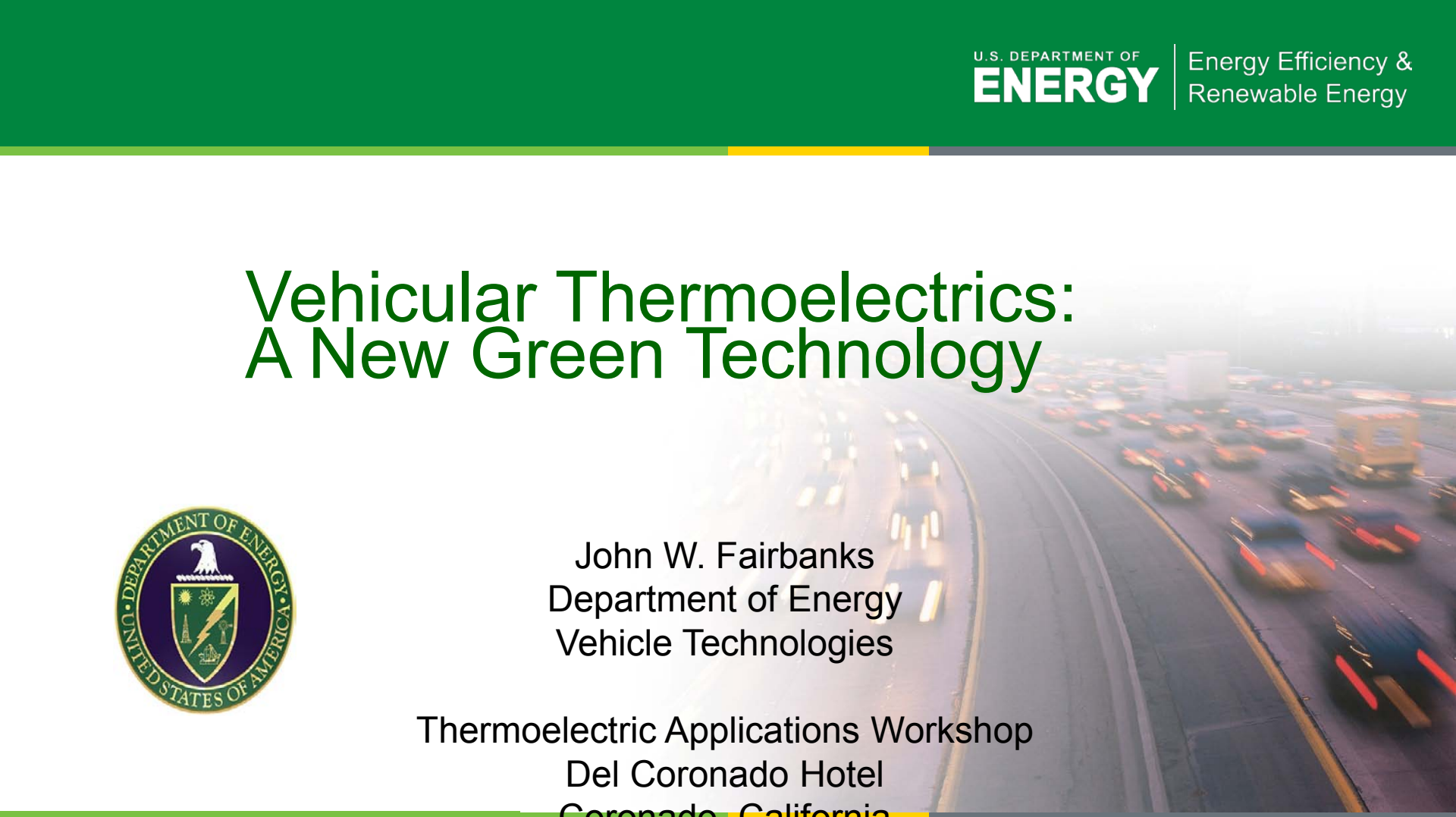
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Vehicular Thermoelectrics: A New Green Technology



John W. Fairbanks
Department of Energy
Vehicle Technologies

Thermoelectric Applications Workshop
Del Coronado Hotel
Coronado, California
January 3-8,2011

Outline

- The Federal Role
- Vehicular Thermoelectrics: A New Green Technology for Enhancing Fuel Efficiency
- Current DOE Projects in Automotive Thermoelectric Applications
  - Thermoelectric Generators
  - Thermoelectric Heating, Ventilating, and Air Conditioning (TE HVAC)
  - DOE/NSF Joint Partnership: Thermoelectrics
- Market Potential of Vehicular Thermoelectrics
- Summary

The Federal Role

- Facilitate development of precompetitive technical knowledge base through investments in fundamental and applied R&D
- Undertake high-risk mid- to long-term research
- Utilize unique Federal laboratory expertise and facilities
- Help create a national consensus
- Enable public-private partnerships to integrate R&D into industrially useful design tools

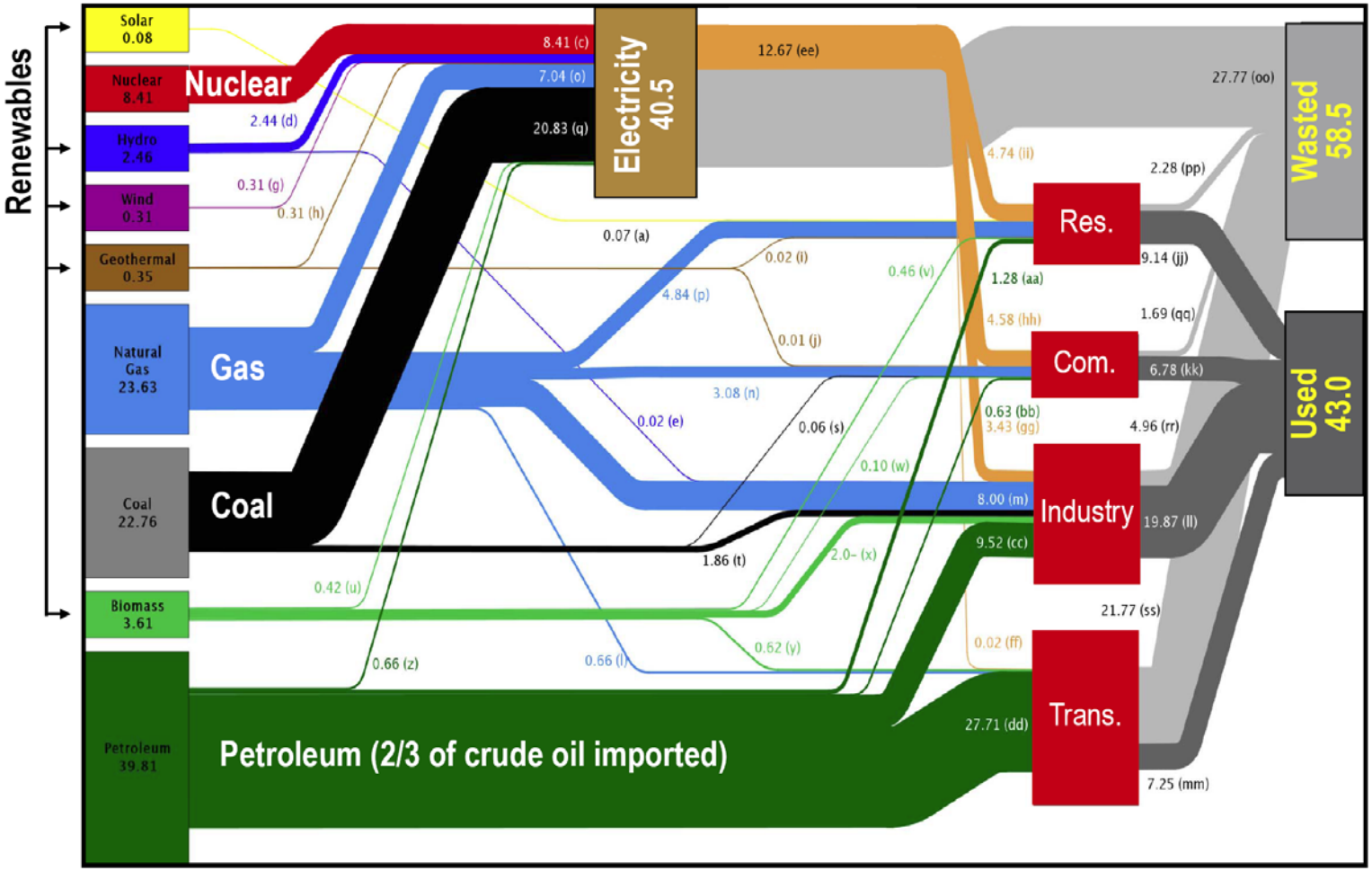
Steven Chu - Secretary of Energy
Nobel Laureate, Physicist

