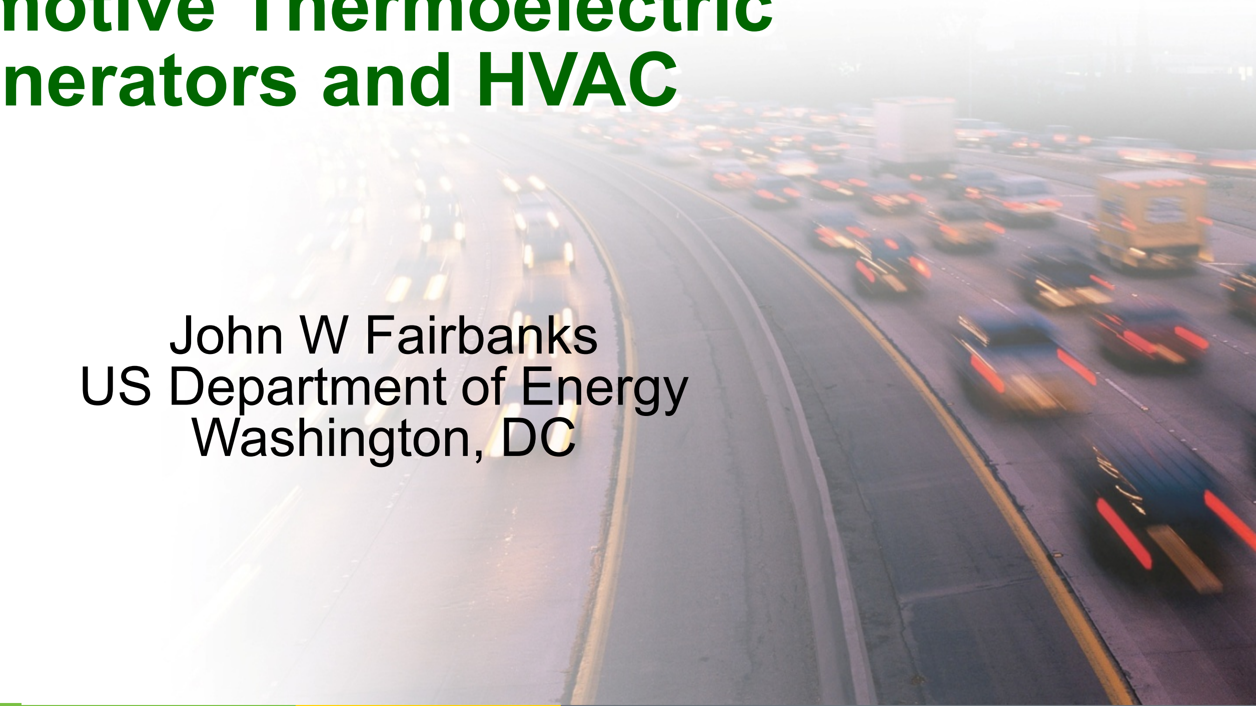
Automotive Thermoelectric Generators and HVAC



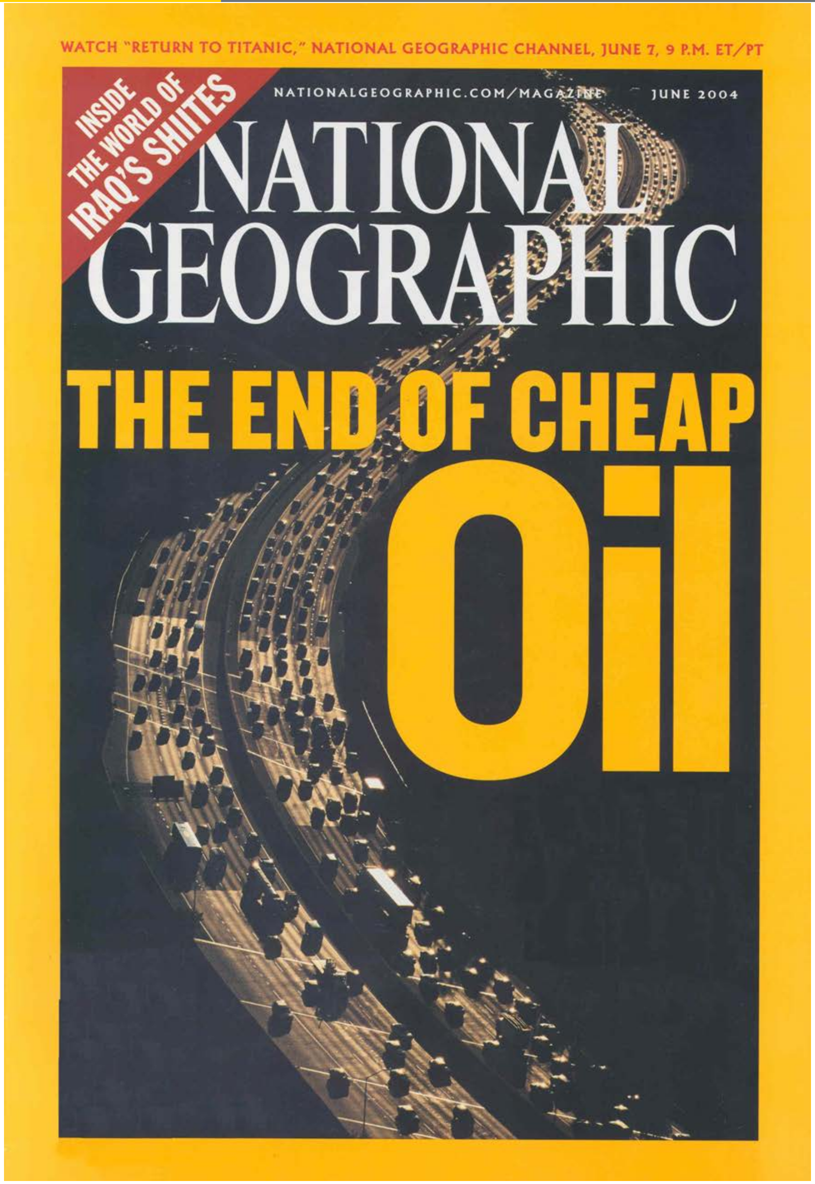
John W Fairbanks
US Department of Energy
Washington, DC

Presented at DEER 2012
Dearborn, Michigan,
October 18, 2012

"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.**"

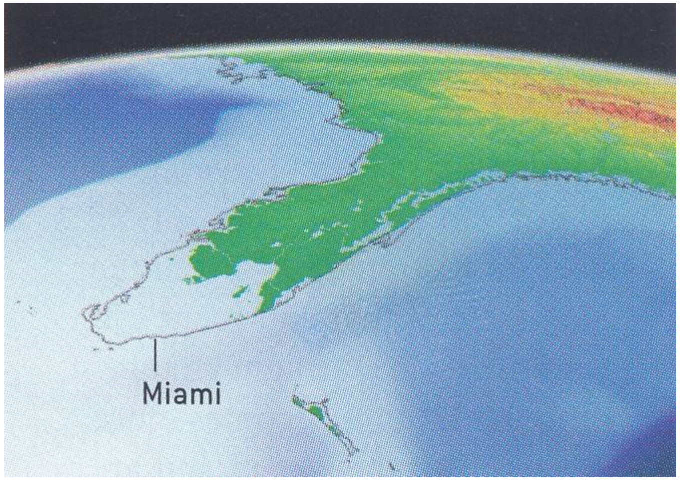
Steven Chu

Environmental and Economic Challenges



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**

Opportunities for Low Grade Heat Harvesting Using Thermoelectrics

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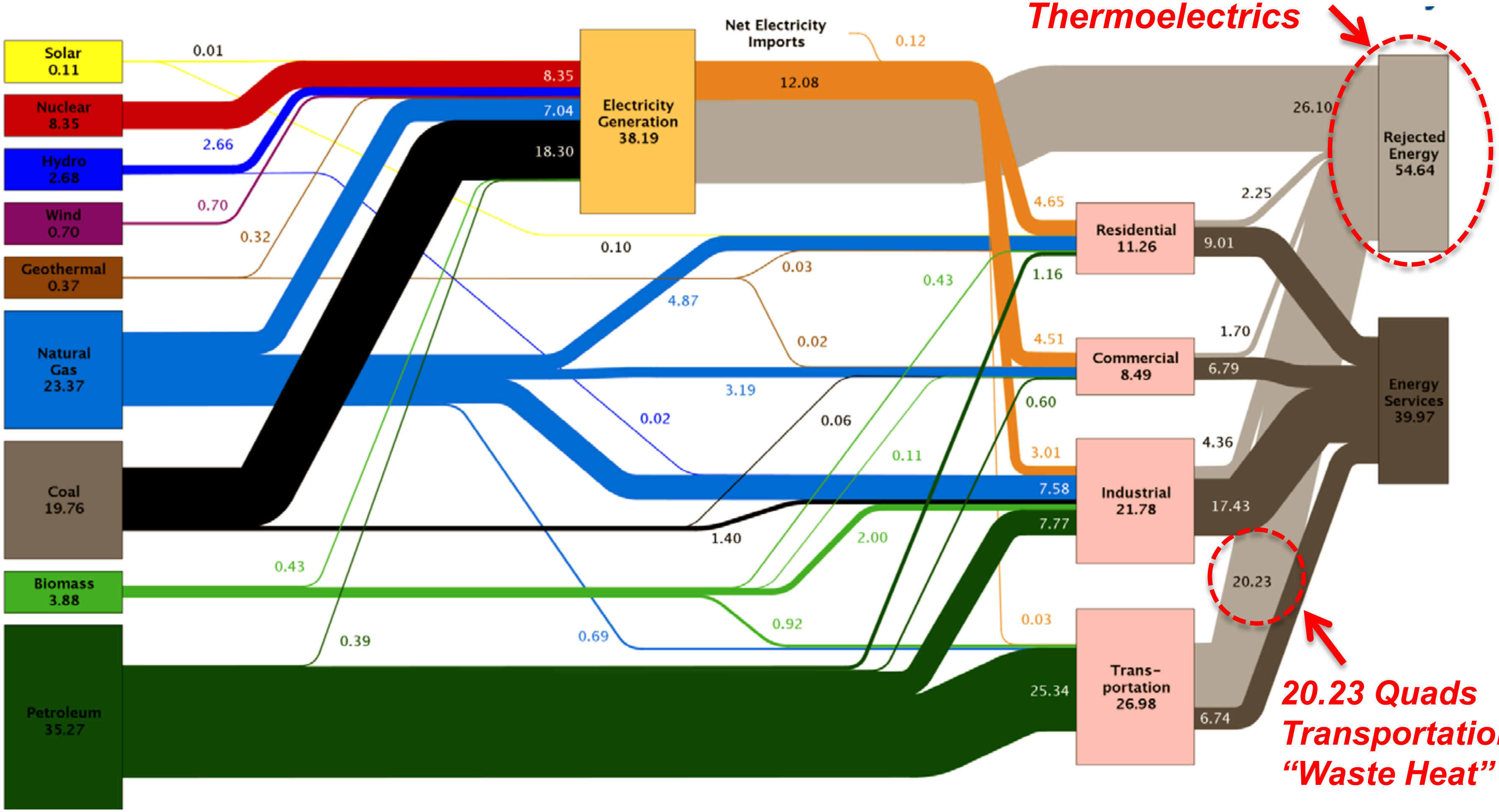
Estimated U.S. Energy Use in 2009 ~ 94.6 Quads

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



20.23 Quads Transportation "Waste Heat"

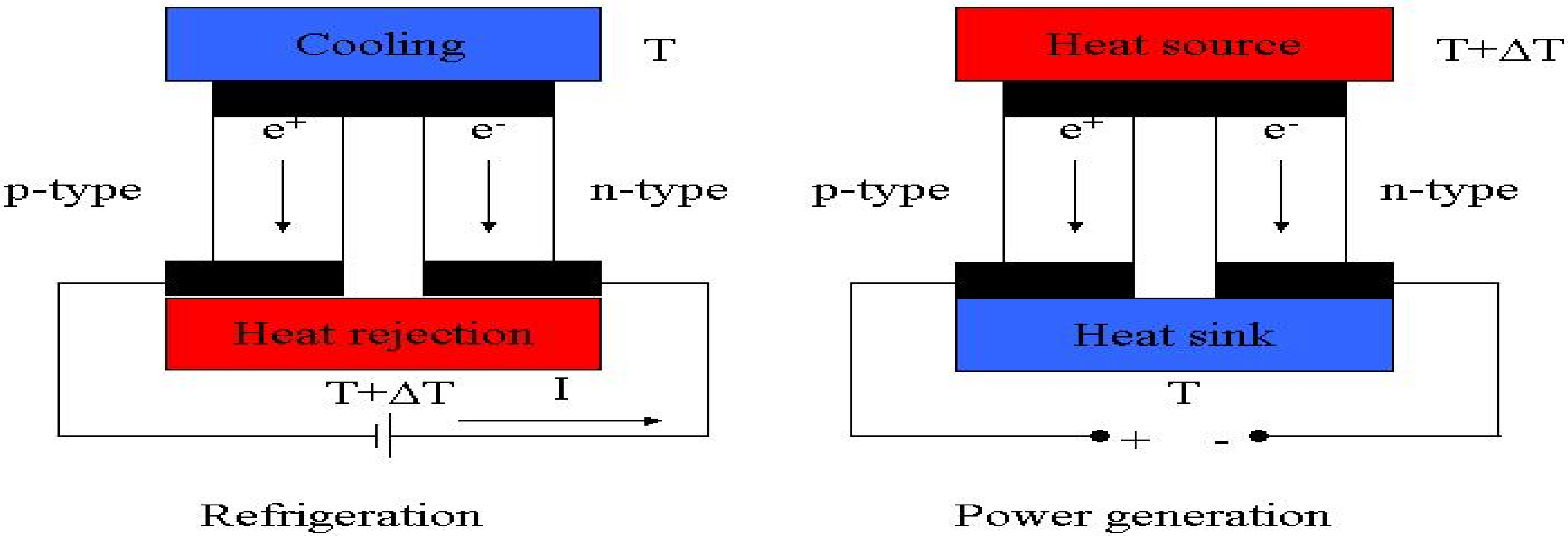
Source: LLNL 2010, data from DOE/EIA -0384 (2009), August 2010.

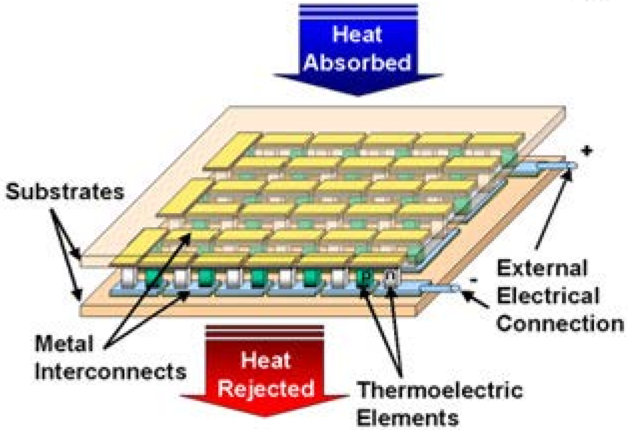
Lawrence Livermore National Laboratory

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?