"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

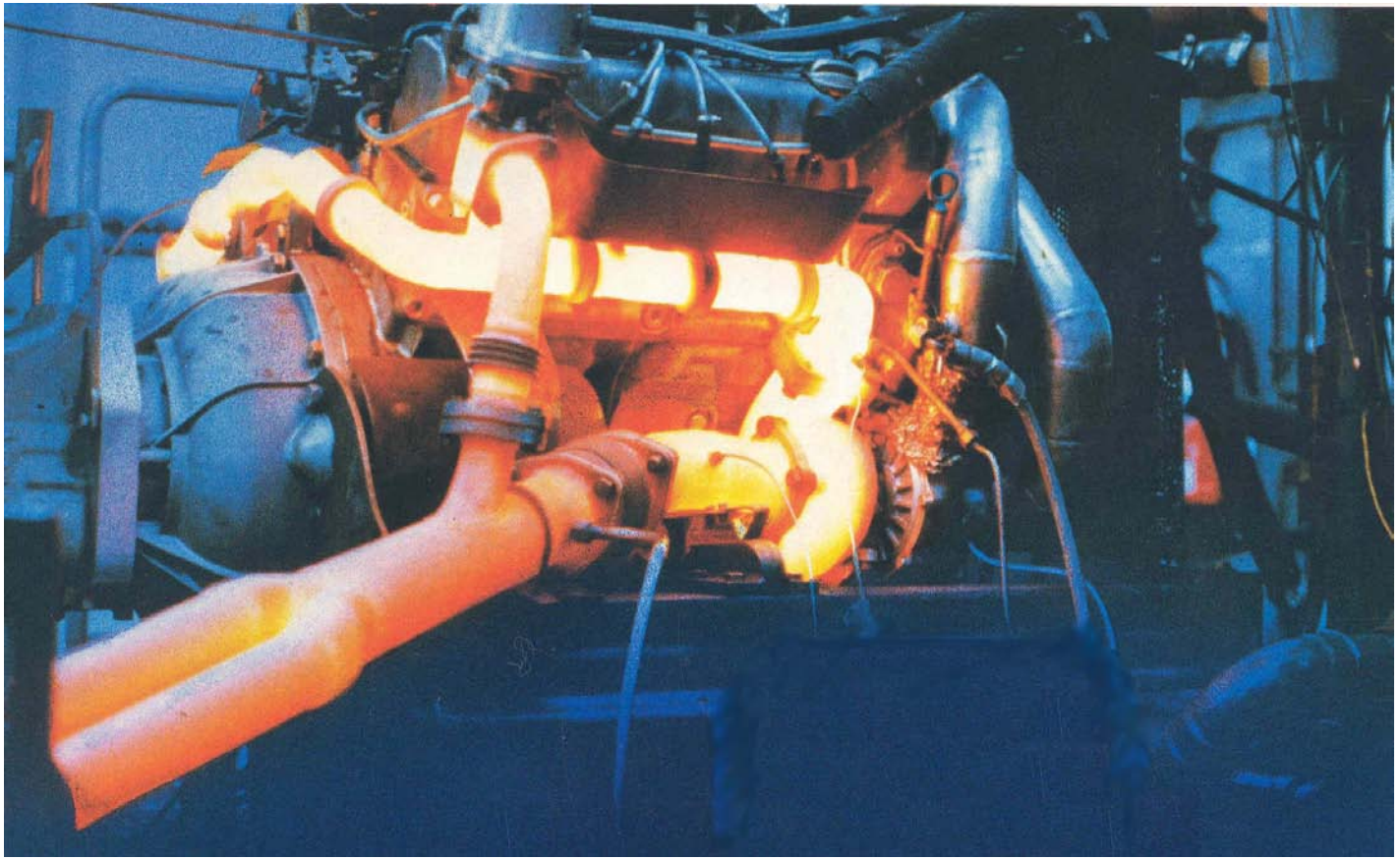
Opportunities for Thermoelectrics

U.S. Energy Consumption ~ 102 Quads (2007)
"Waste Heat" Can Be Utilized Using Themoelectrics

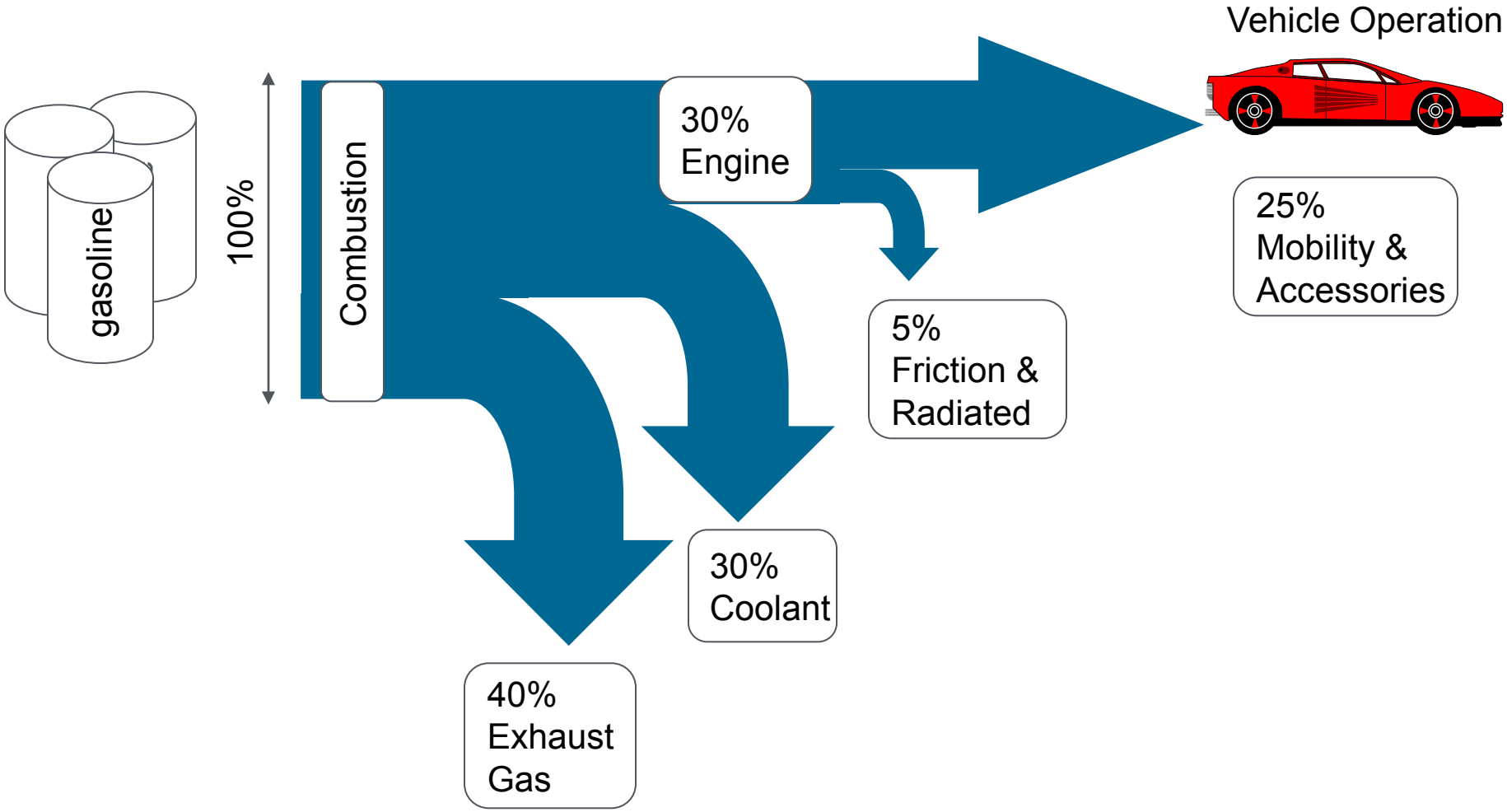


Source: LLNL 2008, data from DOE/EIA -0384 (2006)

Available Energy in Engine Exhaust Can Be Directly Converted to Electricity



Typical Waste Heat from Gasoline Engine Mid-Size Sedan



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

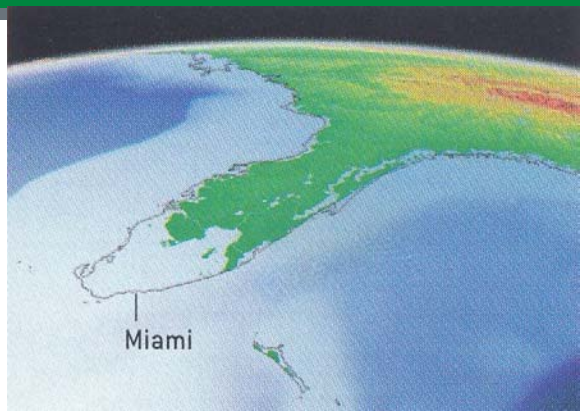
New US Personal Vehicle Fuel Economy Requirements (CAFE)

- 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 0.1 mpg under standard multiplied by manufacturers total production for U.S. market

Global Climate Change Enigma



Global Climate Change is Happening
- Water shortages caused by changing rainfall and/or snowfall patterns
- Reduced Productivity of Farms, Forests and Fisheries
- Sea Level Rising causing Property Loss and Population Displacement
- Increased Damage from Storms, Floods and Wildfires
- Is there a man made contribution?

Business as usual: Greenhouse Gases could triple by end of Century
50 Percent risk of 5^0C Temperature rise
5^0C Temperature change is total change in Earth's Temperature since last ice age

National Academy of Sciences 09/2008

NASA's Carbon Observatory Satellite Program should provide relevant data

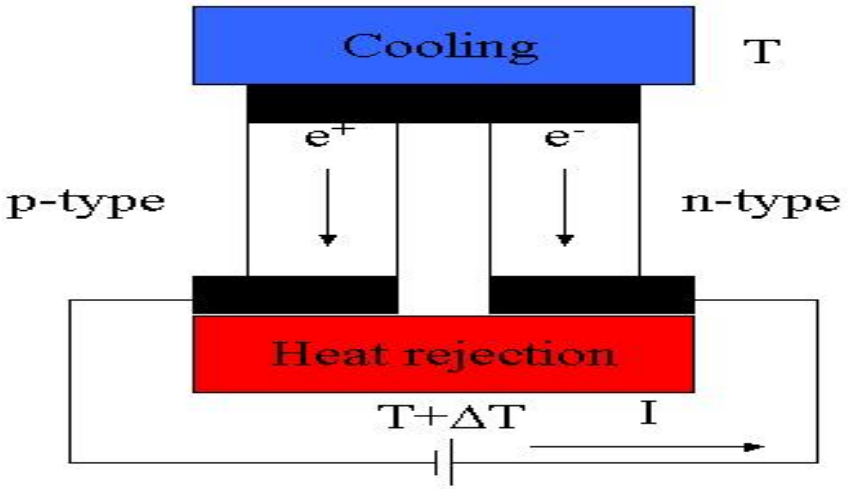
Prudent approach is to limit "Greenhouse Gas Emissions" with economic considerations until issue settled

Reducing CO_2 Emissions from Light-Duty Vehicles in EU

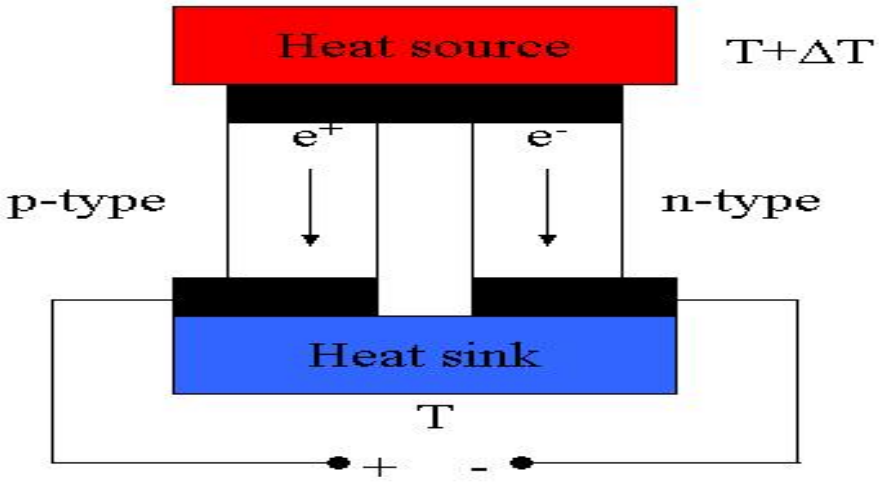
Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009