Thermoelectric Generator and HVAC





Household Thermoelectric Cooling Devices

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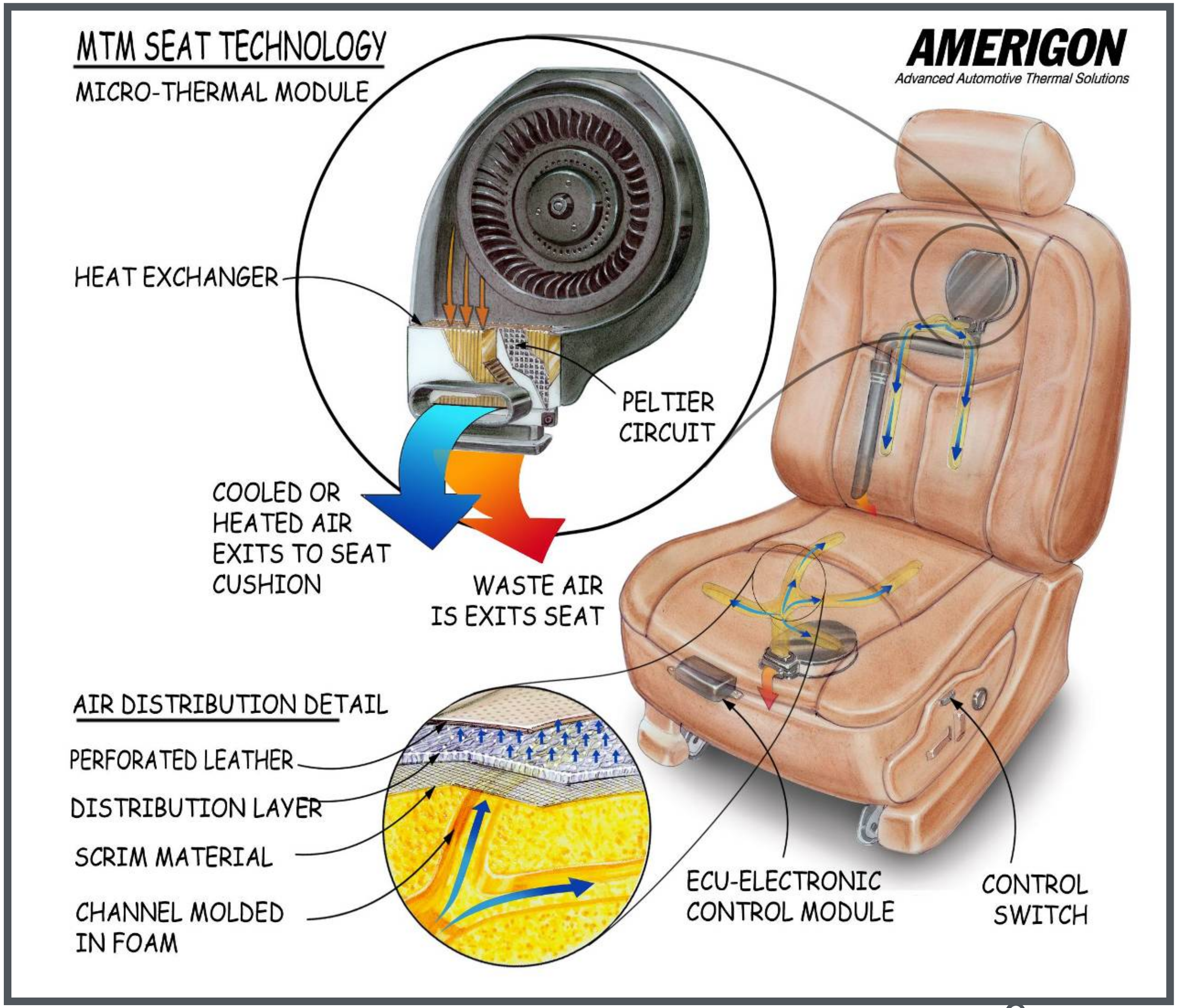
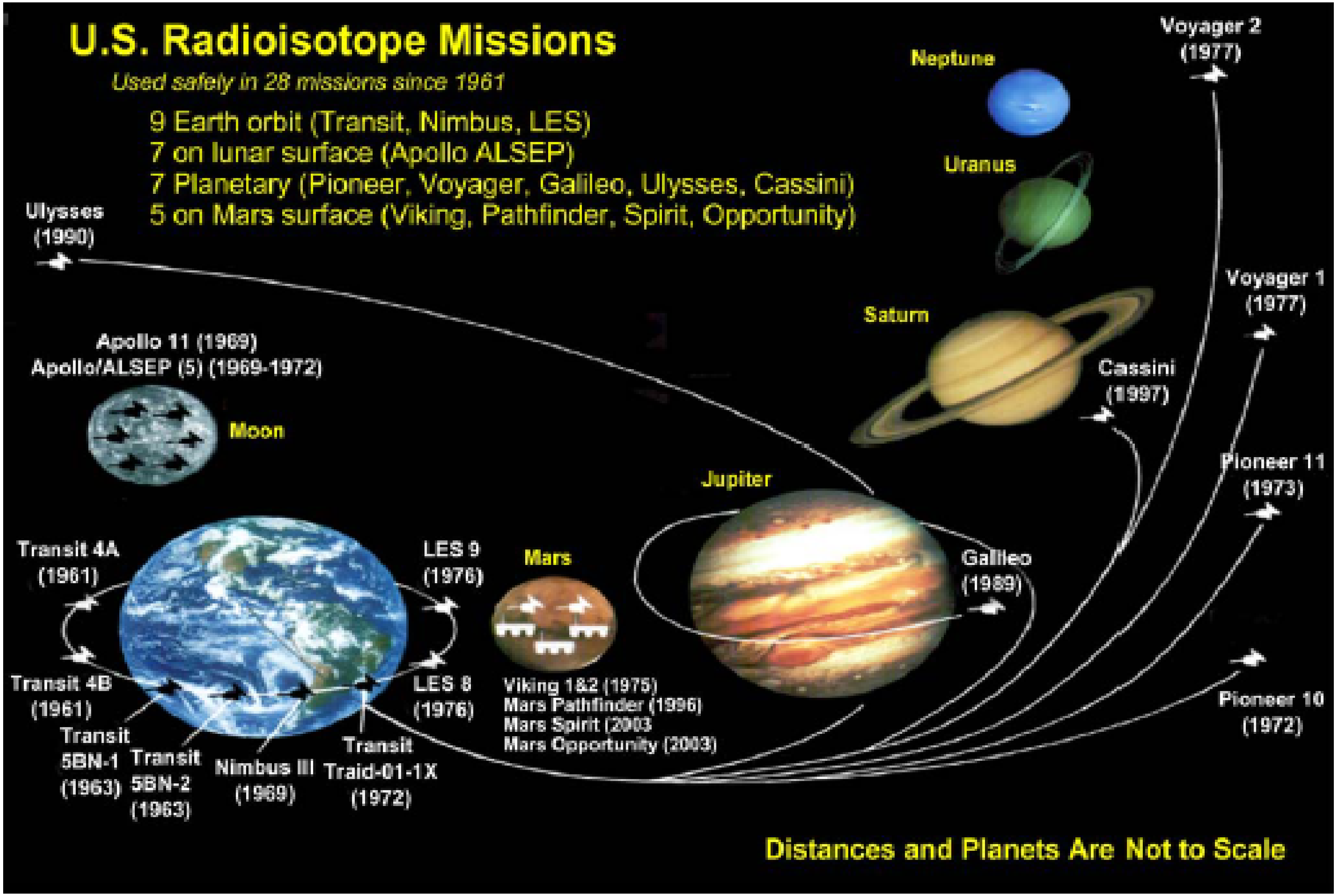
Climate Control Seat™



U.S. Spacecraft using Radioisotope Thermoelectric Power Generators



MARS Science Lab - *Curiosity*

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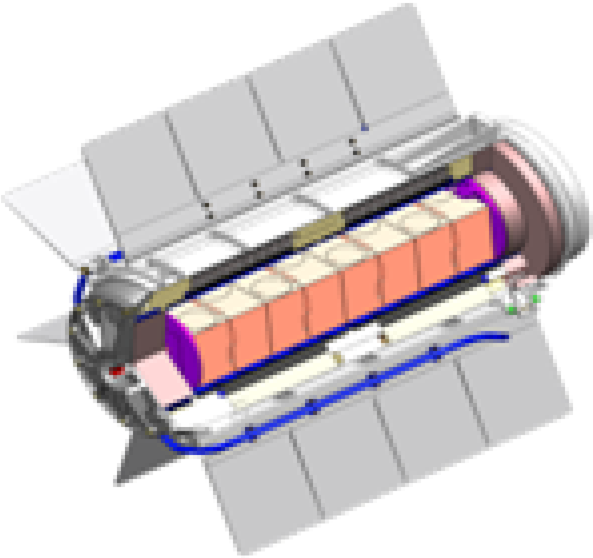
Multi-Mission RTG Overview

- **Ability to operate in vacuum and planetary atmospheres**
  - 23-36 V DC capability, series-parallel circuitry
- **17 years lifetime requirement**
  - Up to 3 years of storage and up to 14 years of operation
- **Ability to withstand high mechanical loads**
  - ~ 0.3 g^2/Hz (random vibrations)
  - Up to 6000 g (pyrotechnic shock)



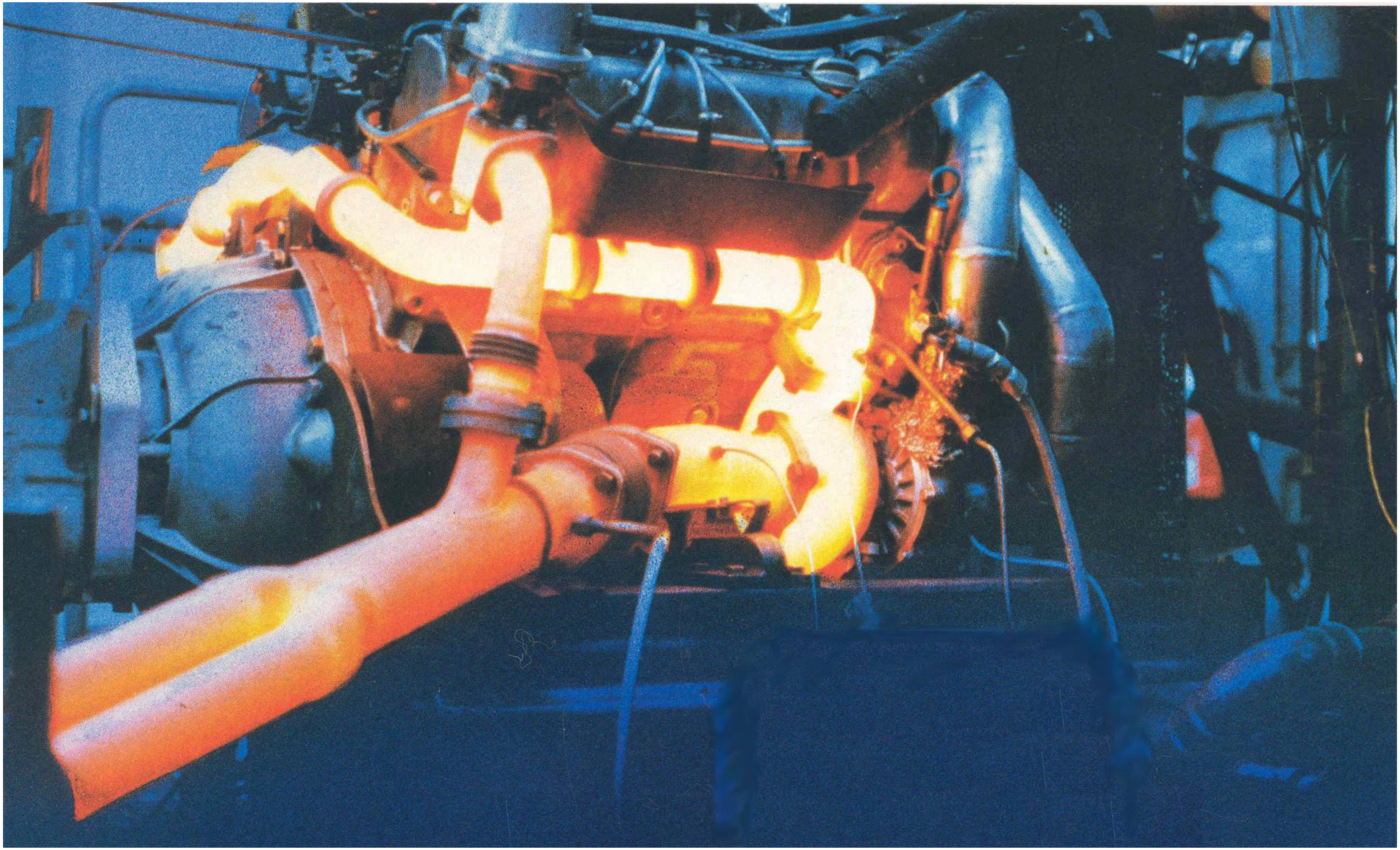
Beginning of Life Performance
~ 125 W
~ 2.8 W/kg

768 <PbTe + TAGS/PbSnTe> couples

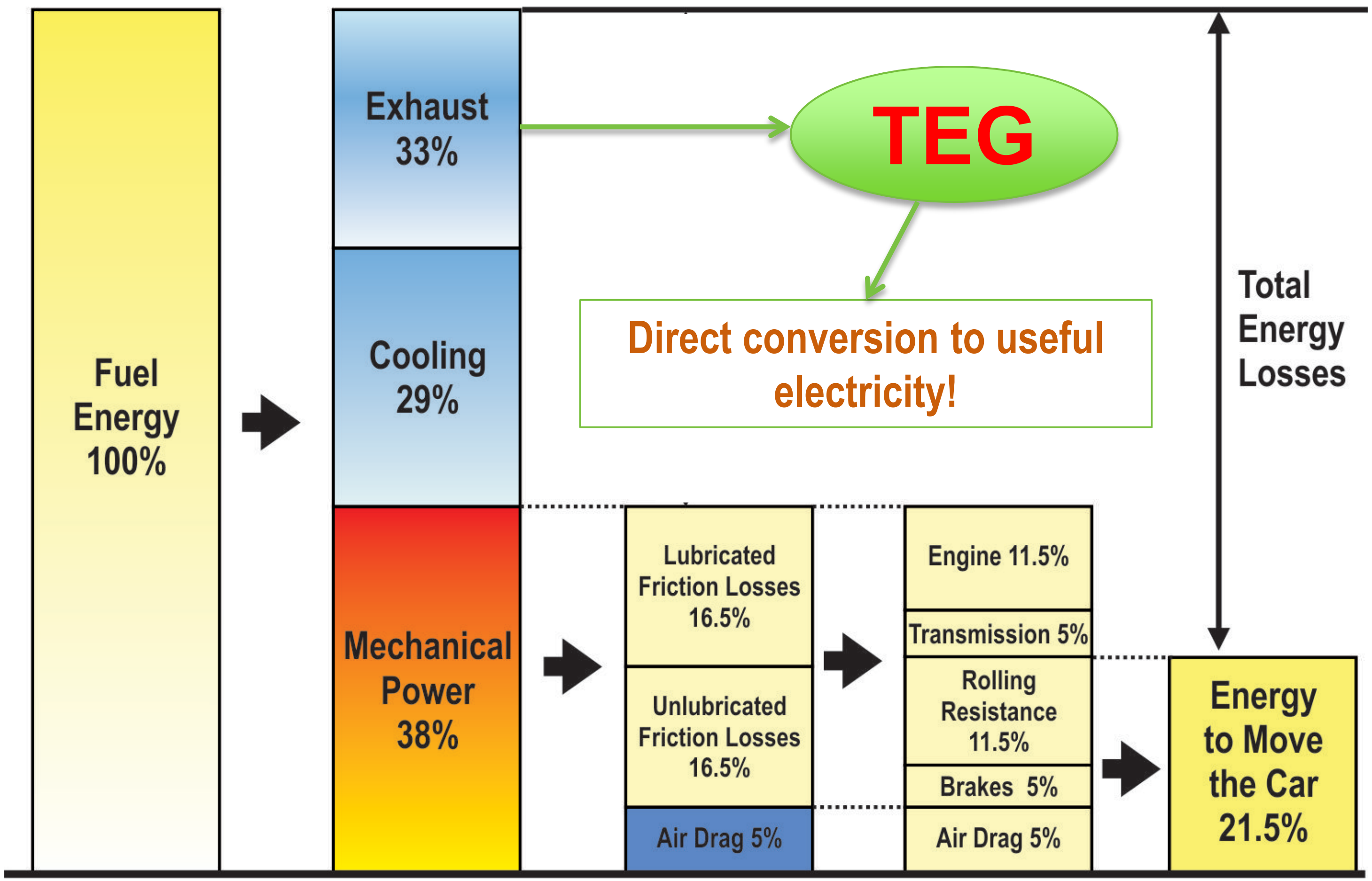
MMRTG Performance modeled by MSL using JPL software tool
Tables are accessed through:

- *Age of Radioisotope Heat Source*
- *Age of Generator since fueling*
- *Generator Fin Root Temperature*

Automobile Engine Waste Heat Energy



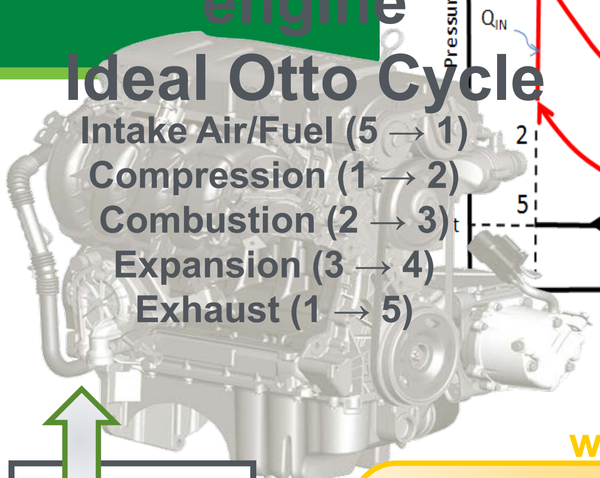
Great Opportunity for Vehicular Thermoelectric Generator (TEG)

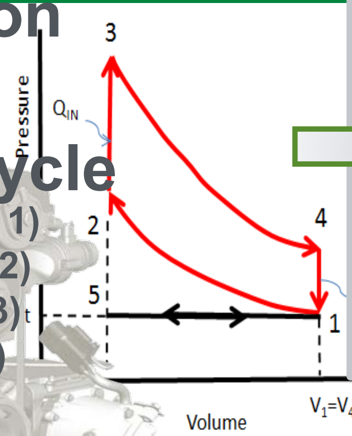


Combustion engine

Ideal Otto Cycle

Intake Air/Fuel (5 → 1)
Compression (1 → 2)
Combustion (2 → 3)
Expansion (3 → 4)
Exhaust (1 → 5)





Maximum Work = $Q_{IN} - Q_{OUT} = Q_{IN} \times$ Ideal Effciciency = $Q_{IN} \times \eta$

$$\eta = \left(\frac{Q_{IN} - Q_{OUT}}{Q_{IN}}\right) = \frac{c_v(T_3 - T_2) - c_v(T_1 - T_4)}{c_v(T_3 - T_2)} = 1 - \frac{(T_1 - T_4)}{(T_3 - T_2)}$$

$$\eta = 1 - \left(\frac{V_2}{V_1}\right)^{\gamma-1} = 1 - \left(\frac{1}{r}\right)^{\gamma-1}$$

r= compression ratio (e.g., r = 8)

$\gamma = \frac{c_p}{c_v}$ = specific heat ratio; (e.g., γ ~ 1.4) **η = 56%**

Heat loss to radiator: ~30% of fuel energy lost (~ 70% is used)

Engine efficiency = $\eta \times 70\%$ = ~40% of fuel energy does

waste heat

Exhaust gas: $(1 - \eta) \times 70\%$ = ~30% of fuel energy in

Decoupled systems

Path 1 OR Path 2

T_H

$T_{catlytic\ converter}$

$T_{exhaust\ pipe}$

$T_{muffler}$

Without waste heat recovery: thermodynamic heat engine with zero efficiency (no useful work)

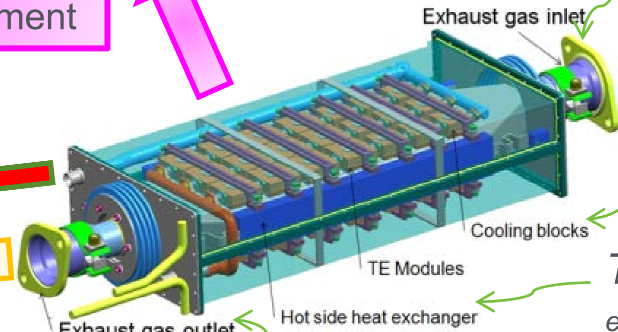
Thermoelectric Generator: heat engine with efficiency:

$$\eta_{TE} = \left(1 - \frac{T_{Coolant}}{T_{Heat\_Exchanger}}\right) \times f(ZT) = 15\%$$

TEG = $(1 - \eta) \times 70\% \times 15\%$ = ~4.6 % of fuel energy

4.6 % fuel savings = 5% FE improvement

Heat dumped to radiator



T_{in}

$T_{Coolant}$

$T_{Heat\_Exchanger}$

T_{out}

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}

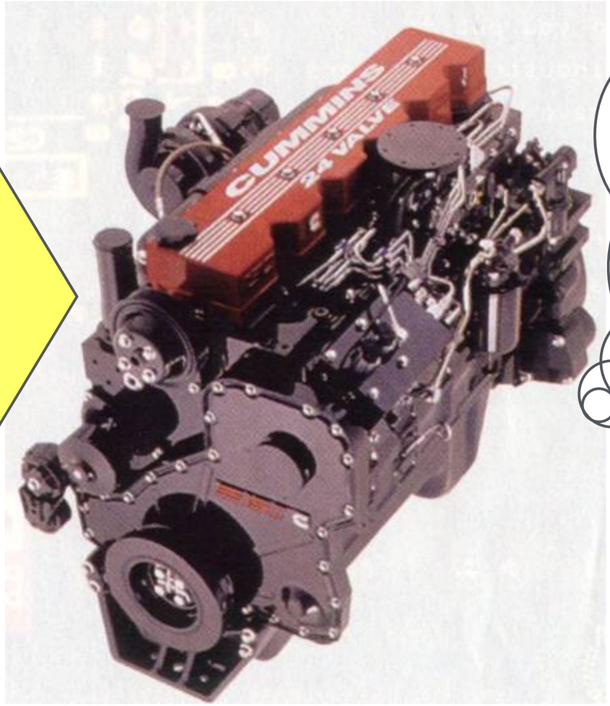
Diesel $C_{18}H_{30}$

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 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
- White House announced an agreement with 13 major automakers for car and light truck fuel economy average 54.5 mpg by 2025