- Limit value curve: fleet average for all cars registered – 130 g/km
- Phasing in: 2012 – 65% of each manufacturers newly registered cars; 75% in 2013; 80% in 2014; 100% in 2015 onwards
- Long-term target – 95 g/km for 2020
  - Review of all aspects of implementation to be completed no later than beginning of 2013
- Until test procedure in reviewed by 2014, manufacturers can be granted maximum of 7 g/km emission credits on average for fleet equipped with innovative technologies

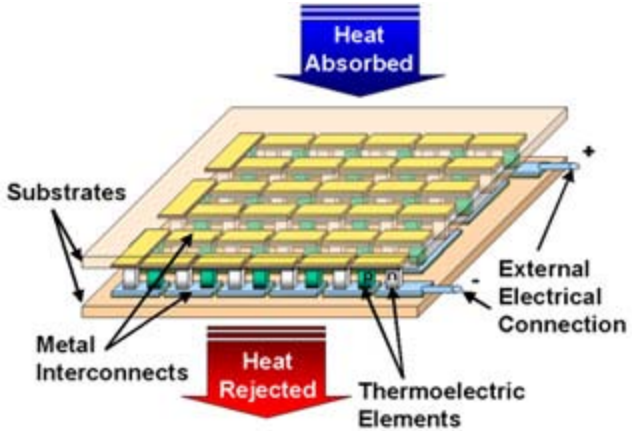
Thermoelectric Generator and HVAC



Refrigeration



Power generation



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

Electrical conductivity

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

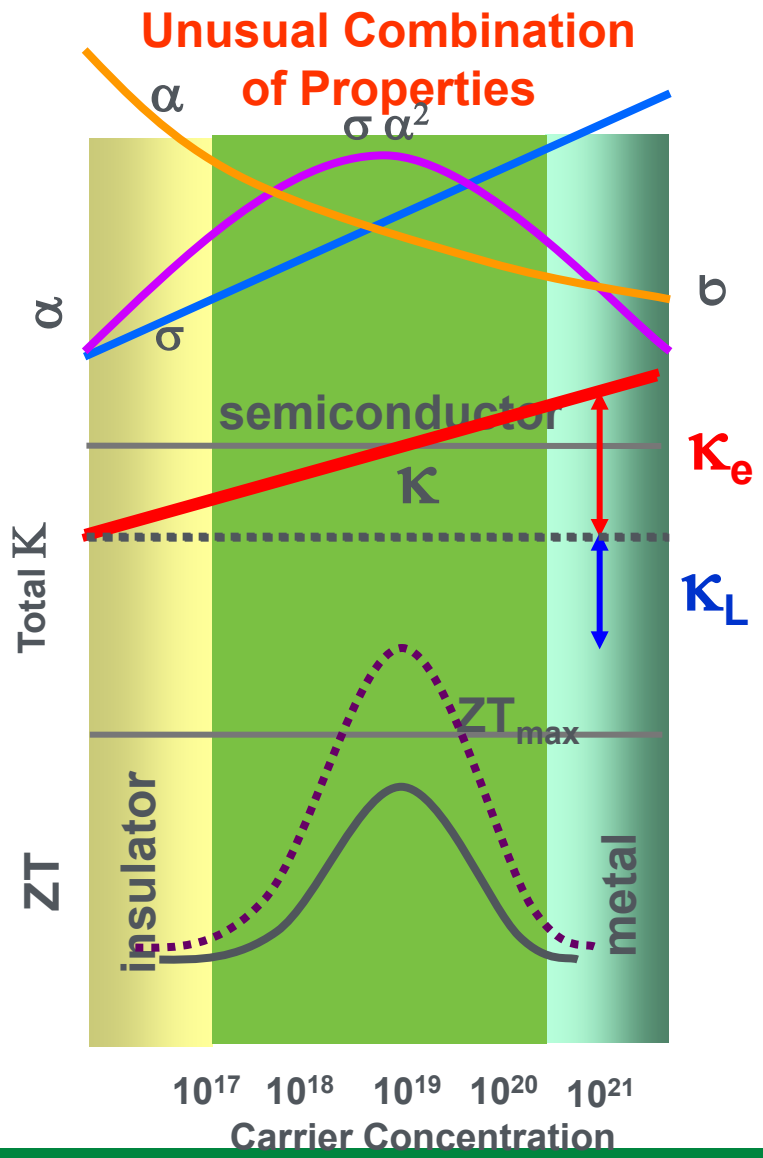
$$ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \bullet T$$

Total thermal conductivity

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

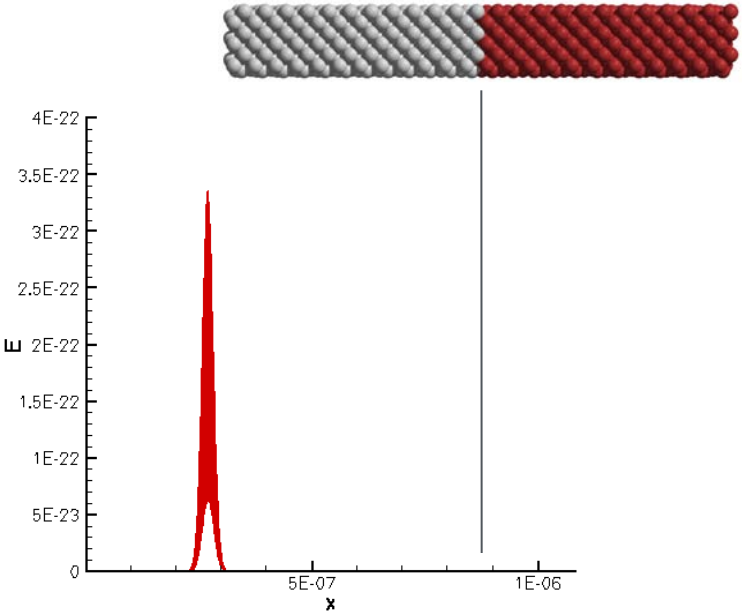
$\sigma = 1/\rho$ = **electrical conductivity**

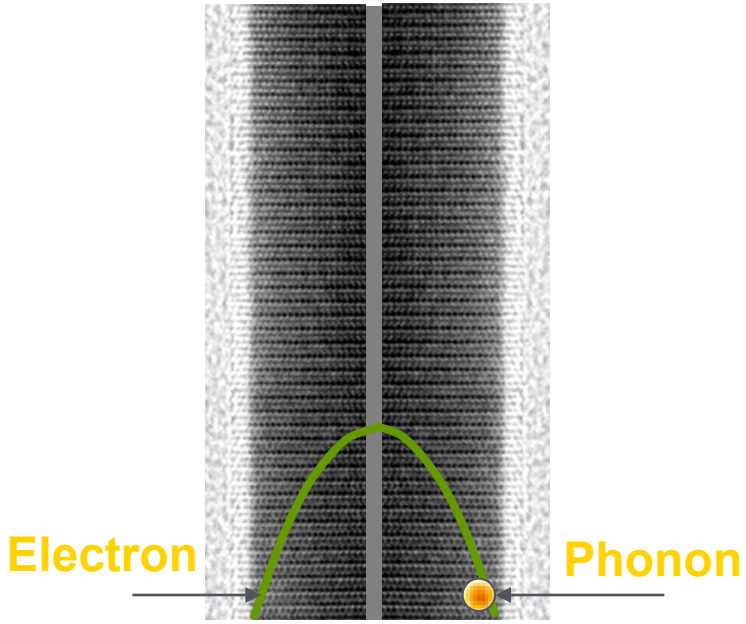
ρ = **electrical resistivity**



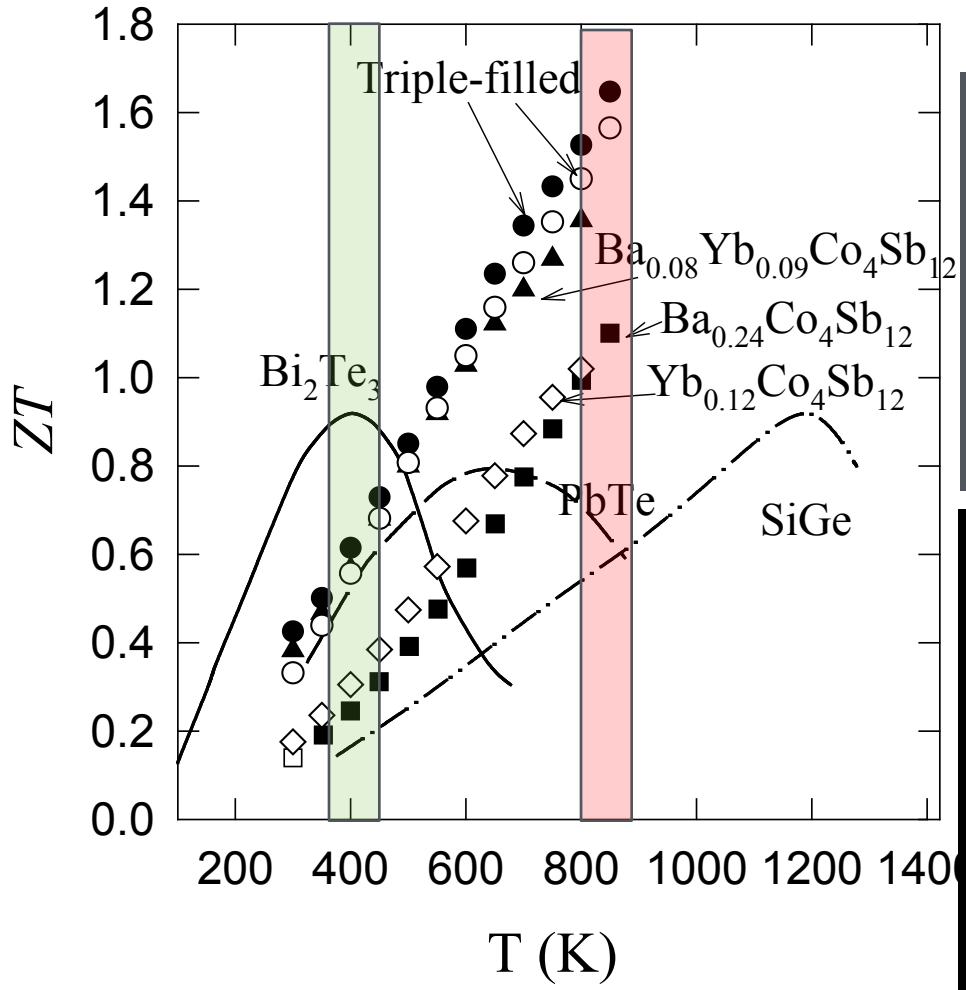
Interfaces that Scatter Phonons but not Electrons