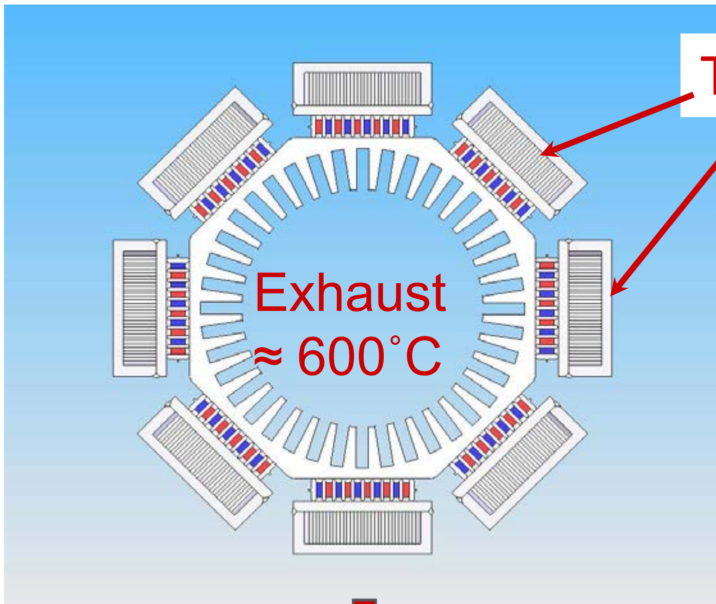
Agreed upon by Ford, GM, Chrysler, BMW, Honda, Hyundai, Jaguar/Land Rover, Kia, Mazda, Mitsubishi, Nissan, Toyota and Volvo

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 ($\Delta V/\Delta T$)

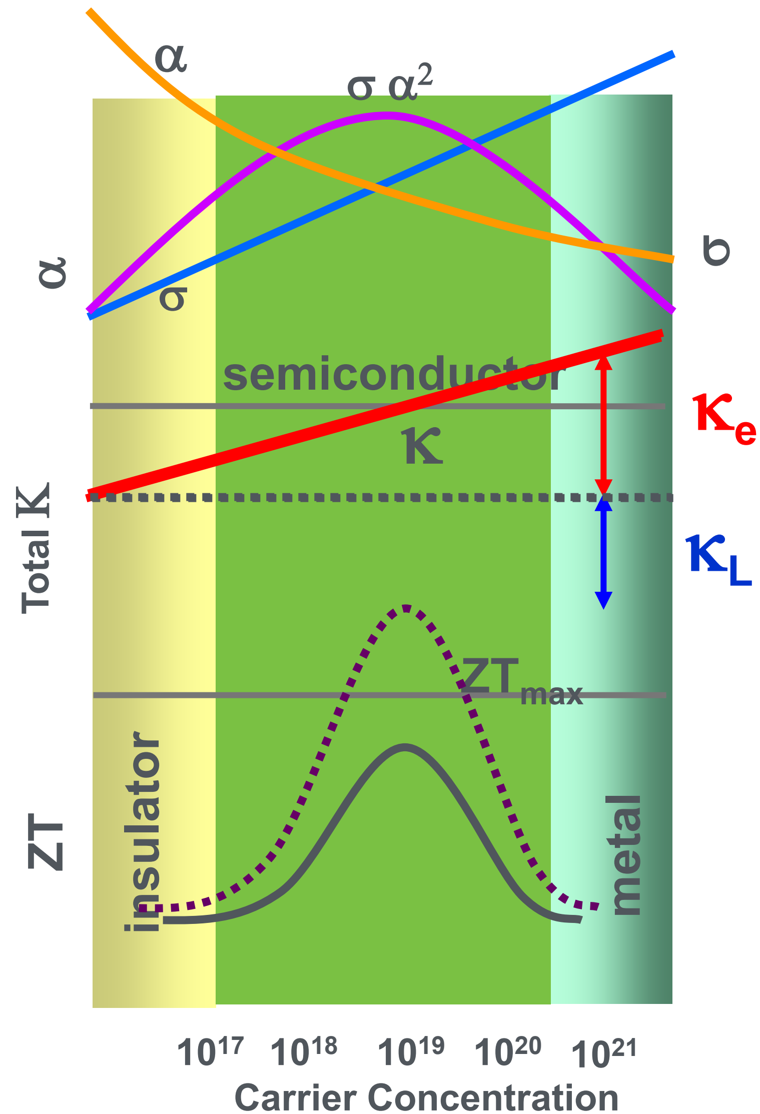
$$ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \cdot T$$

Total thermal conductivity

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

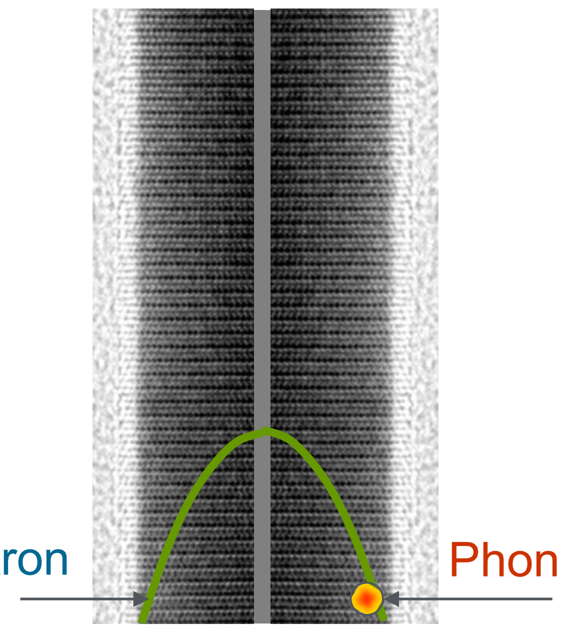
$\sigma = 1/\rho =$ **electrical conductivity**

$\rho =$ **electrical resistivity**

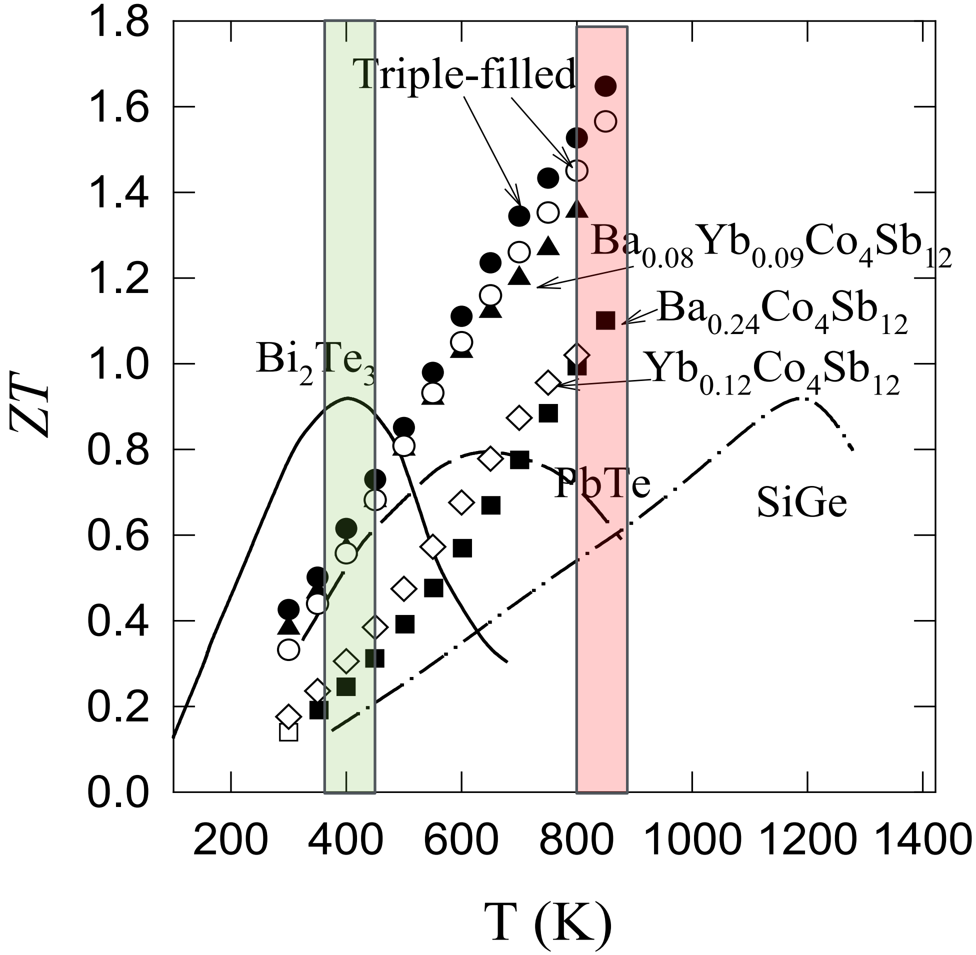


Interfaces that Scatter Phonons but not Electrons

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

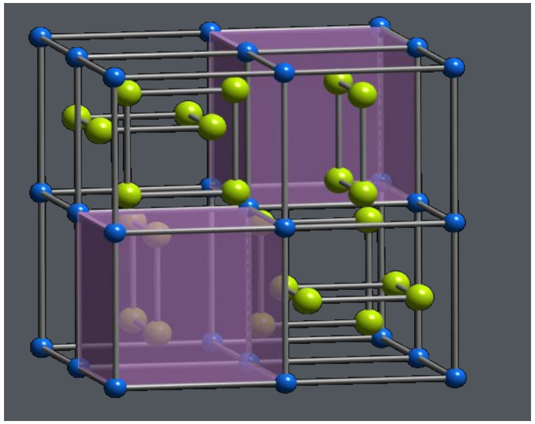


Highest ZT Achieved with Triple-filled Skutterudites (GM and U of Michigan)



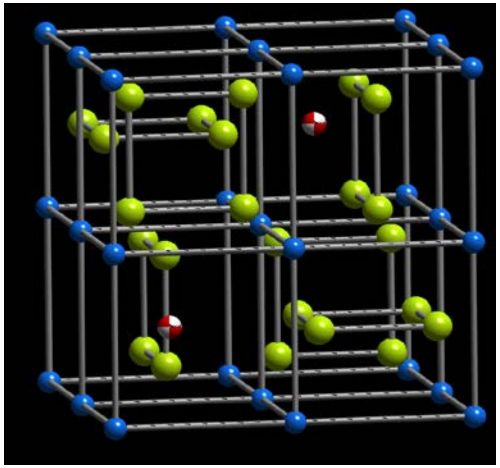
1. X. Shi, et al. Appl. Phys. Lett. 92, 182101 (2008)
2. X. Shi, et al., submitted (2009)

Crystal Structure of Skutterudites



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

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

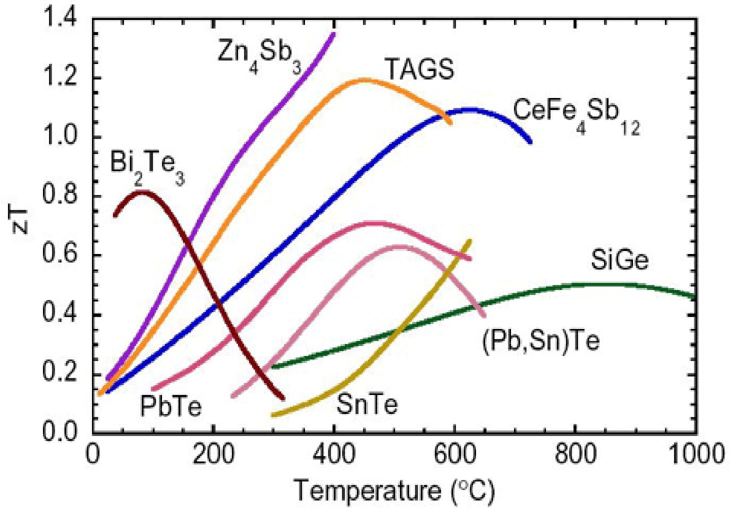


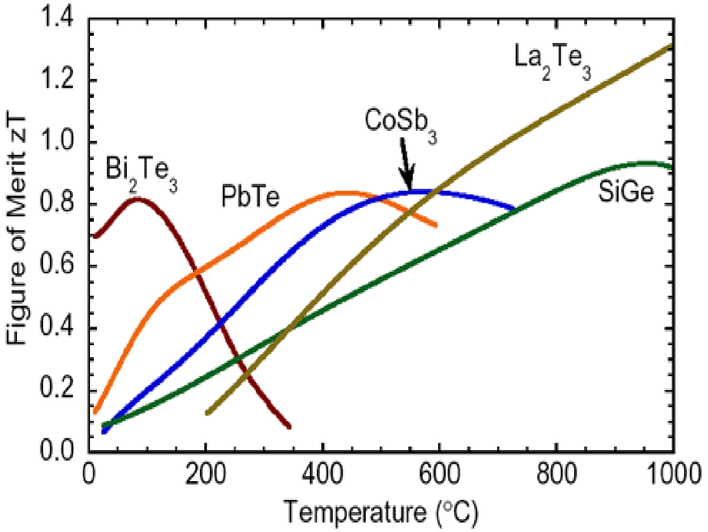
R_xCoSb_3

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]

Current TE Materials



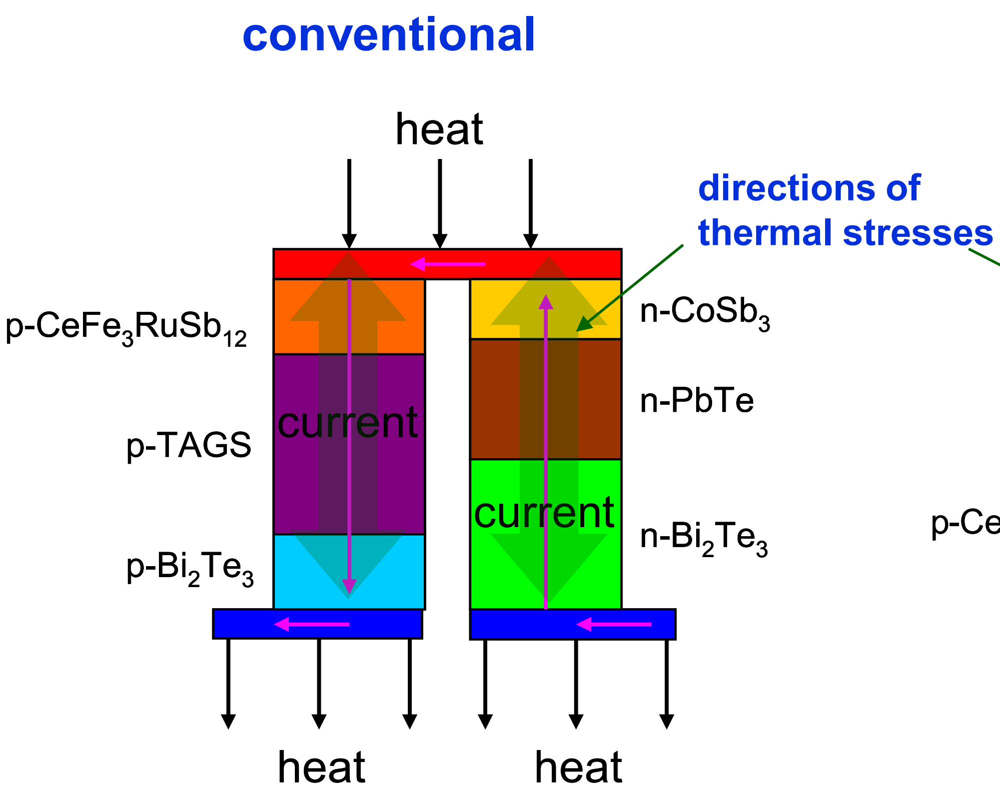


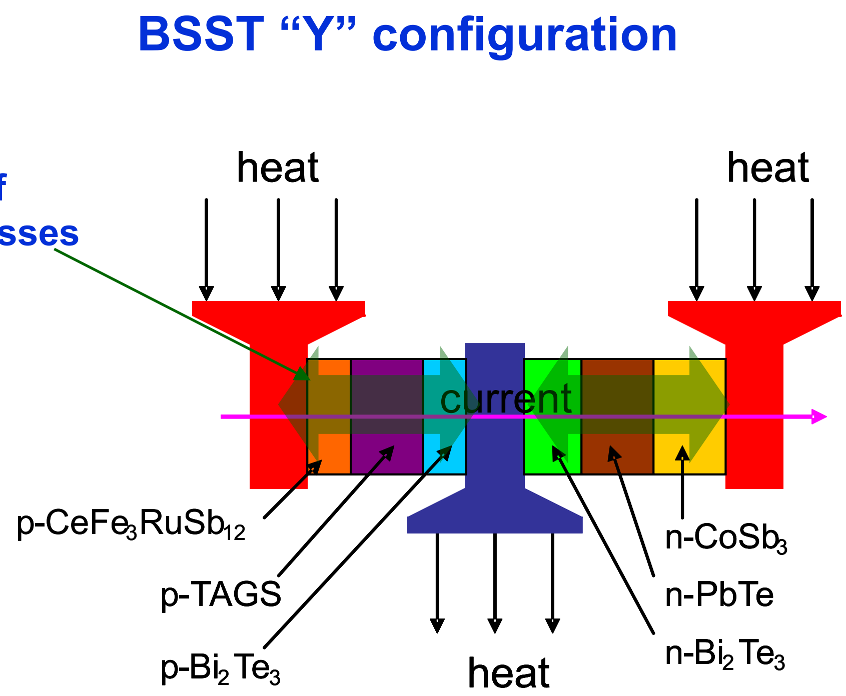
P-type TE material

N-type TE material

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

Segmented Thermoelectric Couple Configurations





Thermal Mismatch Stresses can Separate Material Layers

Thermal Mismatch Stresses are Significantly Reduced

Increase in the Figure of Merit of Thermoelectric Materials

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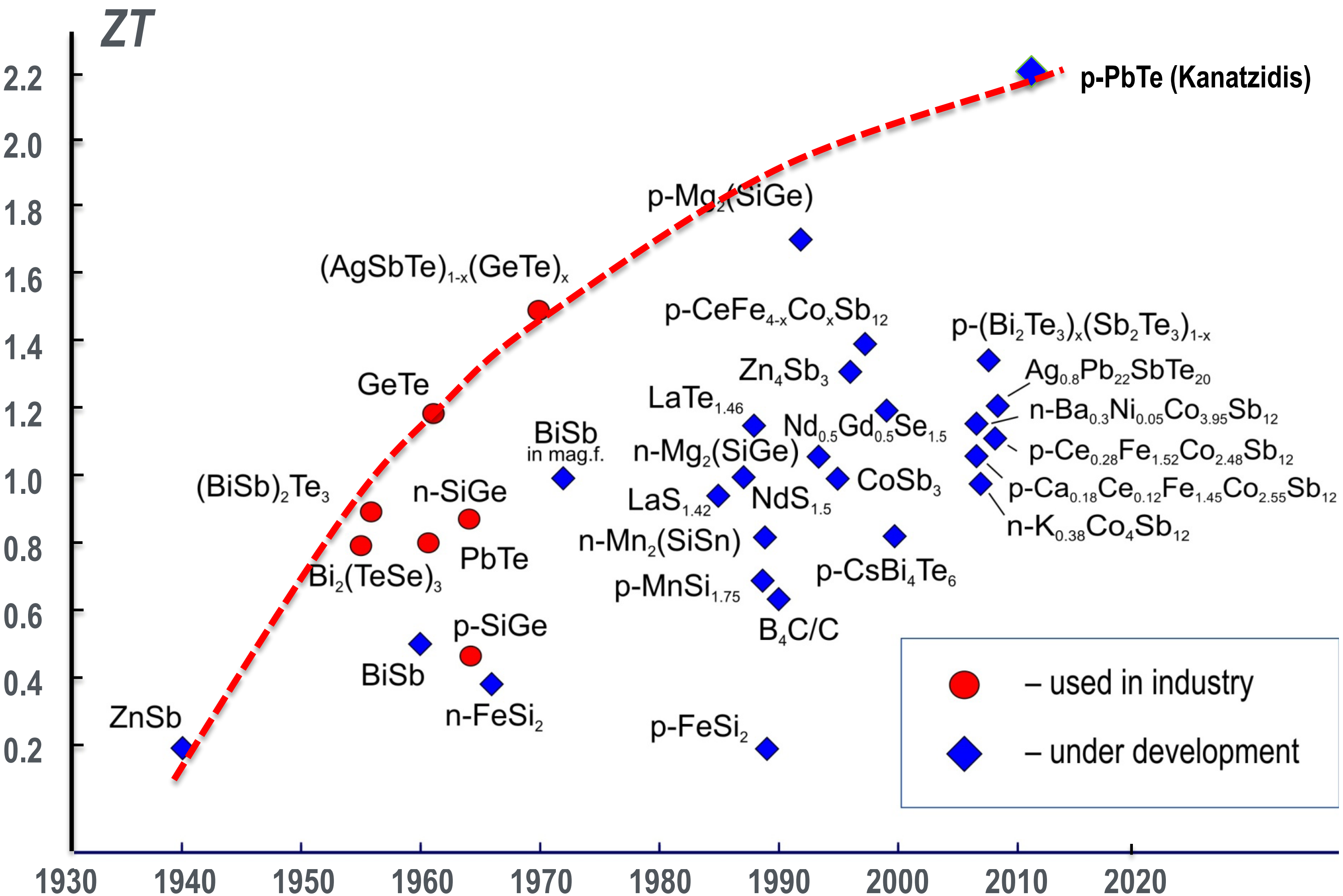
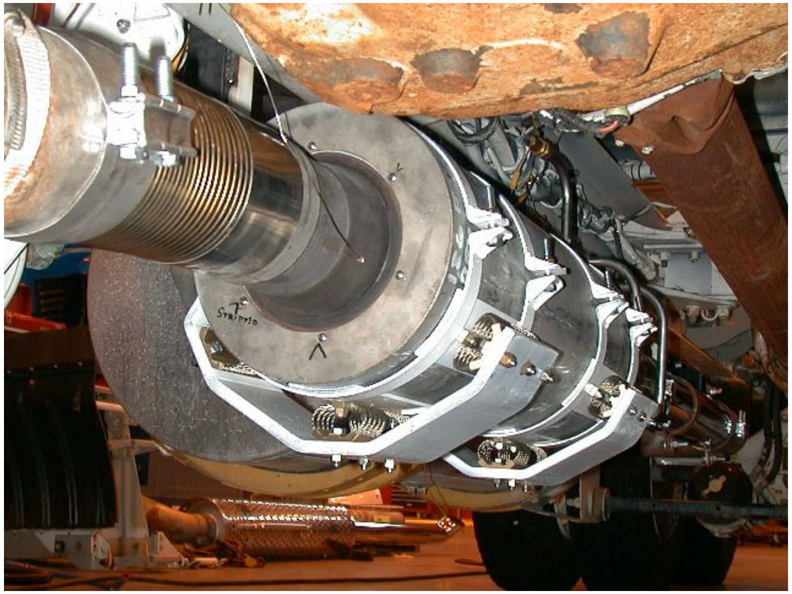
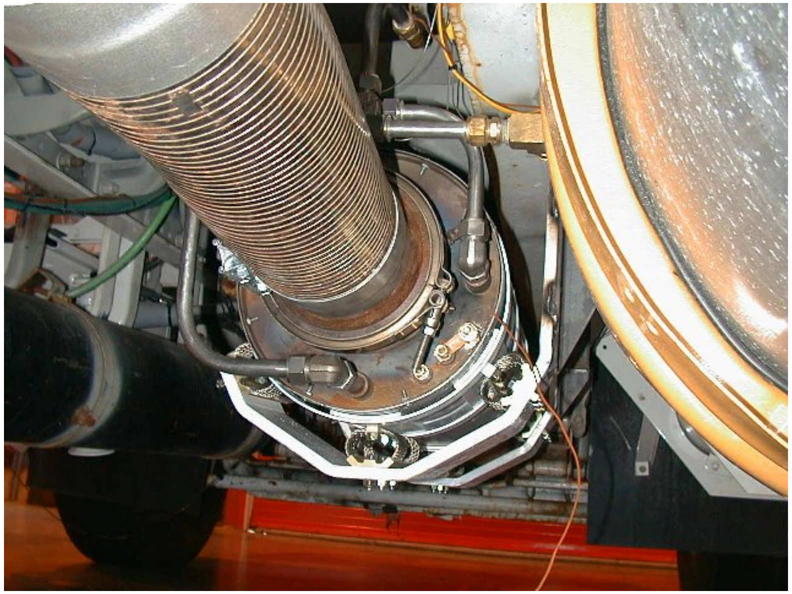


First Thermoelectric Generator Test on Vehicle (DOE/VT, Hi-Z/Paccar, 1994)



Front View



Rear View

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

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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/NETL Vehicular Thermoelectric Generator Projects

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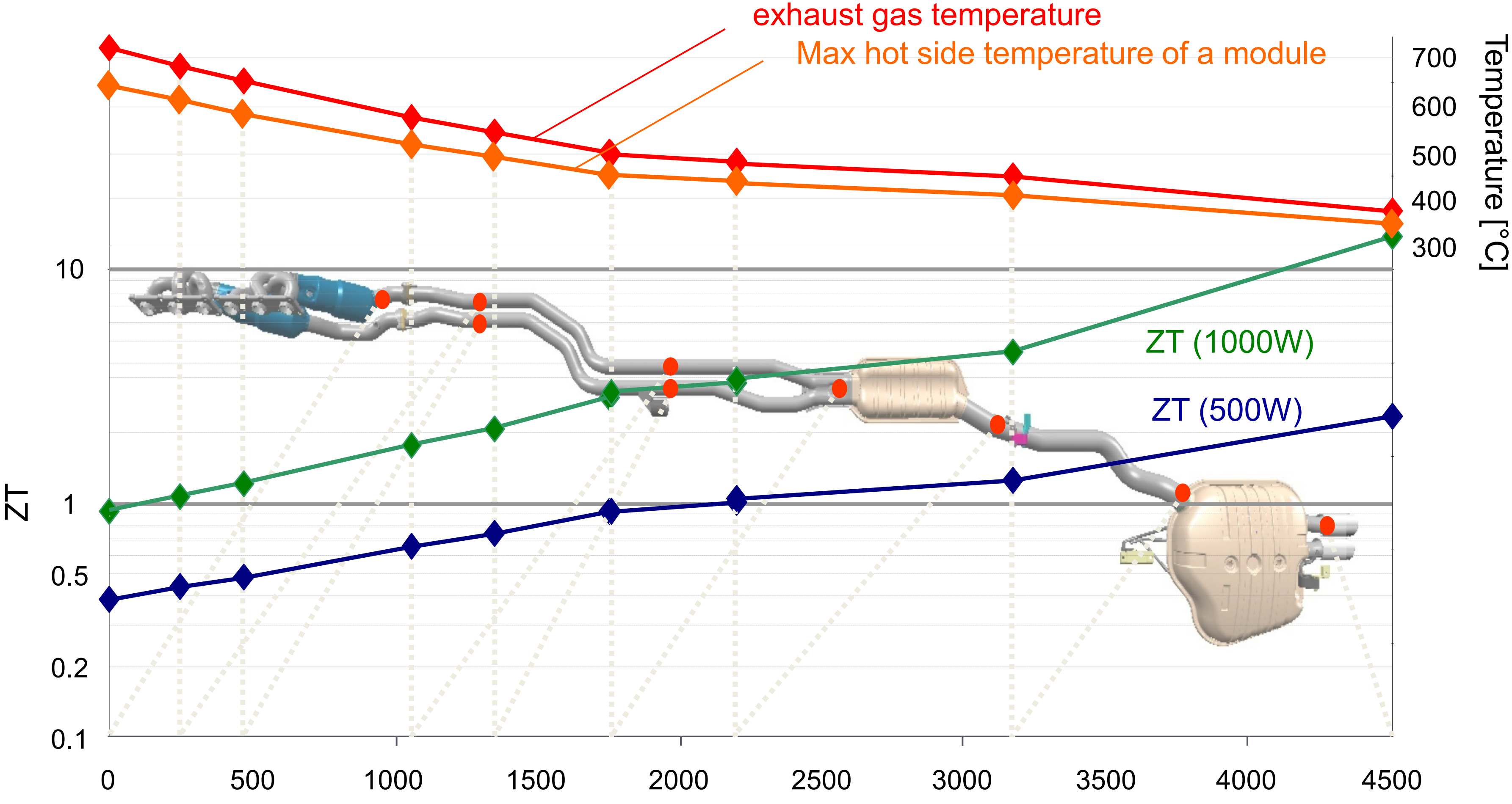
Awardees	Team Members
General Motors and General Electric	University of Michigan, University of South Florida, Oak Ridge National Laboratory, Marlow Industries
BSST, LLC	Visteon, BMW-NA, Ford, ZT Plus, Faurecia
Michigan State University	NASA Jet Propulsion Laboratory, Cummins Engine Company, Tellurex,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

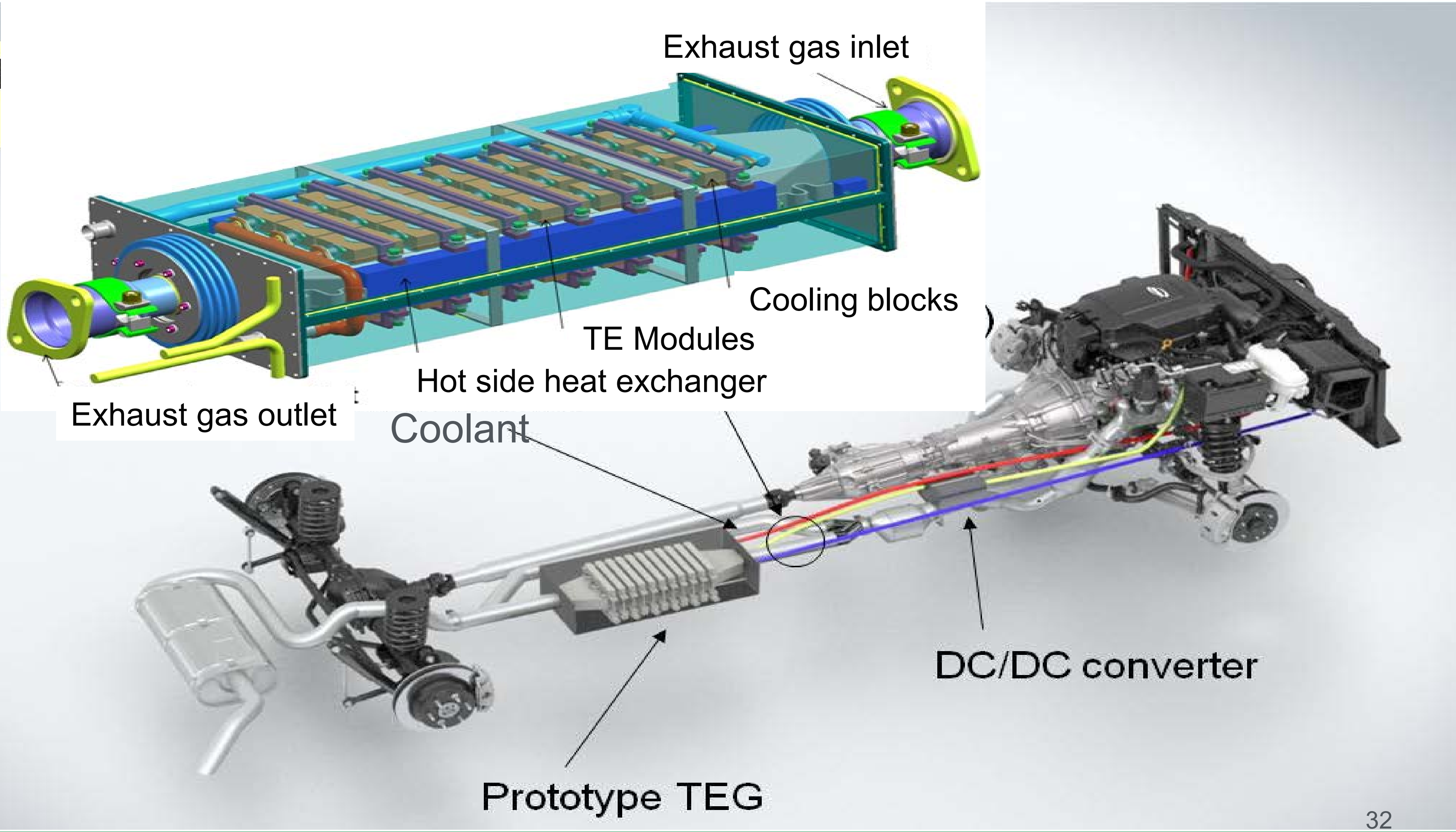
SI Gasoline Engine Exhaust Temperature Profile w/ Potential TEG Locations (BMW)



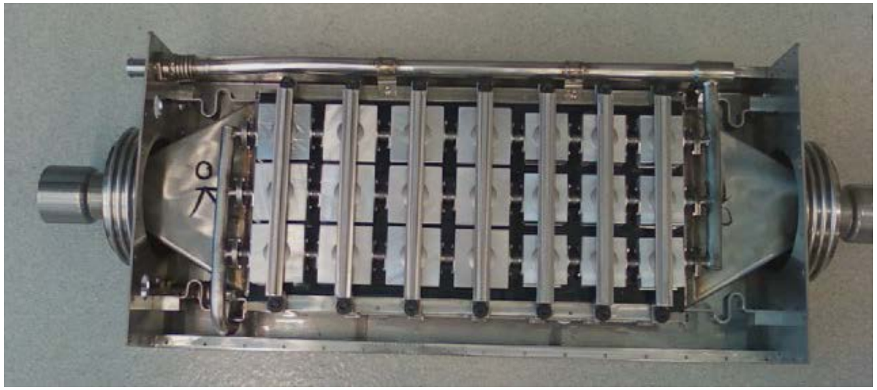
BMW 530iA at 130 km/h, Exhaust gas back pressure limited to 30mbar at 130km/h