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

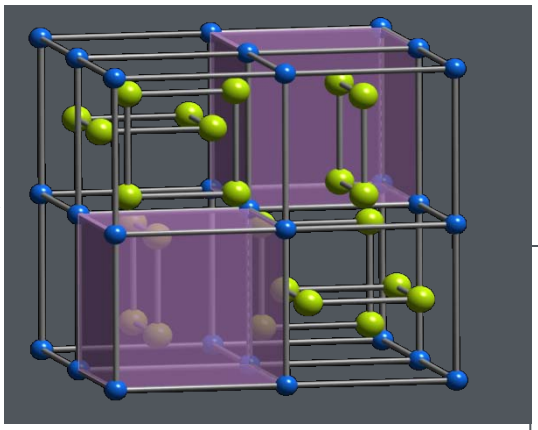


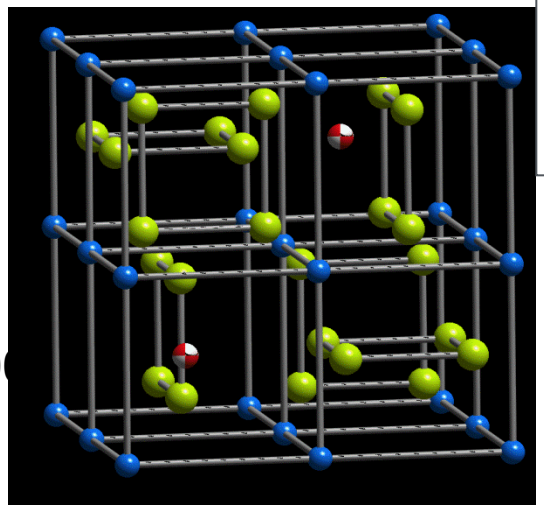


Highest ZT Achieved with Triple-filled Skutterudites (GM and U of Michigan)



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



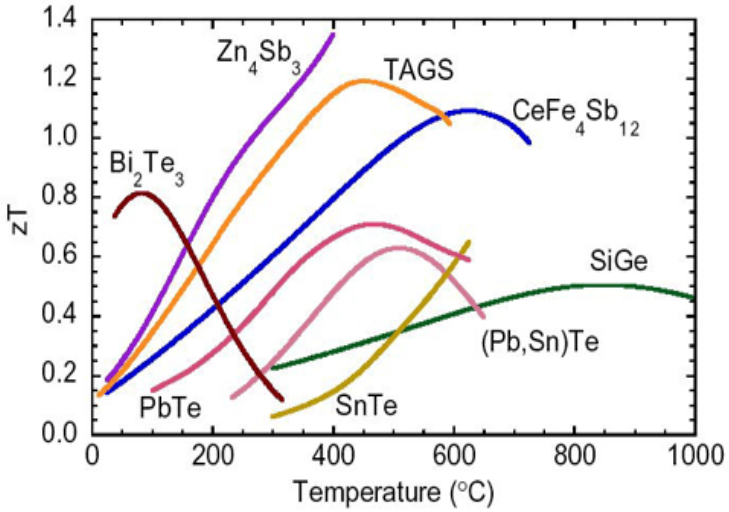


Atoms can be inserted into empty sites. Atoms can "rattle" in these sites – scatter phonons and lower the lattice thermal conductivity.

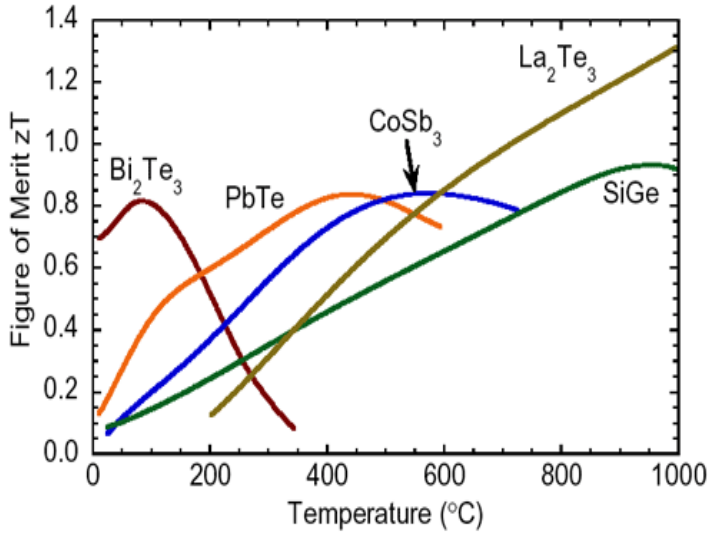
R_xCoSb

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

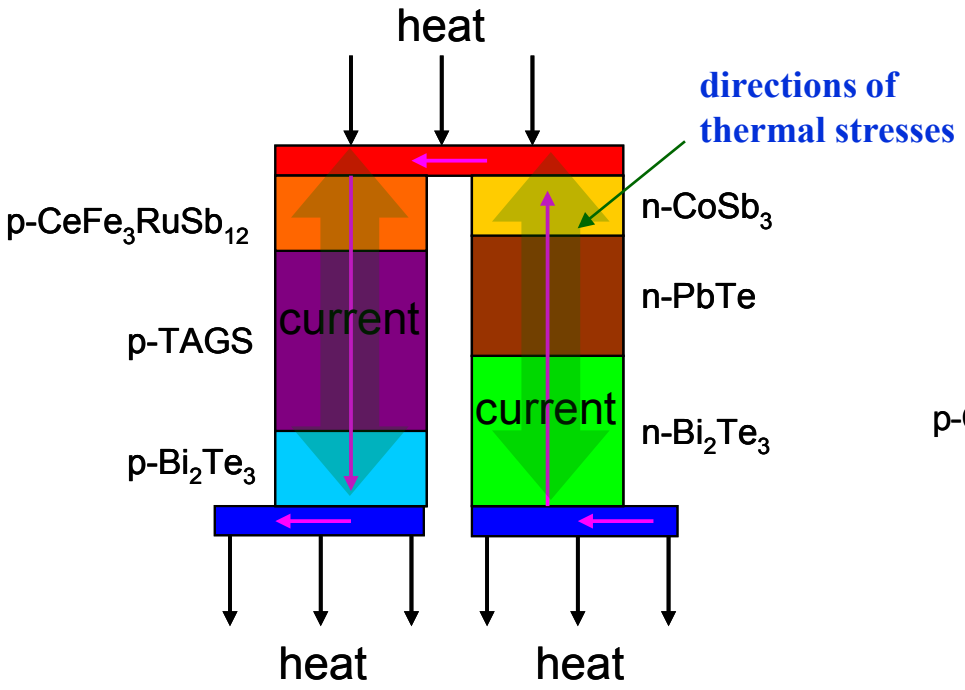


N-type TE material

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

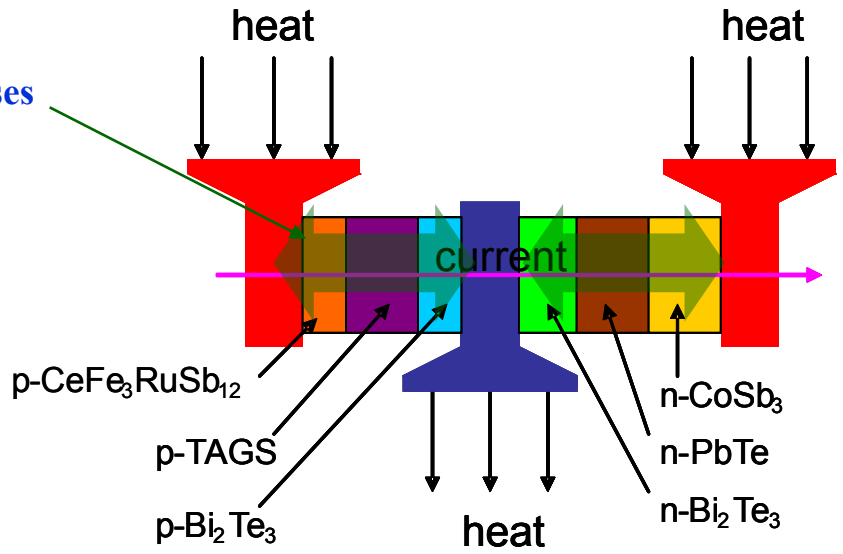
Segmented Thermoelectric Couple Configurations

conventional



Thermal Mismatch Stresses can Separate Material Layers

BSST "Y" configuration



Thermal Mismatch Stresses are Significantly Reduced

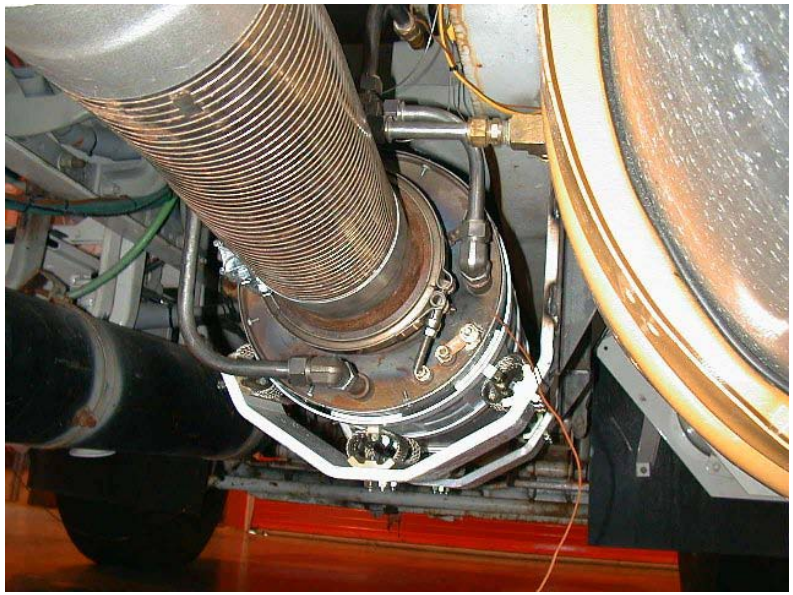
Opportunities for Thermoelectrics

Availability of lower cost high efficiency thermoelectric modules enables cost-effective direct conversion of waste heat to electricity thereby improving energy efficiency of:

- Industrial Processes,
- Power Plants,
- A Range of Military Applications
- Geothermal Energy
- **Vehicles**
  - Passenger and commercial vehicles
  - Marine, rail, and aircraft
  - Off-highway vehicles

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

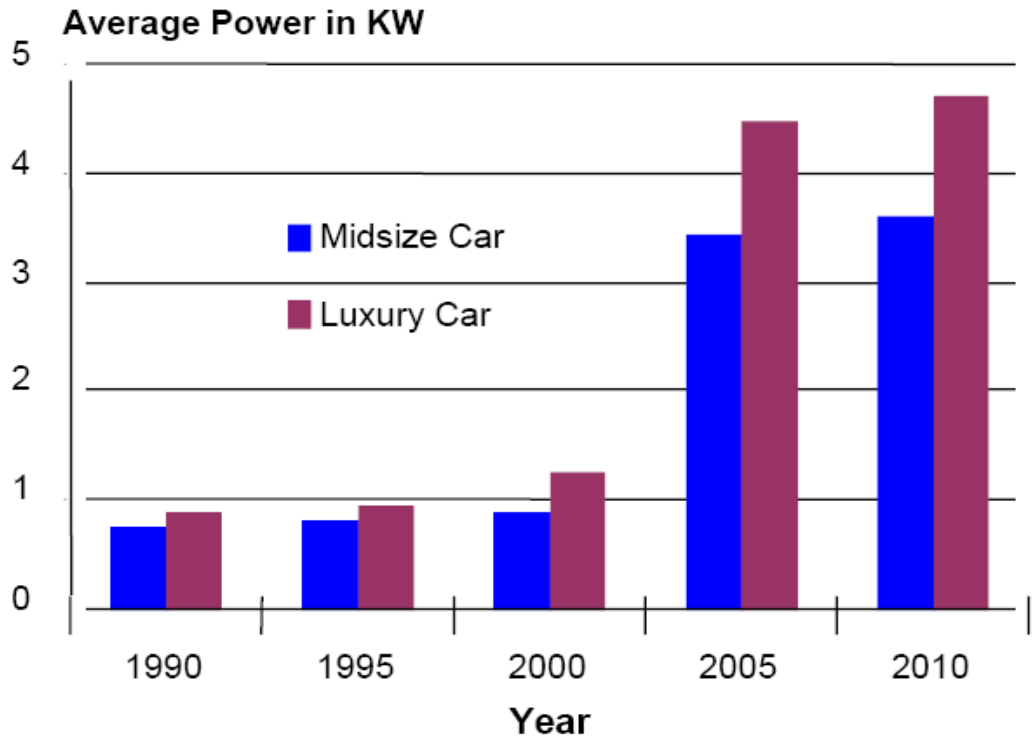
Heavy loaded (over 75,000 lbs)

TEG installed under the cabin

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

Increasing Electrical Power Requirements for Vehicles

- Increased electrical power needs are being driven by advanced IC engine for enhanced performance, emission control, and occupant comfort
  - Stability controls
  - Telematics
  - Collision avoidance systems
  - Onstar Communication systems
  - Navigation systems
  - Steer by-wire
  - Electronic braking
  - Powertrain controllers and sensors



- These requirements are beyond the capabilities of the current generators and require supplemental electrical generation, such as from a TE waste heat recovery unit - *Juhui Yang, GM*

DOE's Vehicular Thermoelectric Generator (TEG) Project Objectives

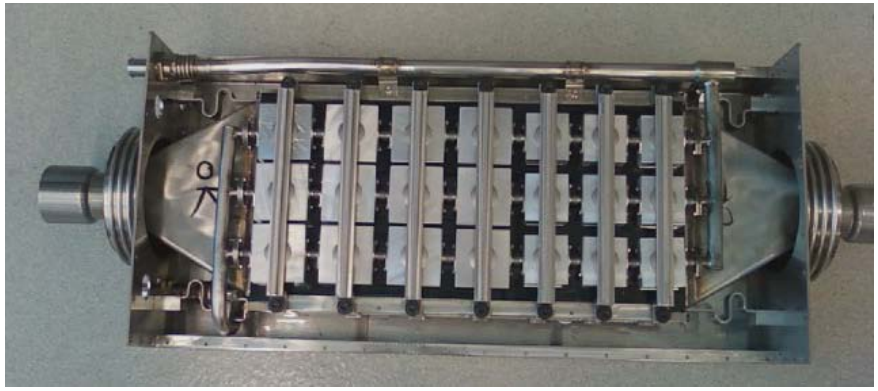
Generate electricity without introducing additional carbon into the atmosphere

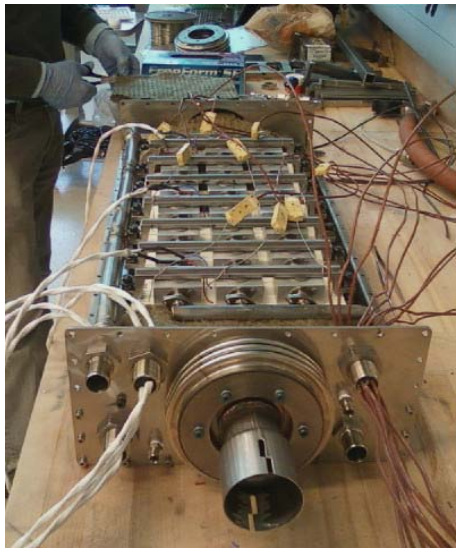
- Improve fuel economy (targets: 5% to 6%)
- Use thermoelectrics to generate electricity from engine waste heat for auxiliary power and for accessories
  - lights, pumps, occupant comfort, stability control, computer systems, electronic braking, drive by wire etc.
- Reduce size of alternator (target: 1/3rd reduction in size)
- Reduce regulated emissions and greenhouse gases

DOE/NETL Vehicular Thermoelectric Generator Projects

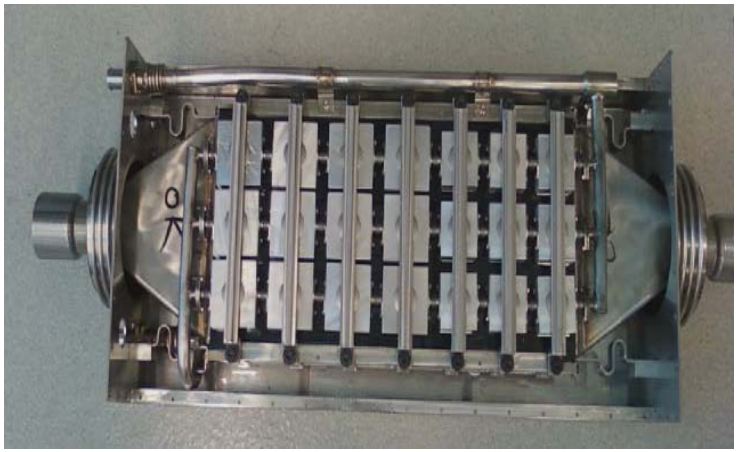
Awardees	Team Members
General Motors and General Electric	University of Michigan, University of South Florida, Oak Ridge National Laboratory, Marlow Industries
BSST, LLC	Visteon, BMW-NA, Ford, ZT Plus, Faurecia
Michigan State University	NASA Jet Propulsion Laboratory, Cummins Engine Company, Tellurex,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