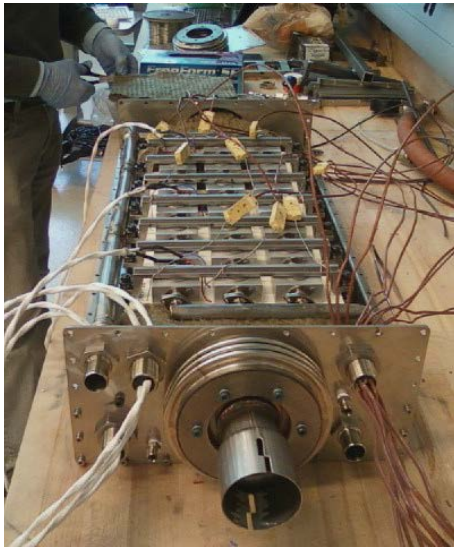
Slide courtesy of BMW

GM Prototype TEG Installation in a Chevy Suburban Chassis

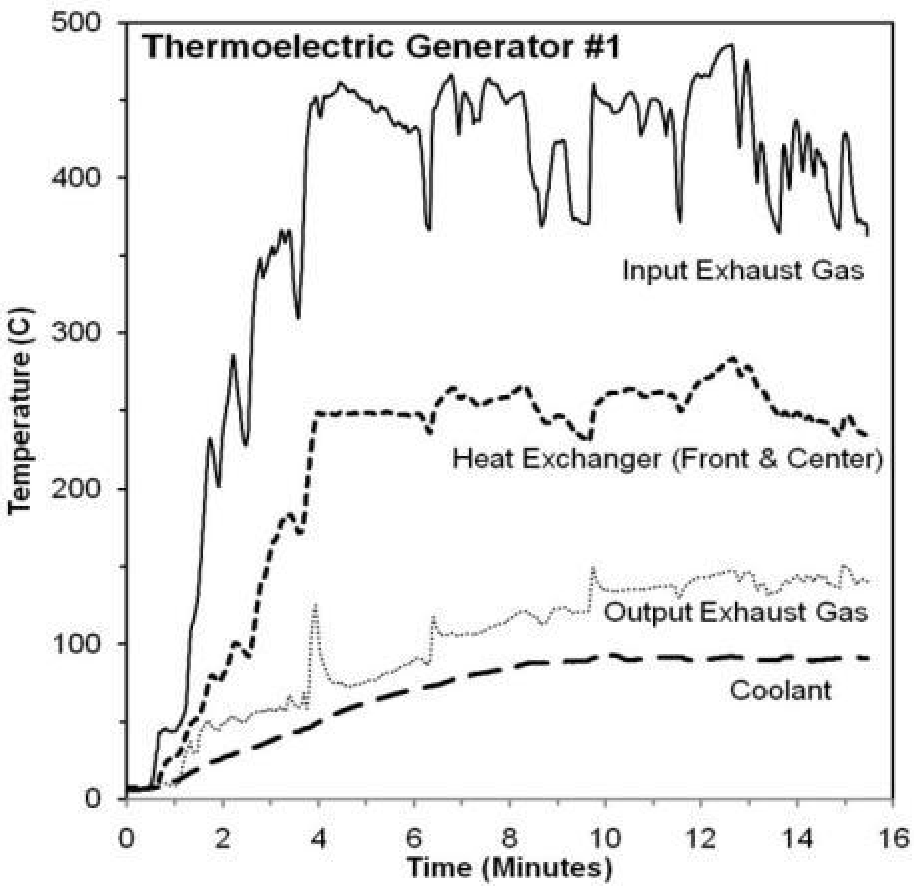


GM Prototype TEG Fabrication





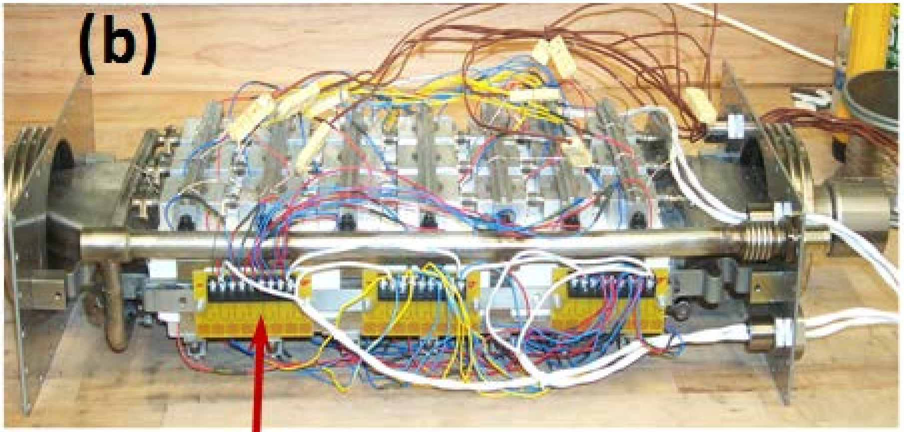
TEG #1
3 Bi-Te modules



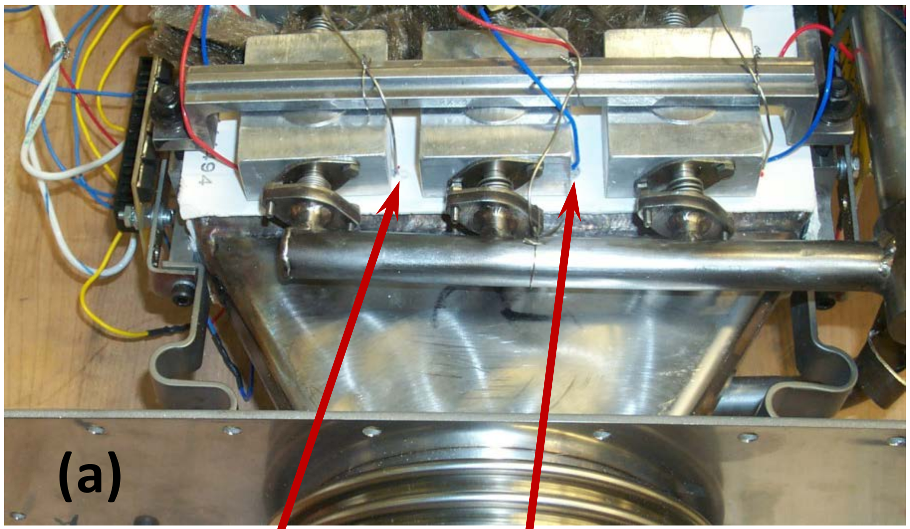
Bypass valve

Drive shaft

TEG #2
42 Bi-Te modules

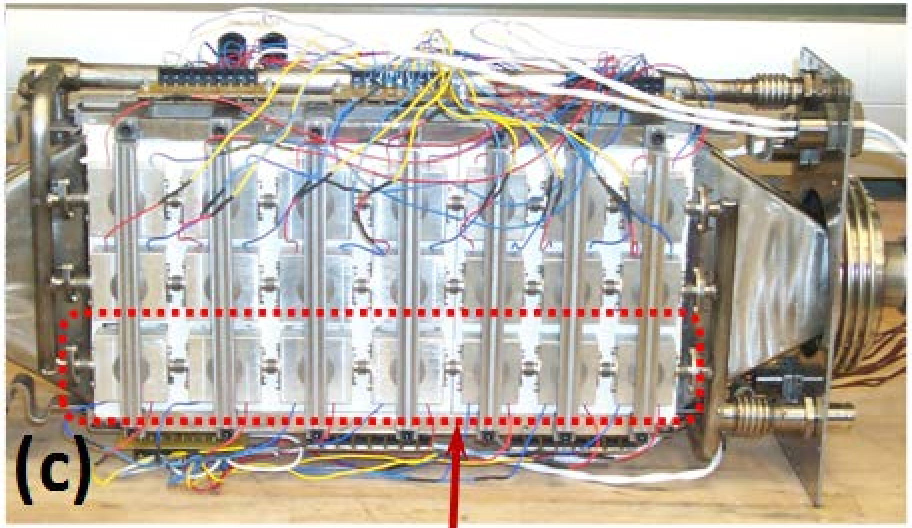


Circuit board for TE module connections



Front Left thermocouple on heat exchanger

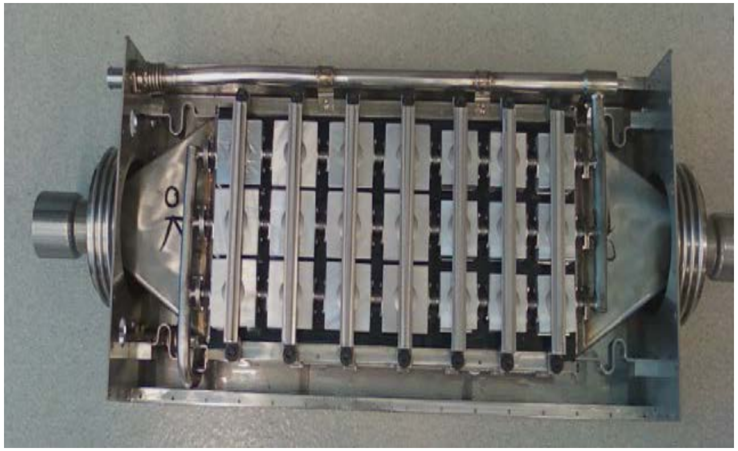
Front Center thermocouple on hot side of Bi-Te TE module

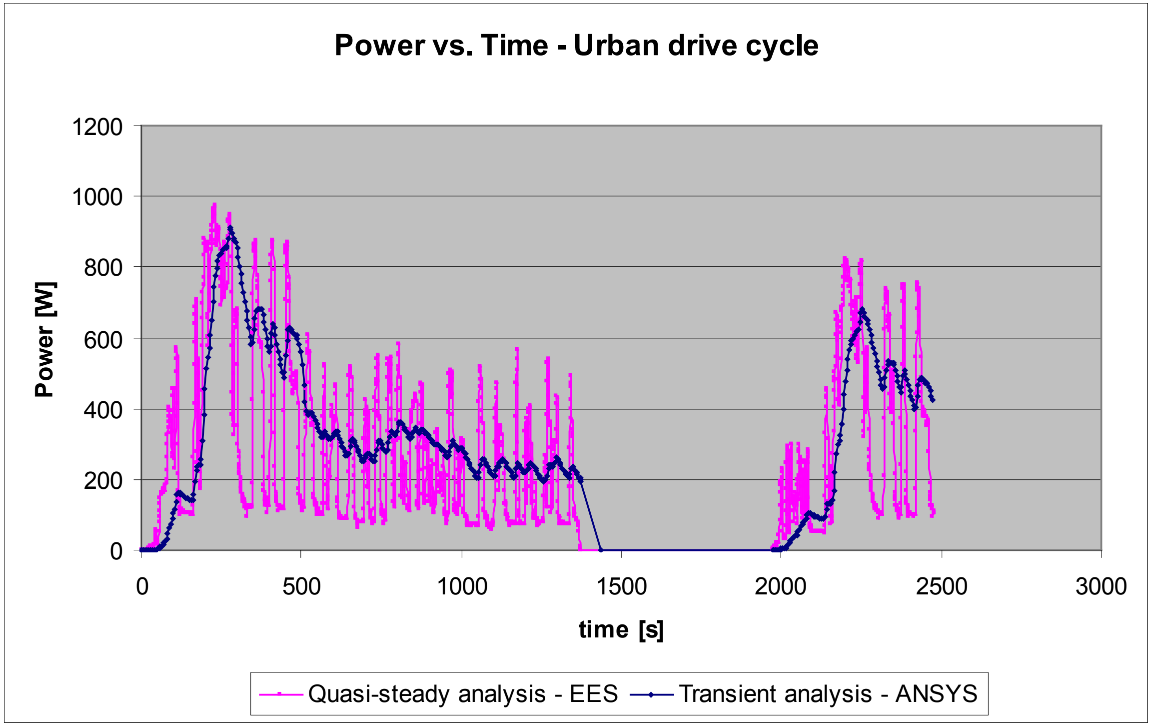


Seven TE module series


GM-USDOE Thermoelectric Generator Prototype &
G.P. Meisner, J.R. Salvador, J. Yang, M.G. Reynolds, J.D. Cowgill*, J.M. Stanek*
GM Global Research & Development and *GM Global Powertrain
Supported by the U. S. Department of Energy Vehicle Technologies
GM
ENERGY

GM TEG Performance in Chevy Suburban

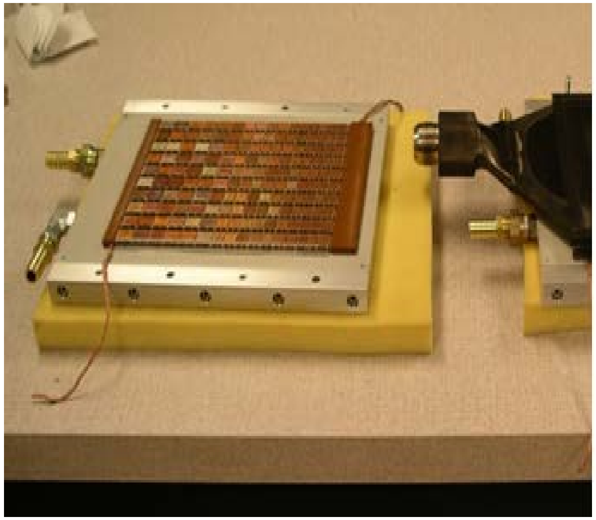


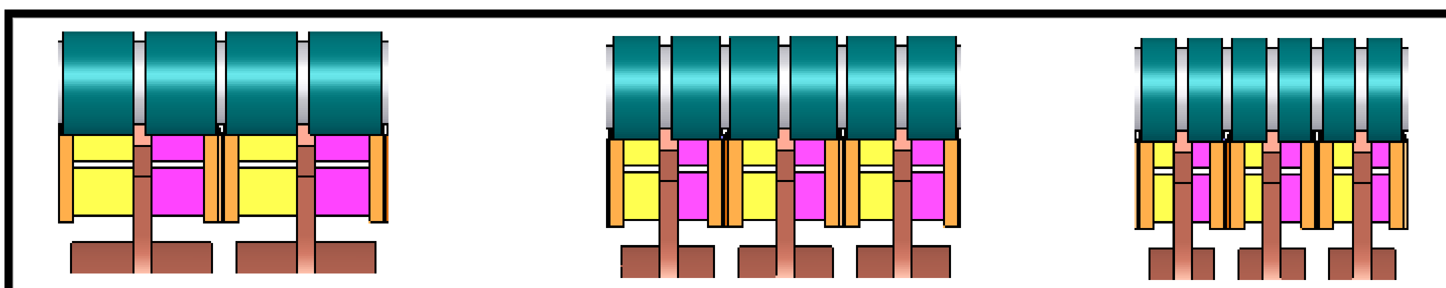


- ~ 1 mpg (~ 5 %) fuel economy improvement on FTP Driving Cycle
  - > 350 Watts City
  - > 600 Watts Highway

TEG #3
Skutterudite + Bi-Te modules

BSST Thermoelectric Generator (TEG) Design Iteration for BMW and Ford Autos



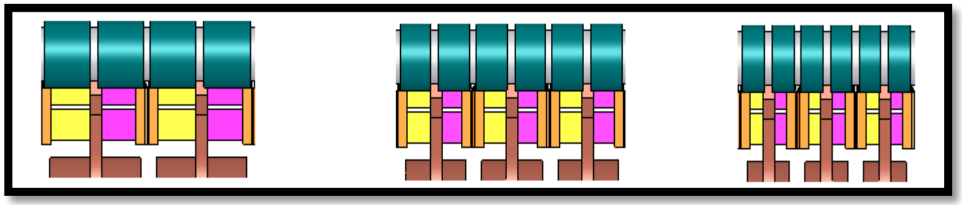


Inlet Region
Relatively long segmented TE elements

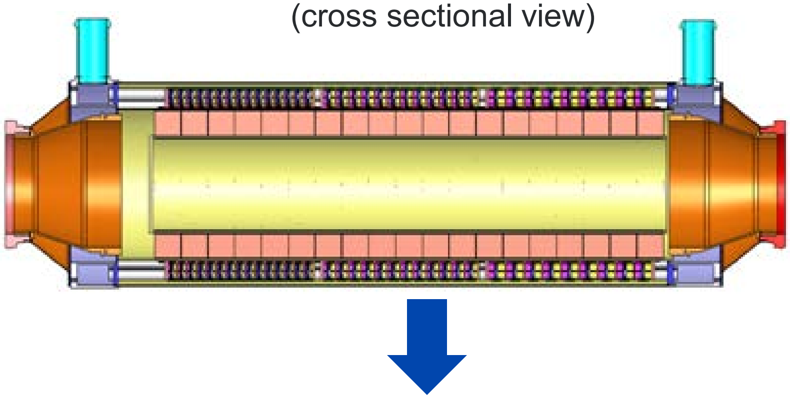
Middle Region
Mid sized segmented TE elements

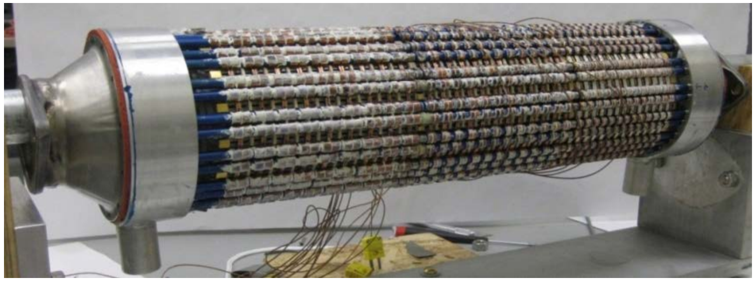
Exit Region
Short, single material TE elements

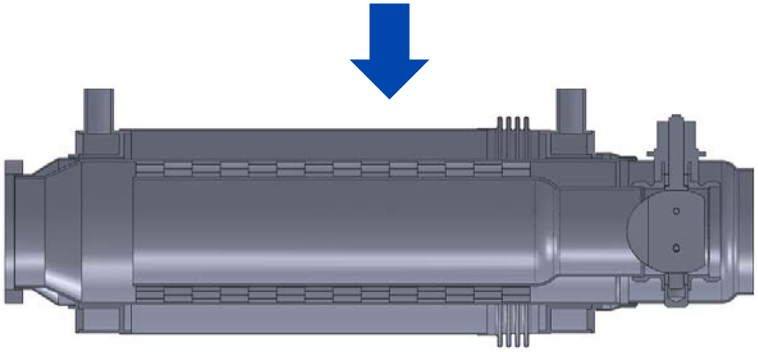
TEG for Ford Lincoln MKT and BMW X6



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

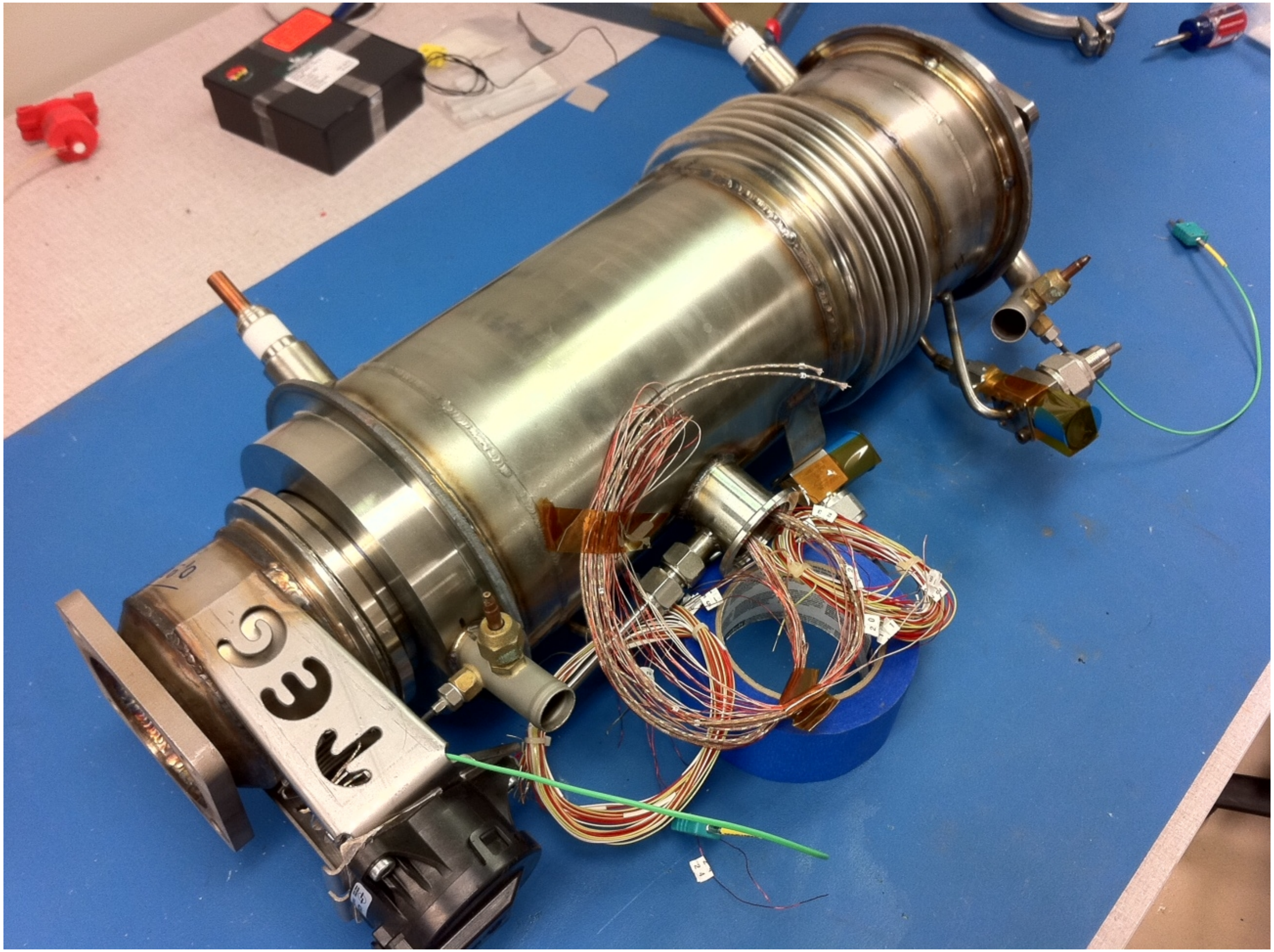






- Designed for 500 watt output driving at 75 mph (120 kph)
- Weights 22.4 lbs (10.2 kg)
- 5 percent improvement in fuel economy on-highway
- Improved performance anticipated with technologies in development