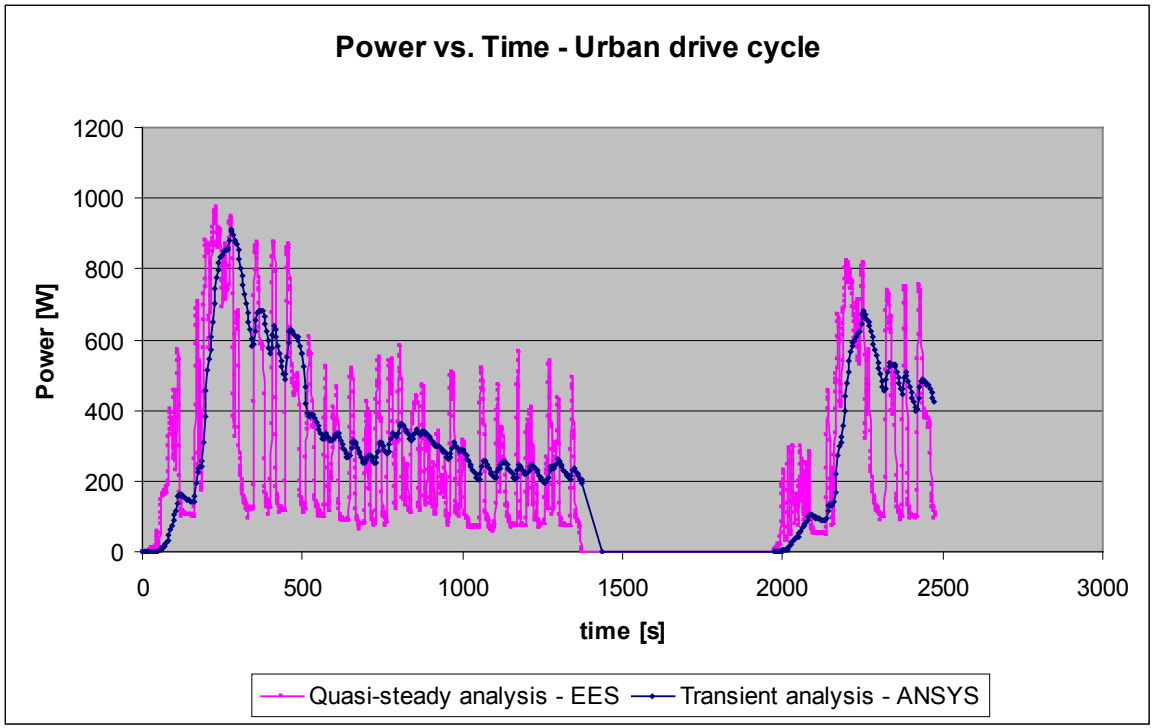
GM Prototype TEG Fabrication





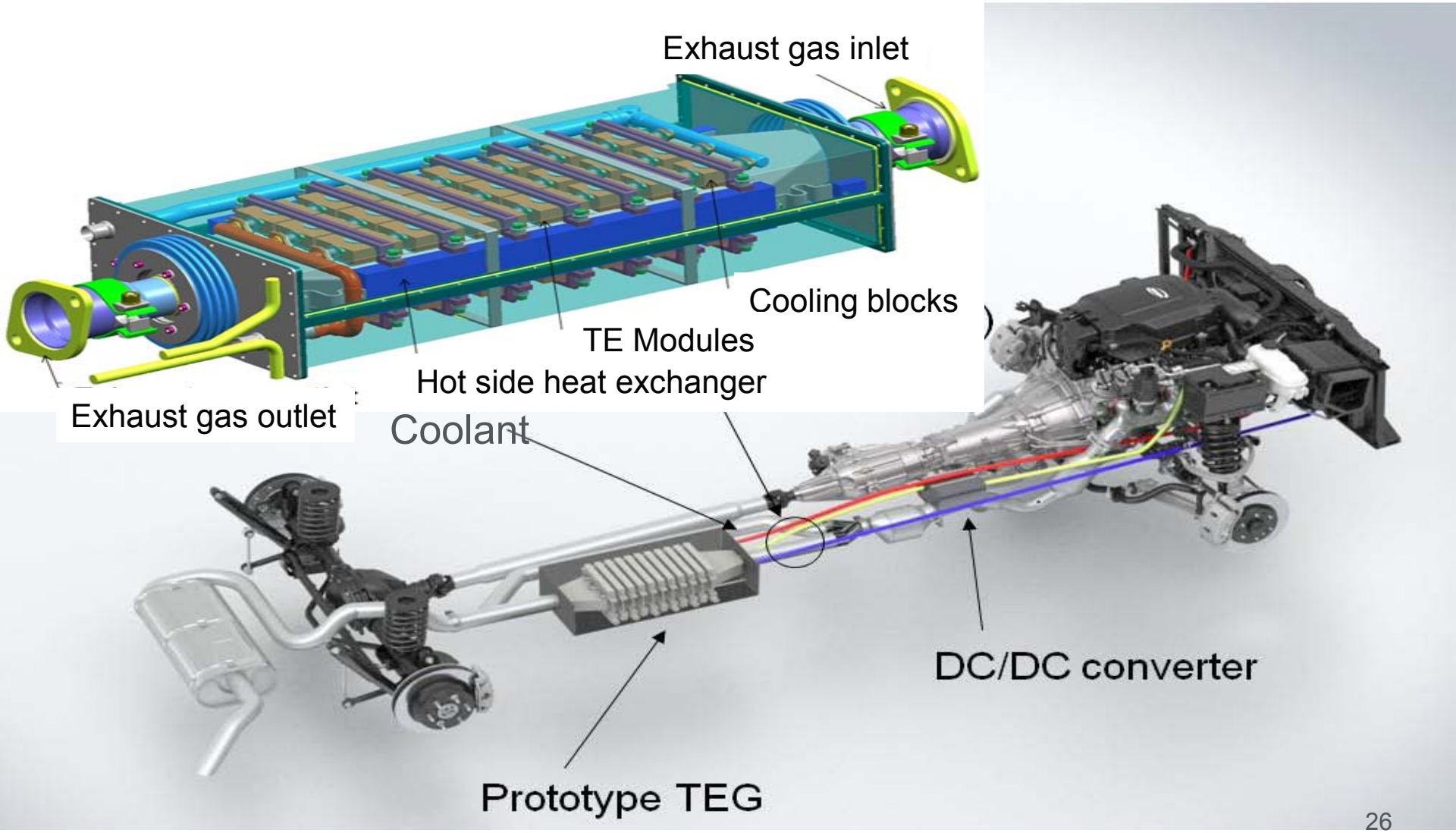
GM TEG Performance in Chevy Suburban



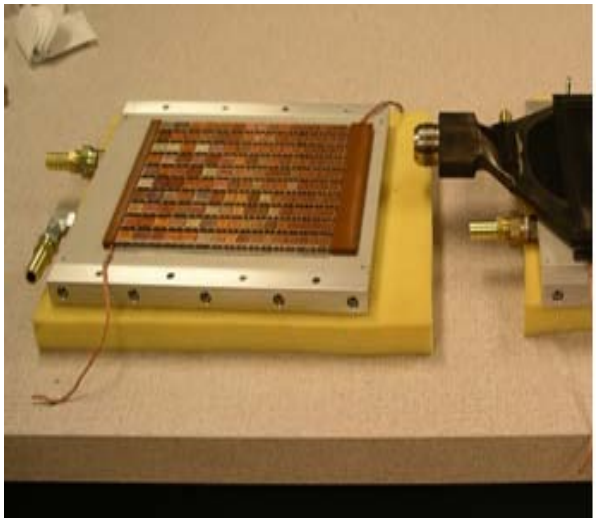


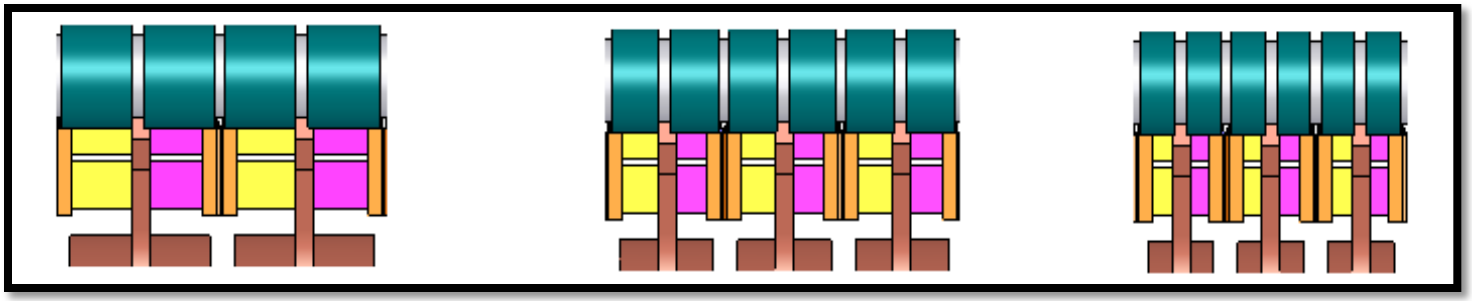
- ~ 1 mpg (~ 5 %) fuel economy improvement on FTP Driving Cycle
  - > 350 Watts City
  - > 600 Watts Highway

GM Prototype TEG Installation in a Chevy Suburban Chassis



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



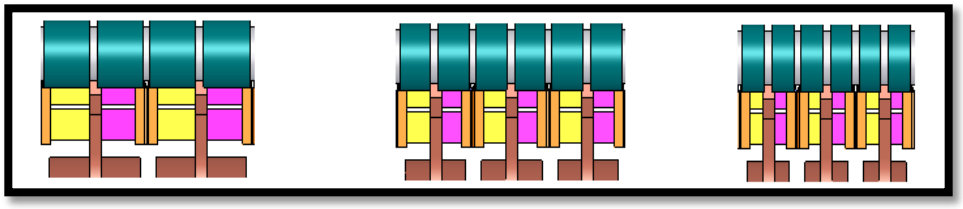


Inlet Region
Relatively long segmented TE elements

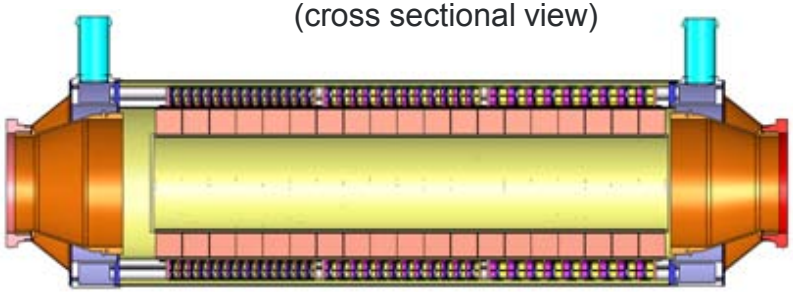
Middle Region
Mid sized segmented TE elements

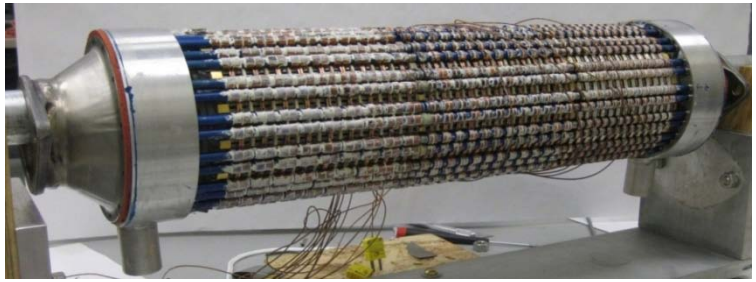
Exit Region
Short, single material TE elements

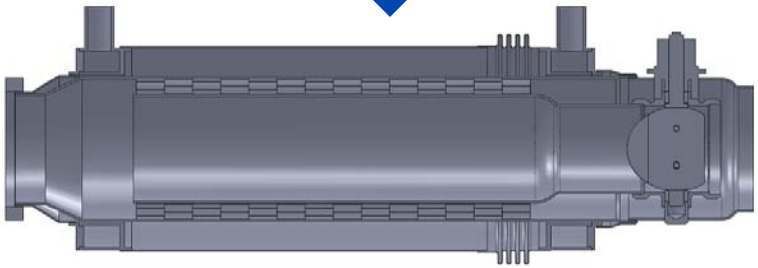
TEG for Ford Fusion and BMW X6



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

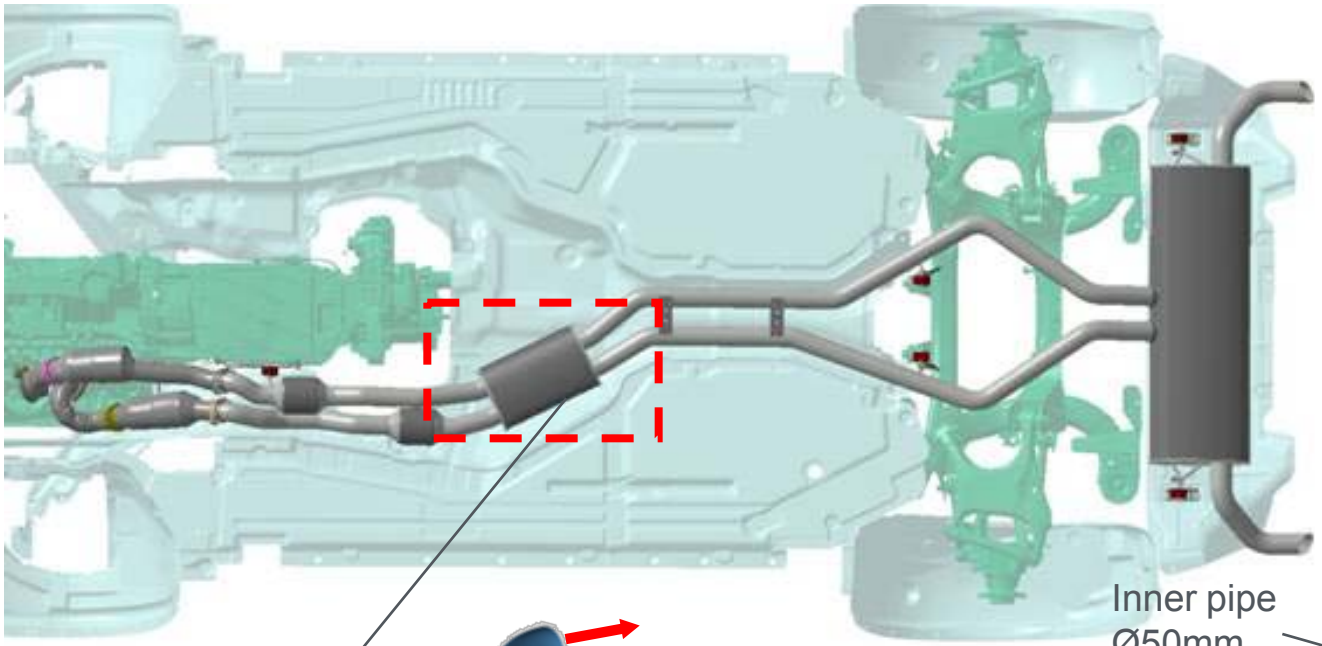


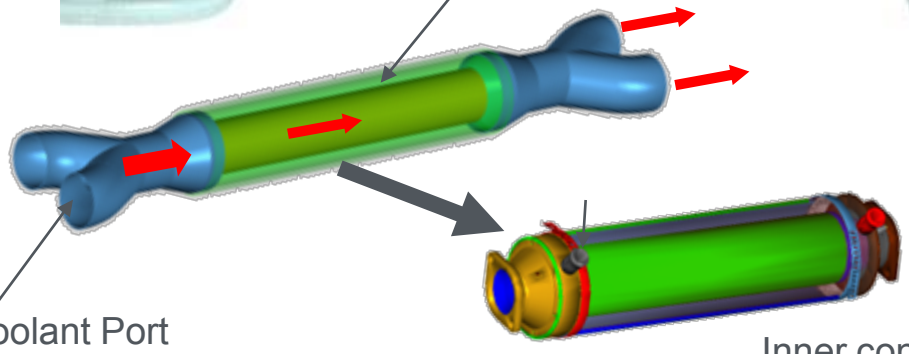


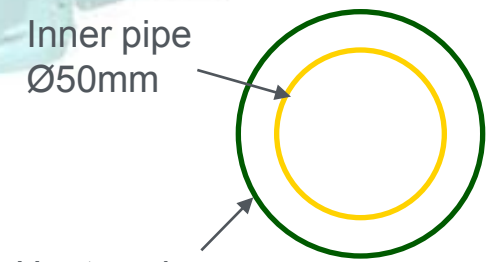


- Designed for 500 watt output driving at 120 kph
- 10.2 Kg weight
- Current 5 percent fuel savings for on-highway driving
- Increased performance anticipated with technologies in development

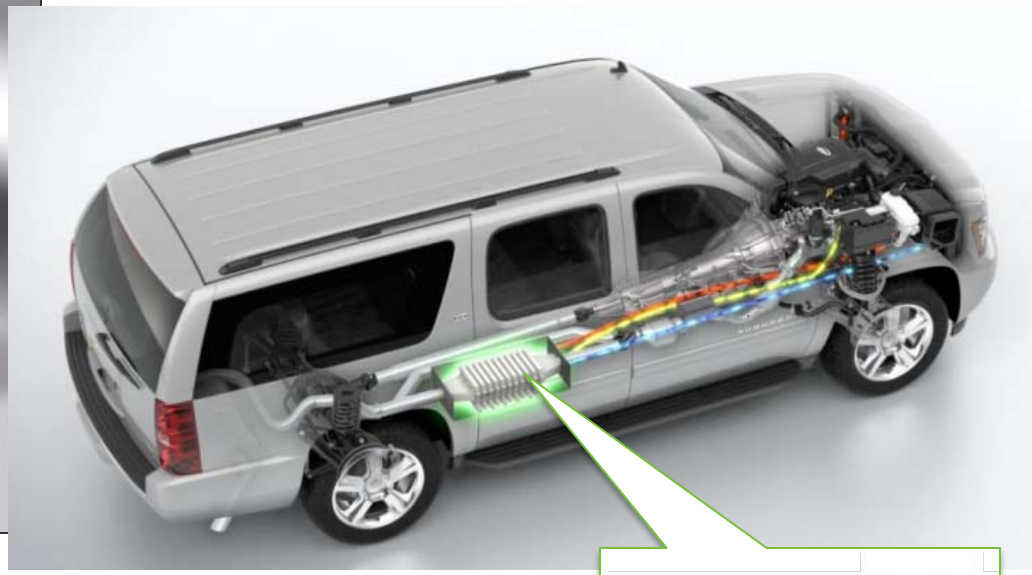
TEG Location on Ford Fusion:

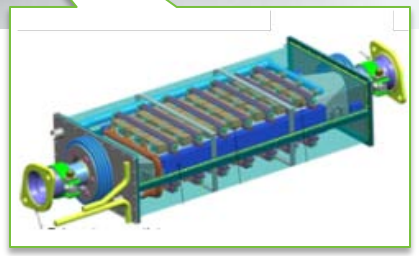






Prototype TEG's In Ford Fusion, BMW X6 and Chevy Suburban- DOE Programs





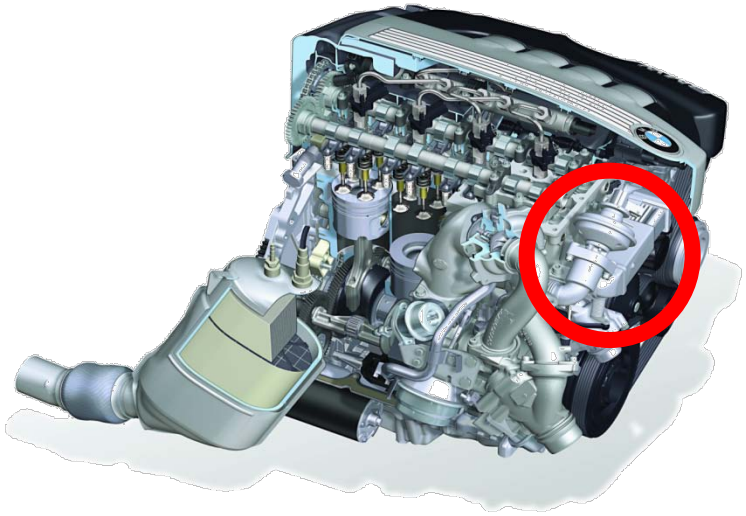
Thermoelectric Power Generation – Analytical Projections for BMW Sedans

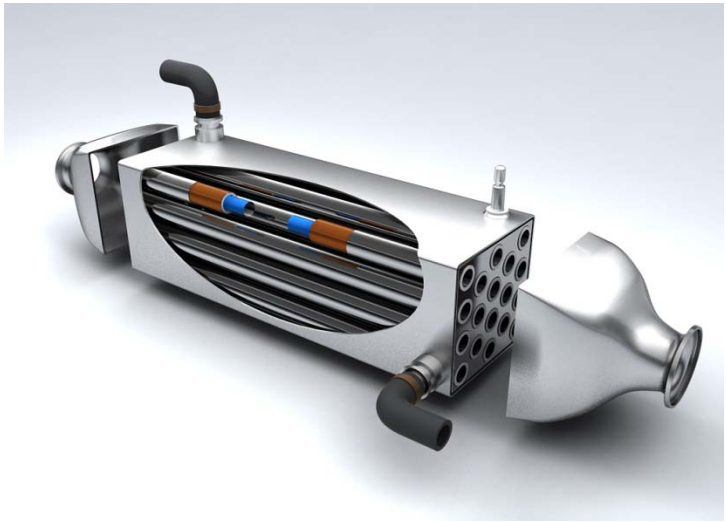
Average demand for electric power
Fraction of electricity on total FC.

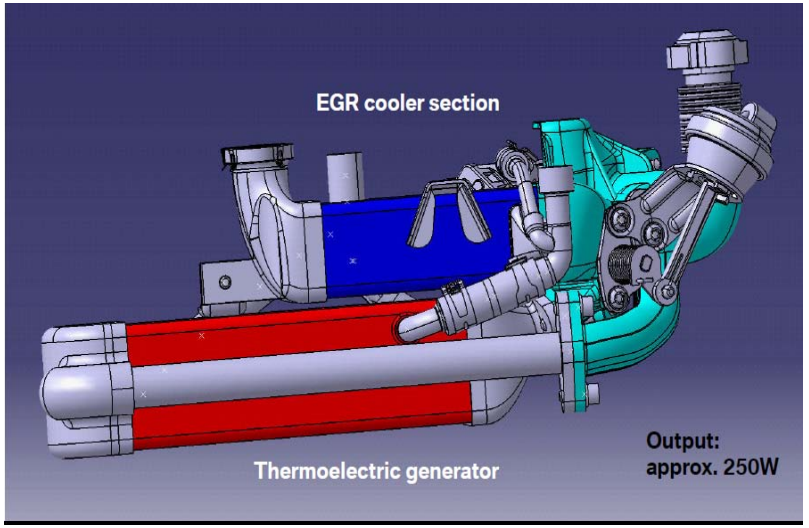
	116i	530dA	750iA
NEDC	190 W 2%	390 W 4%	400W 4%
customer	330 W 3,5%	750 W 6%	1000 W 8%

Source: BMW Group

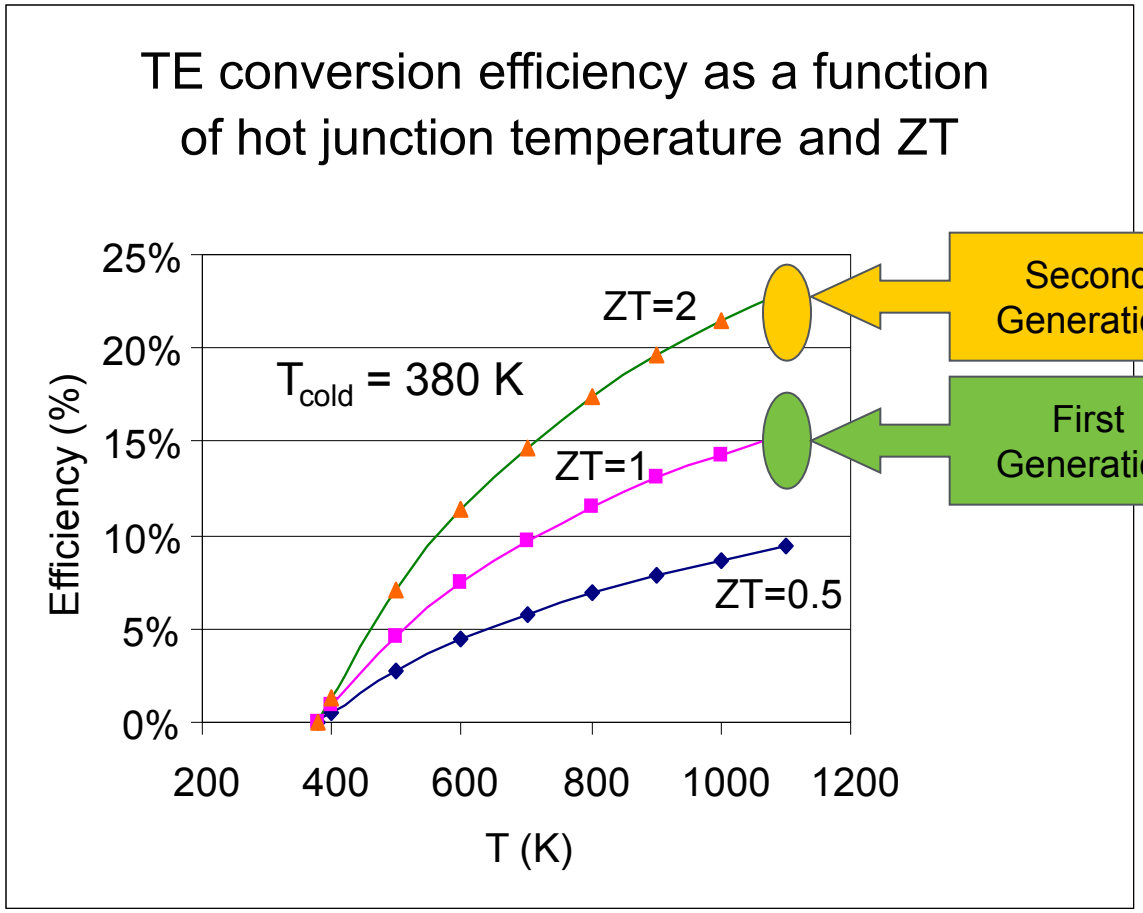
BMW Exhaust Gas Recirculation (EGR) Cooler-TEG on Diesel Engine