TEG for Ford Lincoln MKT, BMW X6



faurecia
Ford
AMERIGON
ThermoElectricGeneration
Converting Exhaust Heat into Power


NOTICE

TEG & Exhaust System in Lincoln MKT

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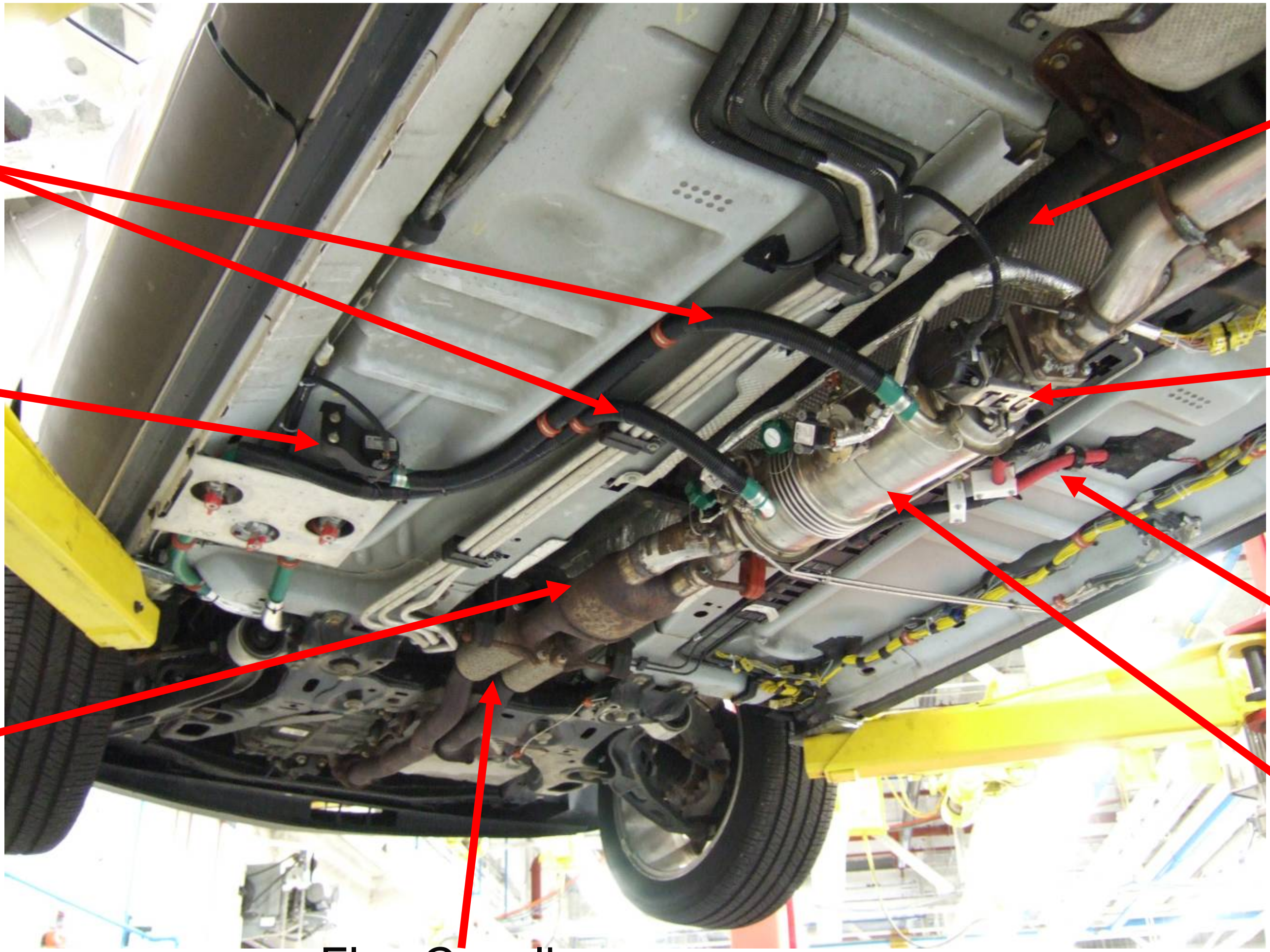


Coolant Lines

Electric Pump

Underfloor Catalyst

Flex Couplings

Driveshaft

Bypass Valve

Electrical Connections

TEG

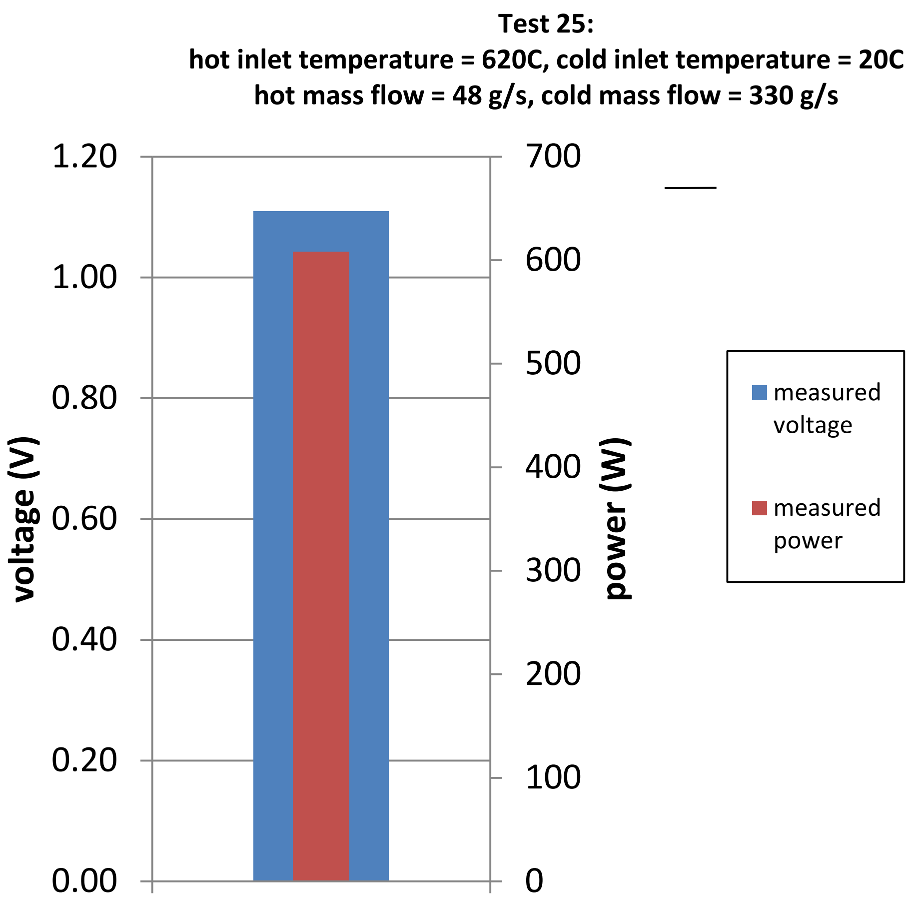
Amerigon Automotive TEG Program

TEG bench tested July, 2011

Peak performance was 608 watts @ 620^{0}C inlet air temperature with 20^{o}C cold side temperature

TEG Being tested in a BMW X6 in Munich

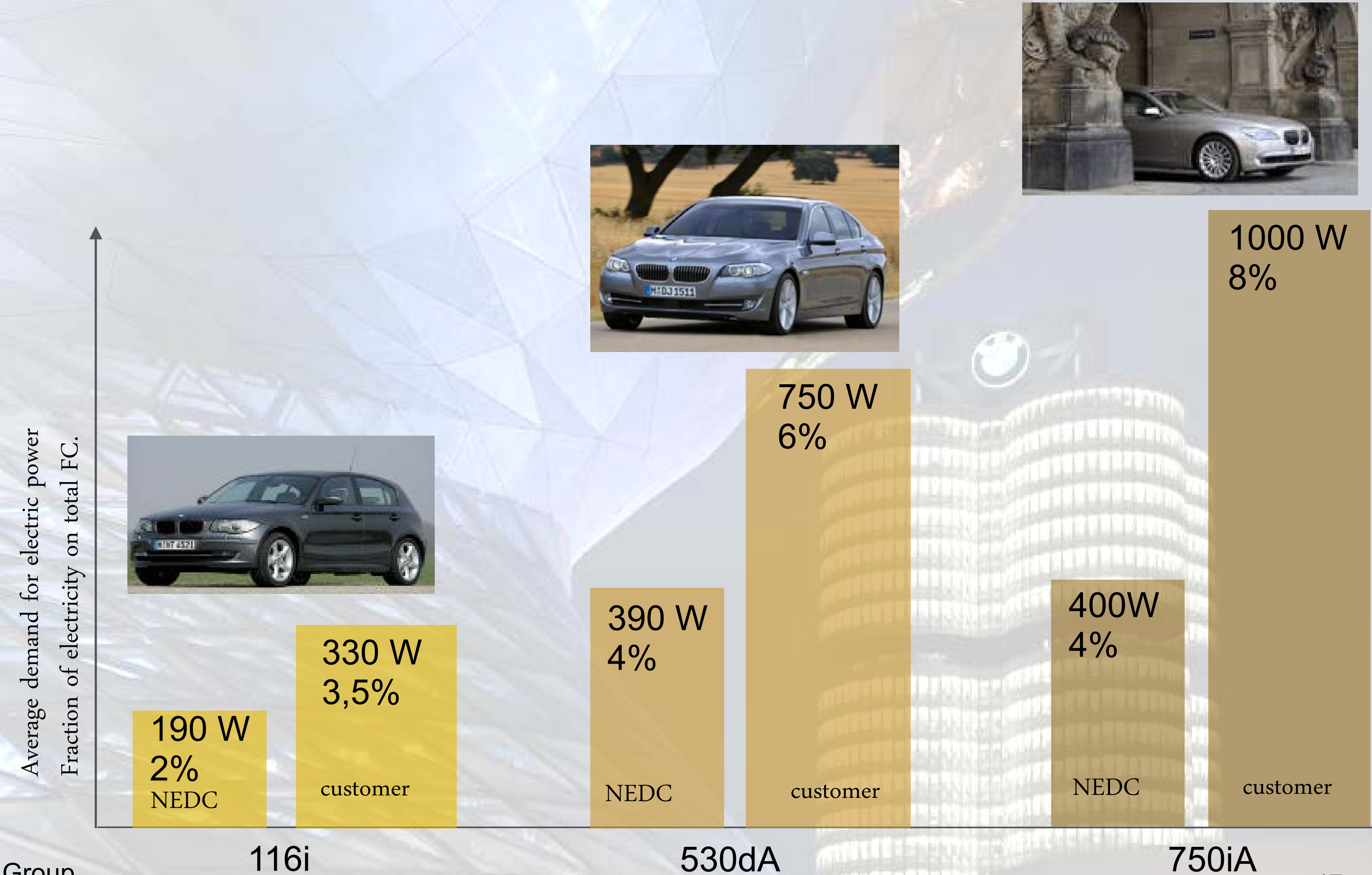
A second TEG is being completed and will be tested in a Ford Lincopln MKT in Dearborn



Prototype Thermoelectric Generators (TEG's) In Ford Lincoln MKT, BMW X6 and Chevy Suburban-Developed in DOE's VTP Programs

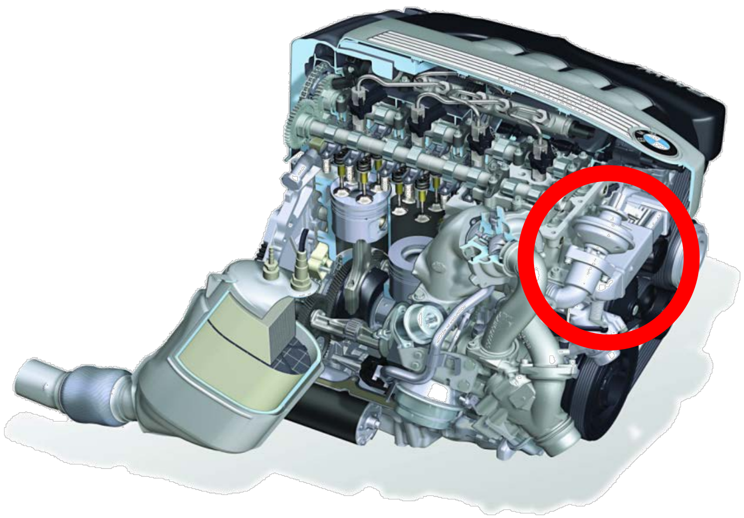
- Amerigon's TEGs Developed for Ford and BMW, and GM's Production Prototype TEG to Provide 5% Improvement in Fuel Economy
- Amerigon's TEG Bench Test Peak output was 608 Watts with 620^0C inlet air and 20^oC cold side temperatures
- TEG being tested in a BMW X6 in Munich
- A second TEG is being tested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

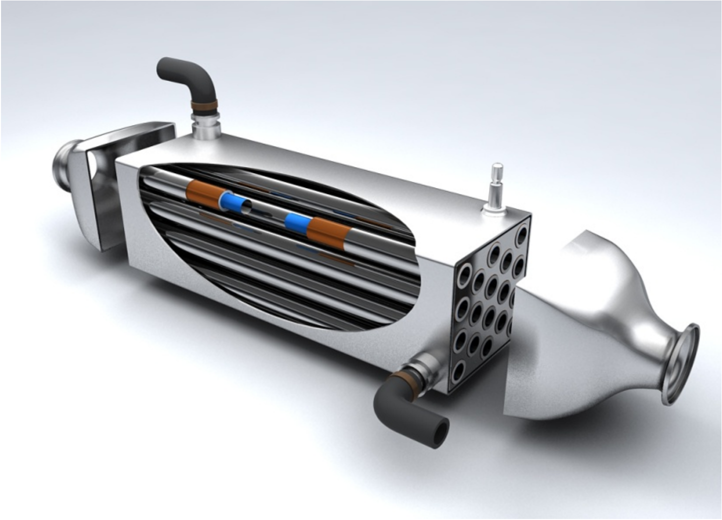
Thermoelectric Power Generation – Analytical Projections for BMW Sedans

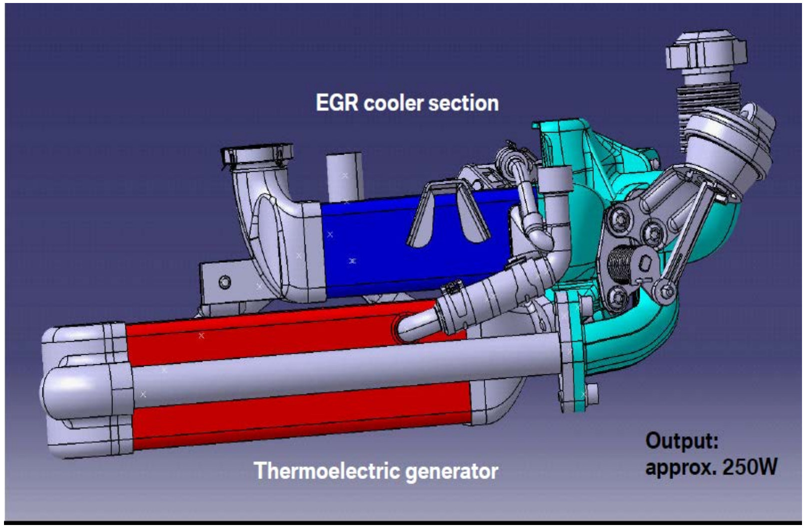


Source: BMW Group

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







Thermoelectric Generator Installed in Volkswagen Transporter (Diesel)

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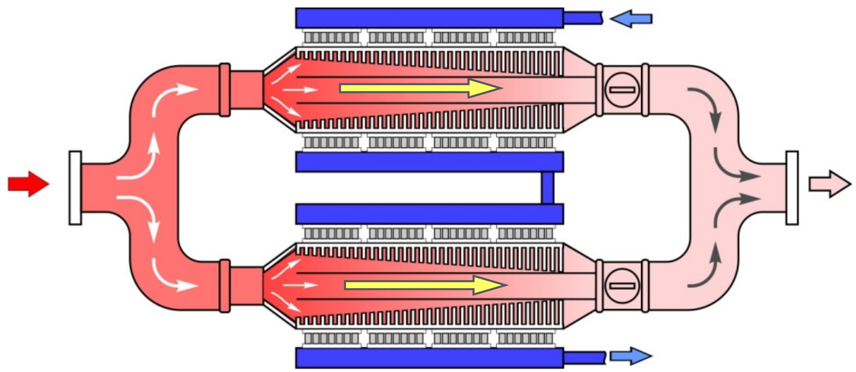
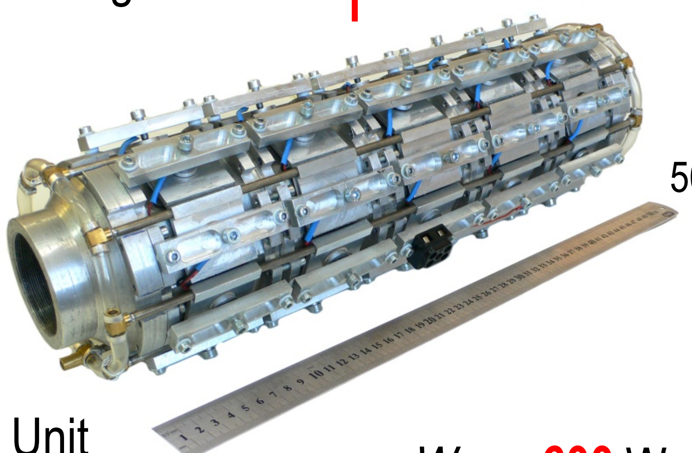
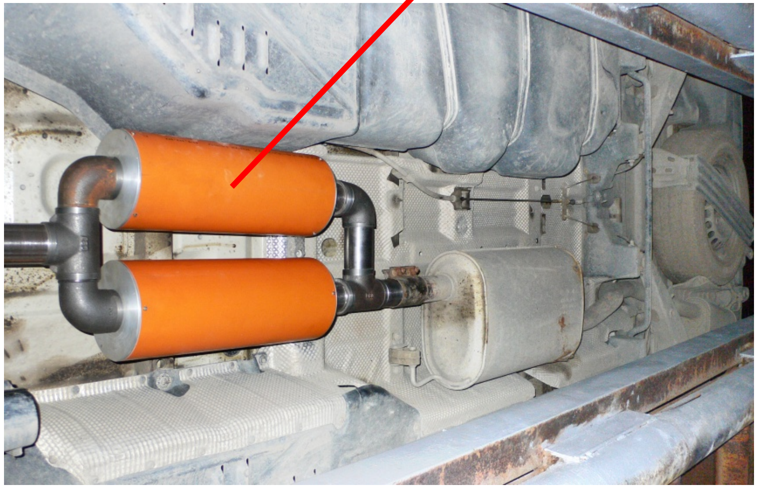


Scheme of the generator



Unit

50 cm

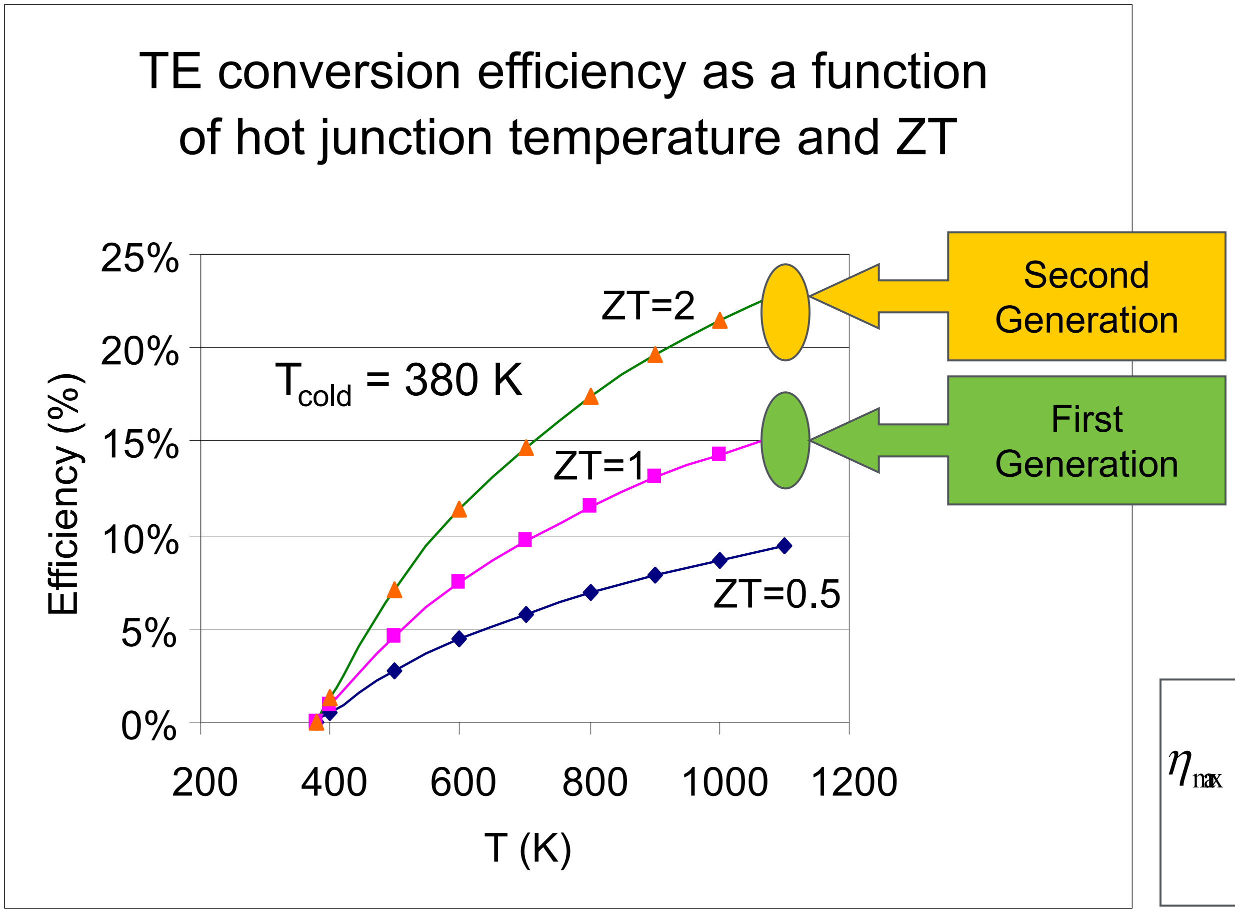


W_{max} = **600** W – 110 km/h

$\overline{W}$ = **160** W – for NEDC

$$\frac{\overline{W}}{W_{max}} \approx \mathbf{0.25}\ \text{W}$$

TE Materials Performance Objective



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

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- ❑ Commercially viable thermoelectric modules
  - ➢ ZT_{avg} = 1.6
  - ➢ Temperature range 350^o - 900^{o}K

Significantly reduce size or 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

Vehicular Thermoelectric HVAC Zonal Concept

- Energy Requirements (Analytical):
  - Zonal Concept cools/heats each occupant independently
  - **630** Watts to cool single occupant
  - Current A/C's **3500 to 4500** Watts cool entire cabin

Defining Vehicle Occupant Comfort

UC Berkeley Thermal Mannequin Evaluation Detailed Localized Comfort Measurements

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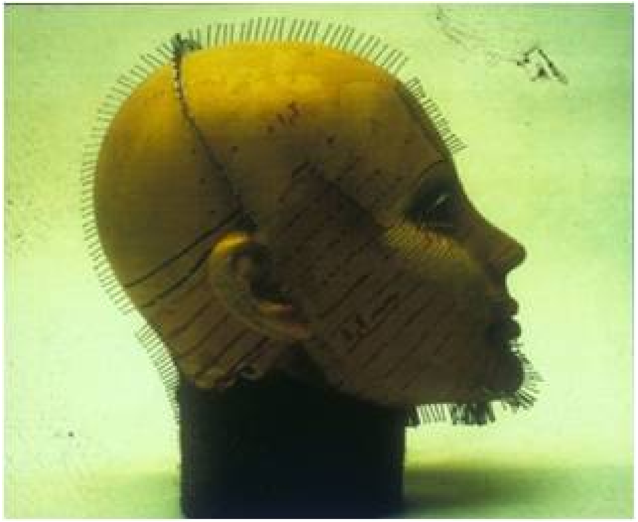

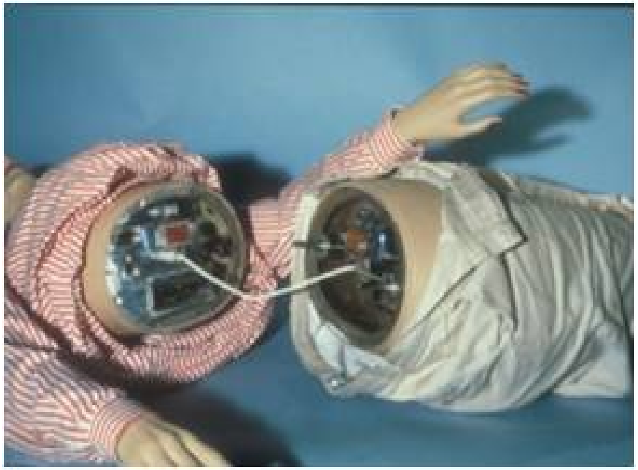

Human Thermal Comfort Model for Localized Cooling and Heating

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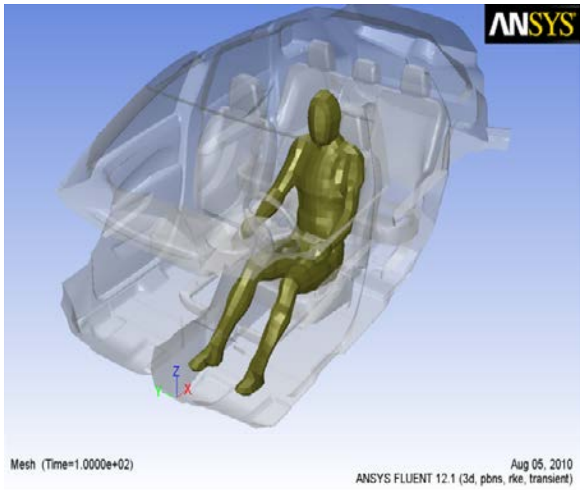
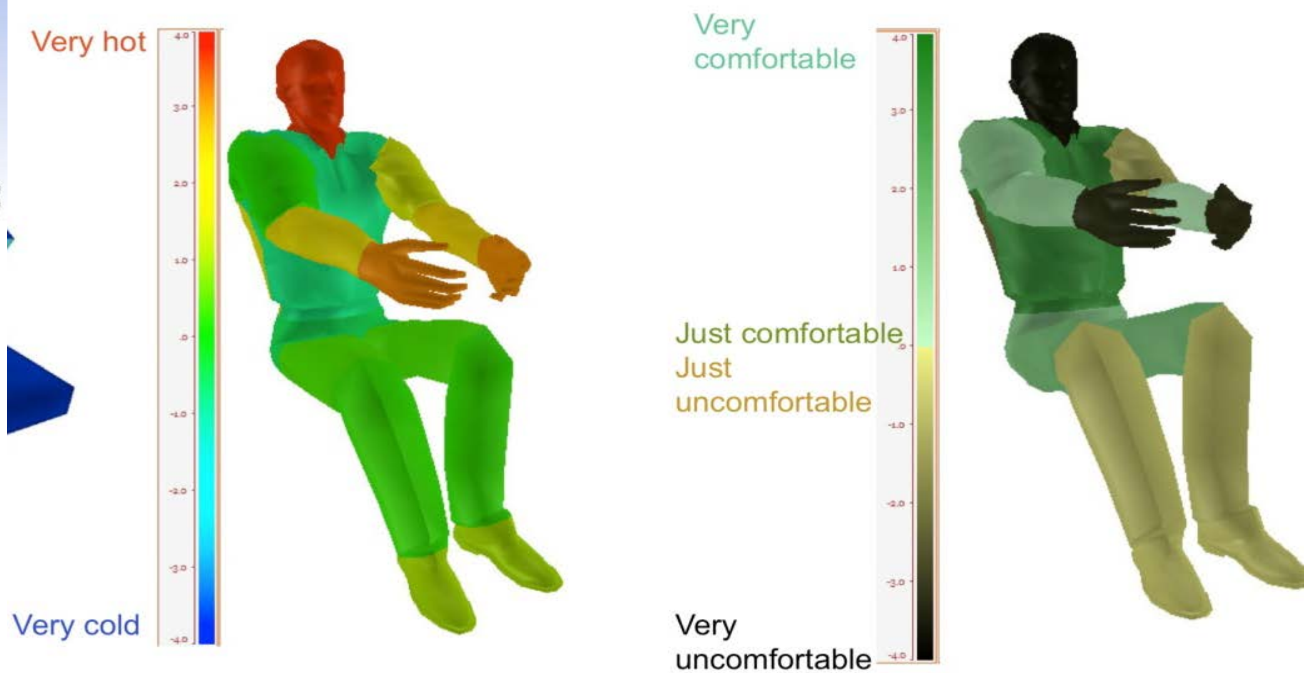
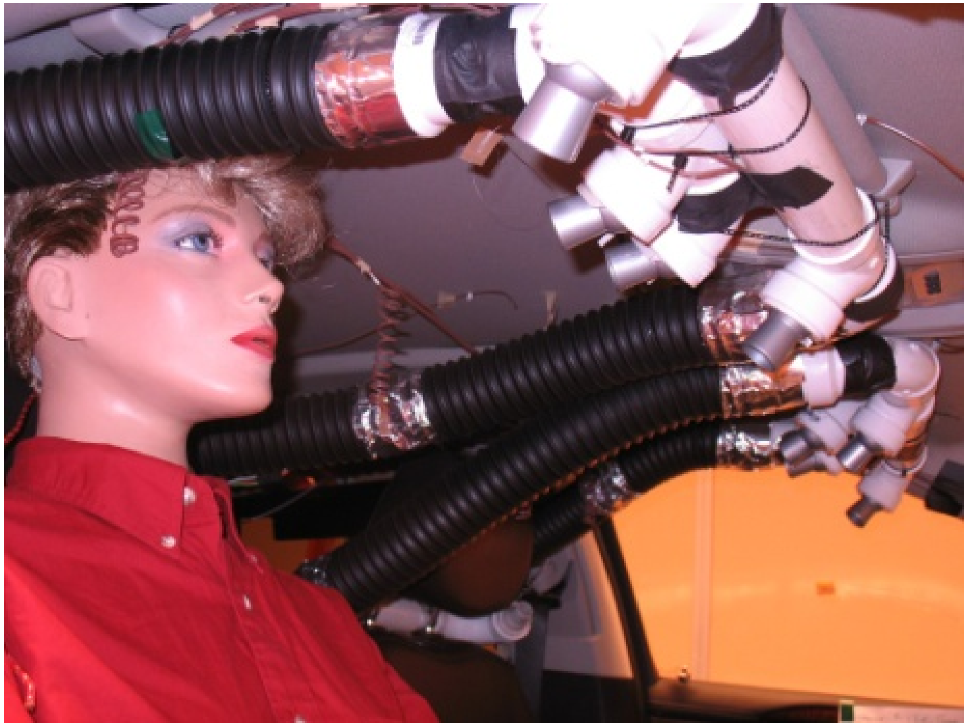


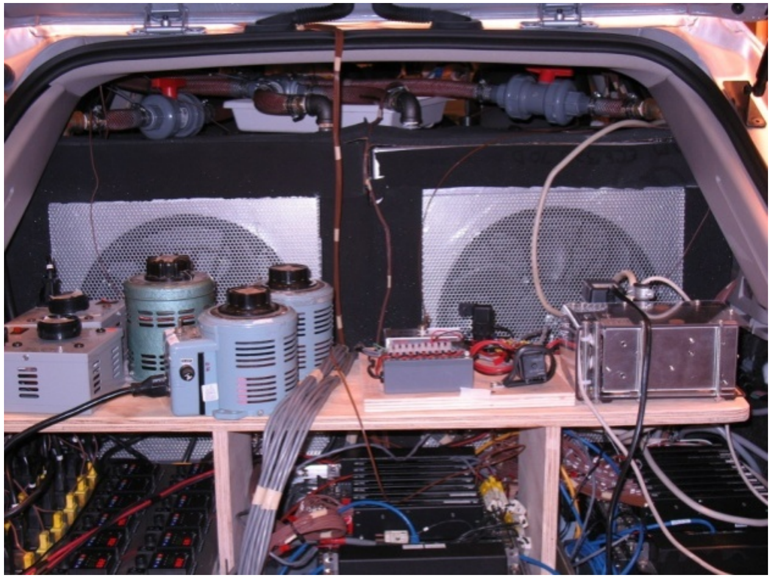


- Correlates well with 16 segment thermal mannequin vehicle evaluations

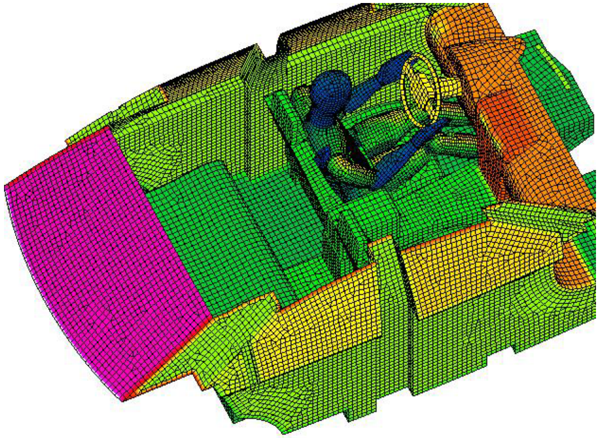
Delphi's Climatic Wind Tunnel Testing to Emulate Local Spot Cooling

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

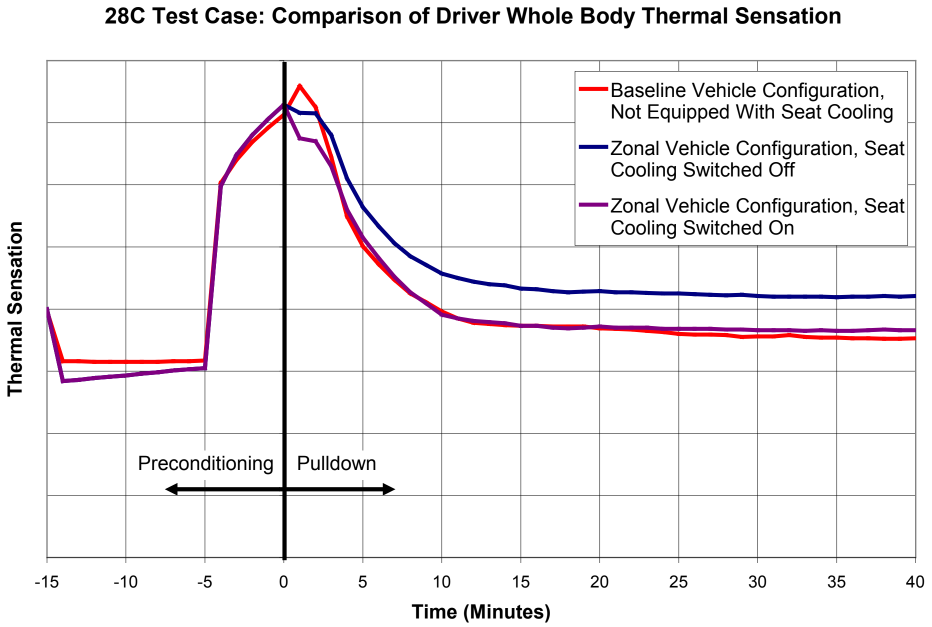




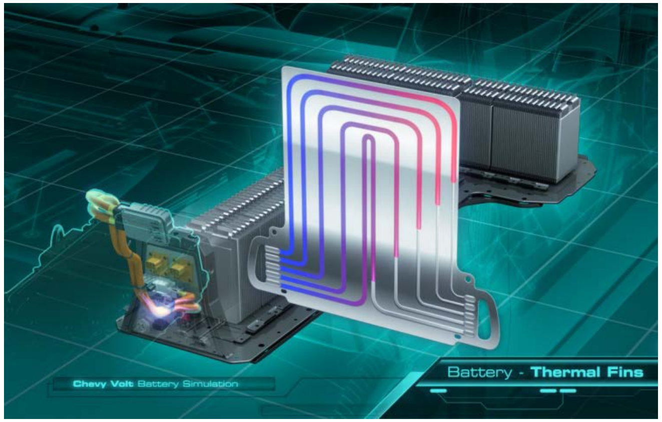
Air Chamber Evaluation System (ACES)



- Fusion vehicle in thermal chamber for evaluation of HVAC concepts
- Capability to independently control various distributed HVAC elements
- ACES used to validate CAE Comfort Model predictions includes Wind Tunnel Testing conditions as a baseline



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



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

DOE/ORNL Supported Thermoelectric Materials Characterization

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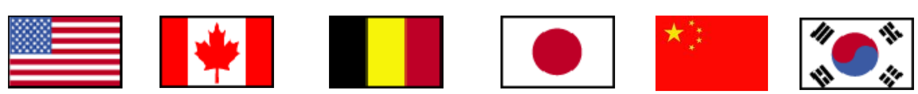
Main HTML functions in thermoelectric research

- 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)

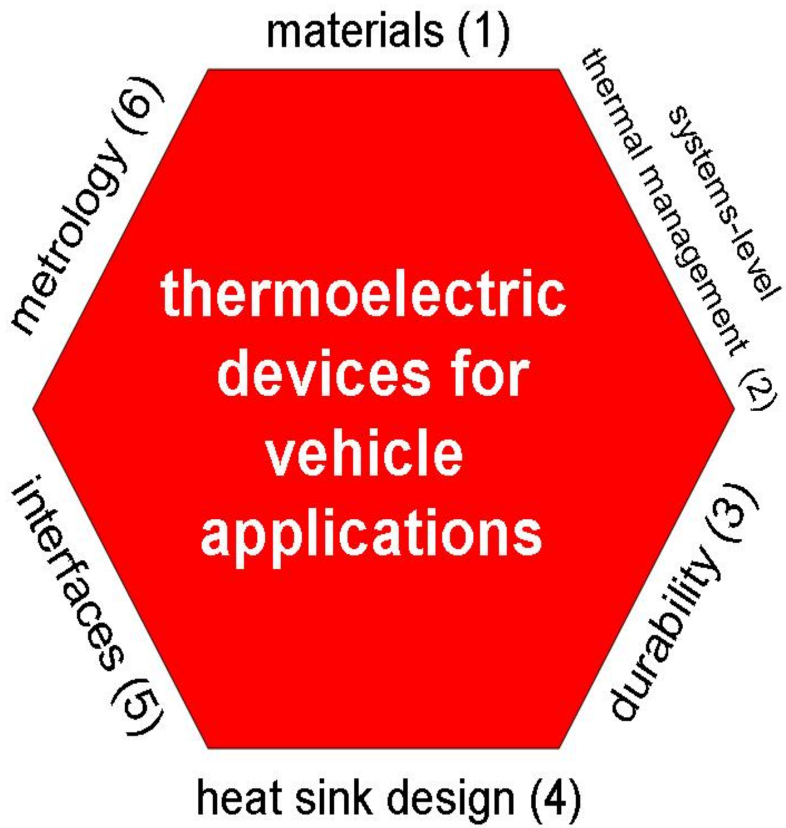
  Annex VIII on thermoelectrics led by ORNL
  - **Participating countries: USA, Canada, Germany, Japan, China and South Korea**
  - **Participating labs: more than 10**

iea International Energy Agency



DOE/NSF Partnership in Thermoelectric R&D

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

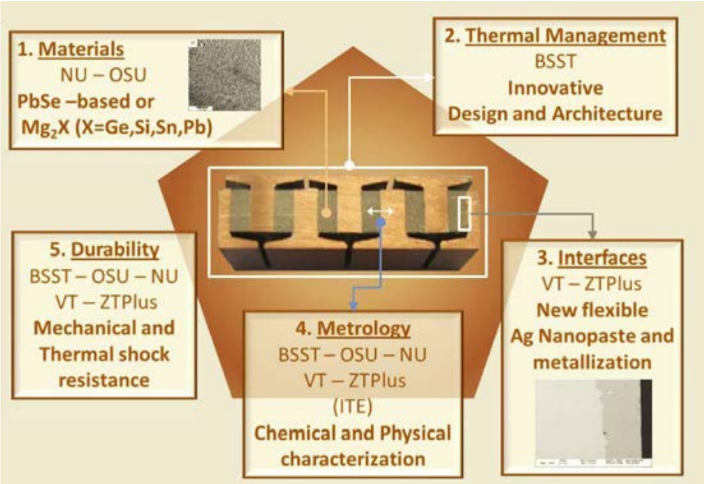


2010 NSF/DOE Partnership - Thermoelectric Devices for Vehicle Applications

- 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)
- 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

DOE/NSF Thermoelectric Partnership : Project SEEBECK (OSU, Northwestern, BSST)

- **Objective:** Develop elements for an automotive TEG for exhaust gas energy harvesting that is commercially viable and durable.
- **Approach**
  - Develop high-ZT (ZT>1.5) low-cost materials made from available elements,
    - Materials with no rare or toxic elements (Te, Tl)
  - Design new thermal management strategies, specifically:
    - Cross-flow designs, heat and charge flux normal
  - Minimize electrical and thermal interface resistances:
    - Compliant, to accommodate thermal expansion
    - High thermal and electrical conductance across interface
  - Metrology:
    - Materials characterization
    - Thermal interface resistance measurements
    - Electrical interface resistance measuremensts
    - Overall system performance measurements
    - Internal check: all of the above are redundant
  - Durability:
    - Compatible with automotive durability requirements

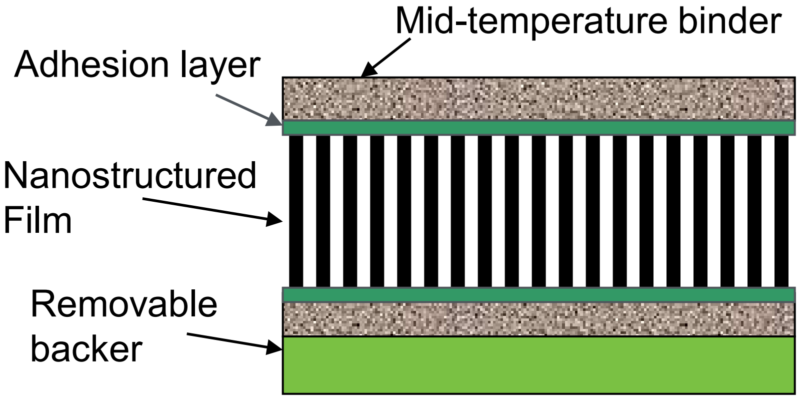


NSF-DOE TE Partnership: Automotive TE Modules with Scalable Thermo- and Electro-Mechanical Interfaces (Stanford, Univ. South Florida, Bosch)

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)

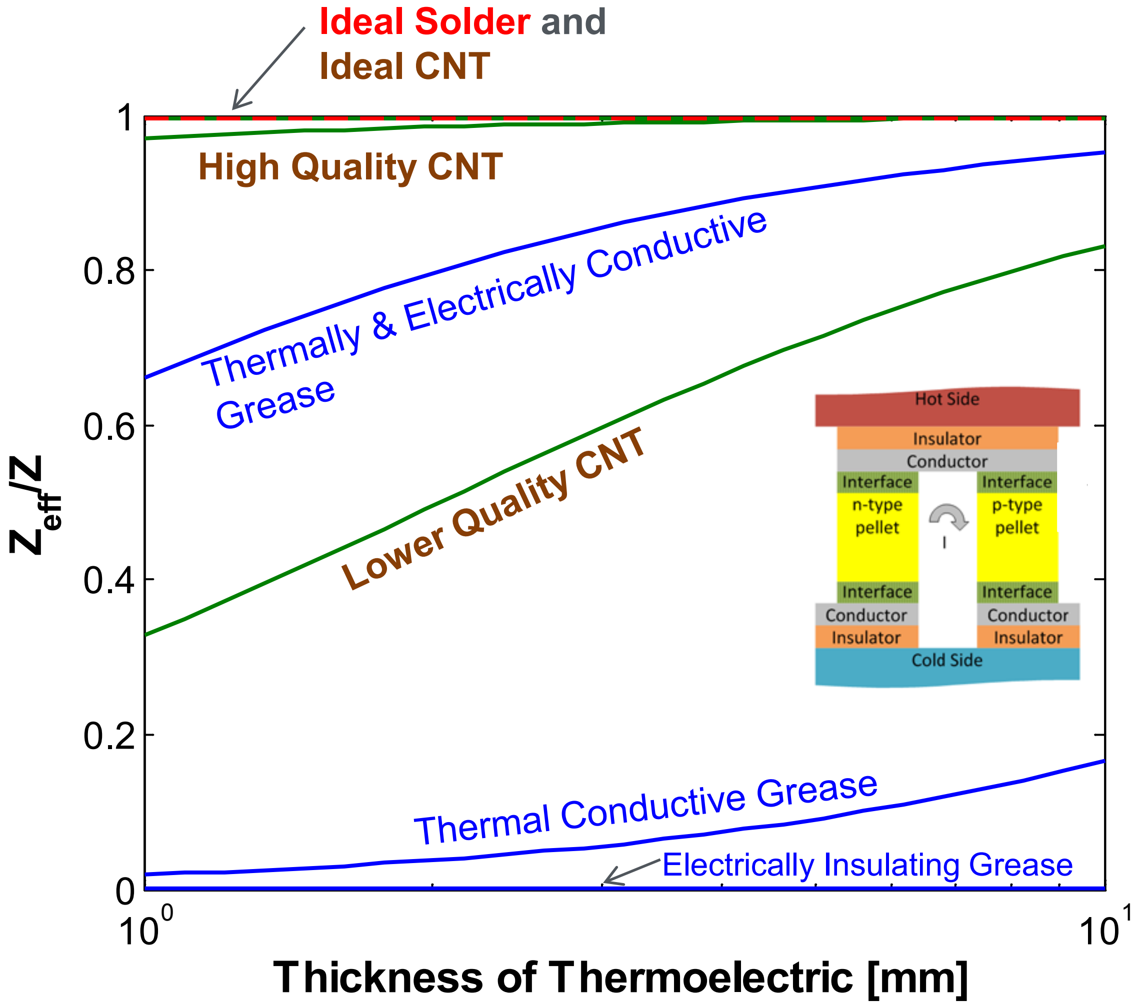
Approach

- 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

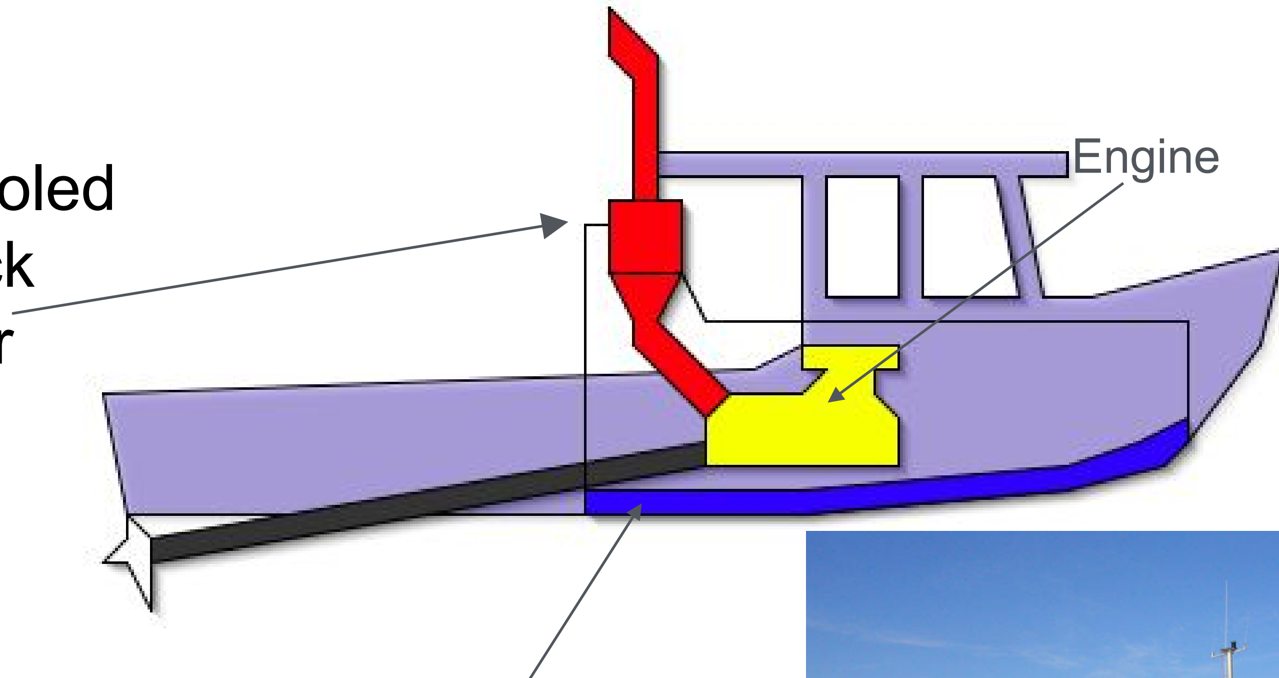


Using model of Xuan, *et al.* International Journal of Heat and Mass Transfer 45 (2002).

Interface Material	R''_{th} [W/m²/K]	R''_{e} [Ω m²]
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}

TEG Trickle Charge Battery: Sea Water--Ambient Air 24/7 Underway: Engine Exhaust--Sea Water

Maine Maritime Academy



Market Factors Involving Automotive Thermoelectric Applications

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- 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

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**

Evolution of Personal Transport

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1902

2012

Plan "C" Entering the 22 Century?

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- All-electric vehicles
- 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

TE applications: distributed energy generation

CENTRO RICERCHE FIAT

Thermoelectricity for Mobile Systems

THERMOBILE - *under evaluation*

SEVENTH FRAMEWORK PROGRAMME

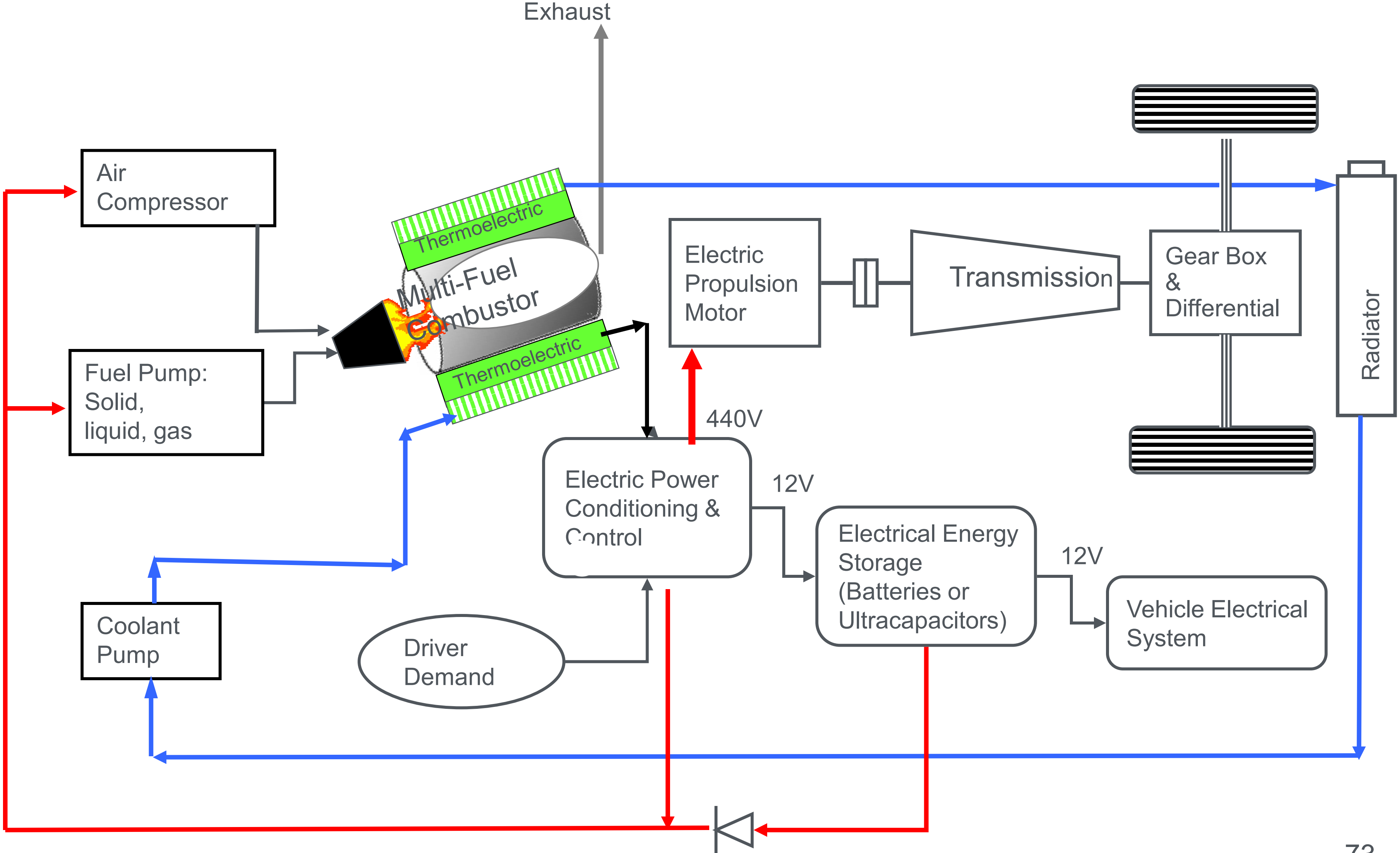
	CNRS – France
	CRF – Italy
	SNCF – France
	CEA – France
	EMPA – Switzerland
	DTU – Denmark
	BOSCH – Germany
	Termo-Gen – Sweden
	BASF - Germany

Thermoelectric Activities of European Community within Framework of Program 7

- Harold Bottner, Fraunhofer IPM, presentation at 3rd Thermoelectric Applications Workshop Baltimore, MD March 2012
  - EU's 7th Framework Program calls for development of new nanoscale thermoelectric materials for ZT~3
    - Partners in 12 countries
  - ZT= 3 means TEG efficiency is 27 %
  - When TEG efficiency reaches 25%, it could replace the automotive internal combustion engine (ICE)*

Francis Stabler, GM Powertrain, MRS Boston, November 2009

Vehicular Thermoelectric Hybrid Electric Powertrain Replacing the ICE



Questions?


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

Quote of the Day

"The budget should be balanced, the treasury should be refilled, public debt should be reduced, the arrogance of officialdom should be tempered and controlled, and the assistance to foreign lands should be curtailed lest we become bankruptears"

Cicero, 63 BC

Any Questions?

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