TE Materials Performance Objective



Second Generation

First Generation

TE Materials for Vehicular TE Generators

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

Carnot | TE Materials

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
- Large volume commercial availability

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

- Competitive Awards to teams led by Ford and GM (September 2009)
- Co-funded with the California Energy Commission
- Objective: Develop Thermoelectric Zonal or Distributed Cooling/ Heating Concept
  - Maintain occupant comfort while reducing vehicle fuel consumption
  - Reduce energy used for automotive HVAC's by >30%
  - Integrate with compressor downsized by ~1/3
  - Develop production prototype
  - Integrate, test, and deliver TE HVAC in a 5-passenger vehicle
  - Eliminate all toxic, greenhouse, and flammable gases associated with automotive HVAC

Concept of Zonal Thermoelectric Air Conditioner/Heater (HVAC)

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

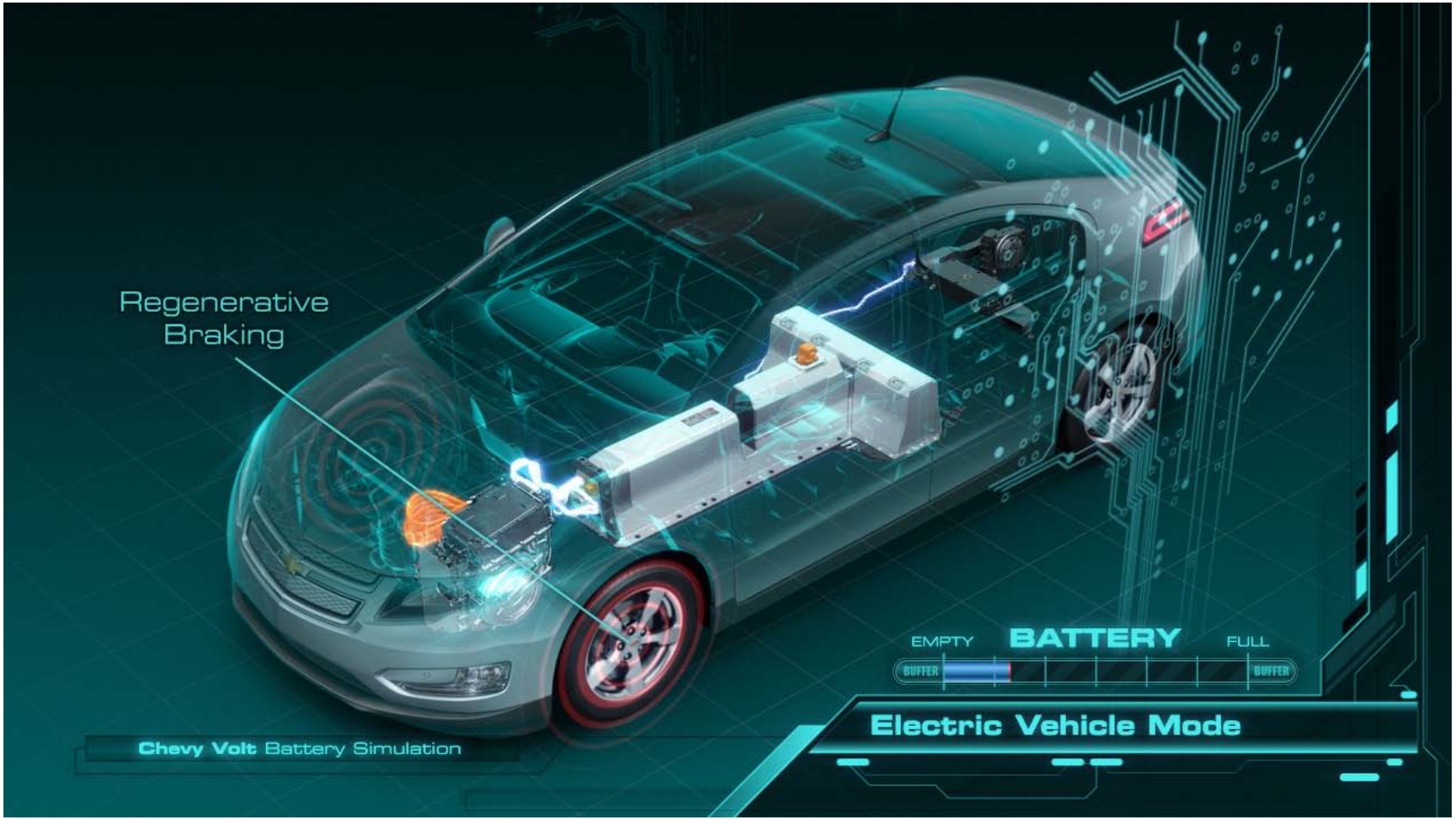
Thermoelectric HVAC Advantages for Plug-in Hybrids and Electric Cars

- Occupant Heating During Battery Propulsion (No Engine Heat)
  - Inefficient Electrical Resistance Heating Occupant Cooling
  - Electric vapor compression refrigeration needs R134-a replacement refrigerant gas
- Thermoelectric HVAC Zonal Concept
  - Cooling COP > 1.5; can augment or replace compressed refrigerant gas unit
  - Heating COP > 2.5; can replace electrical resistance heaters with typical heating COP ~ 1.0

Market Factors Impacting Automotive Thermoelectric Applications

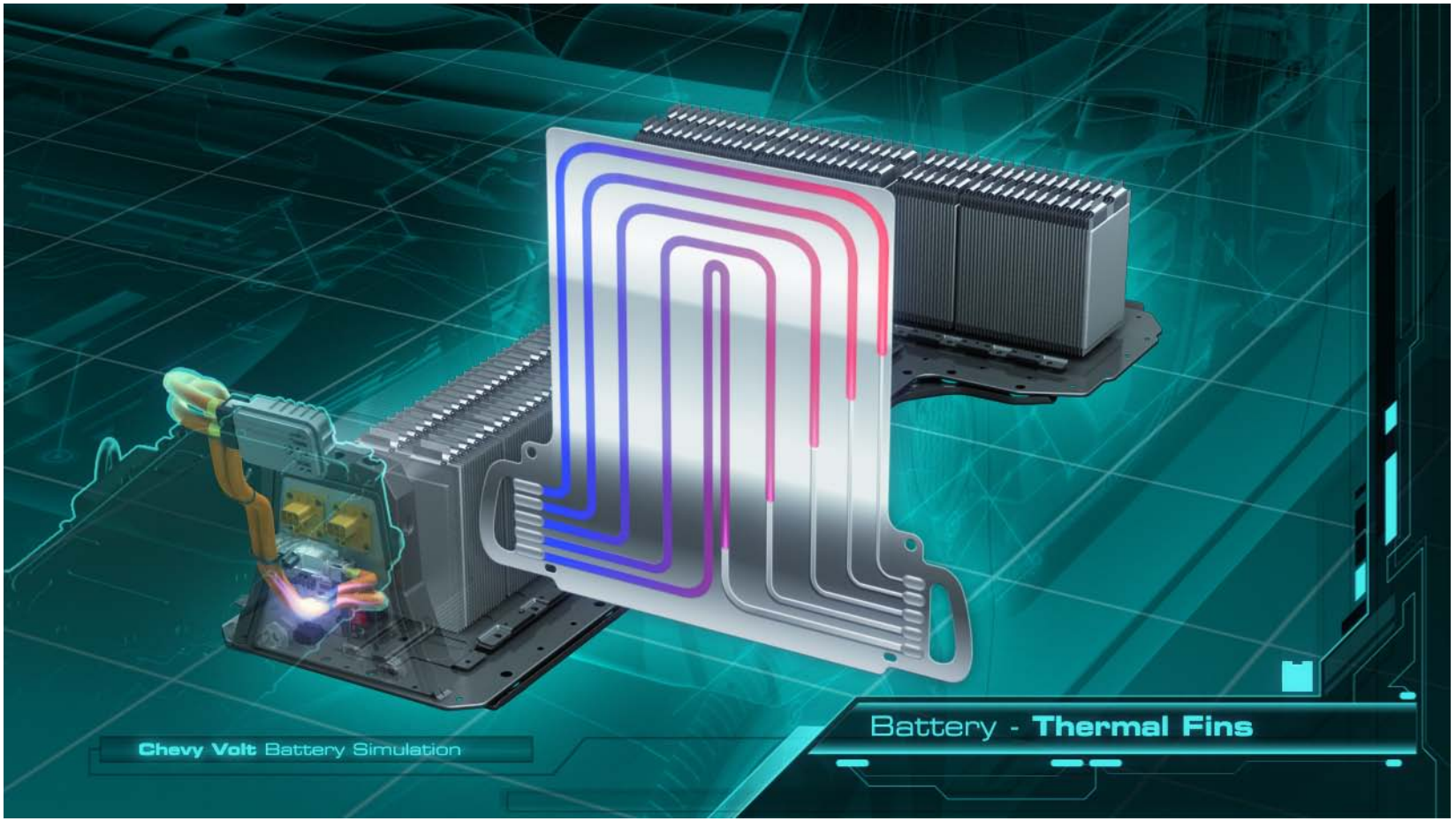
- Dramatic increase in demand for large quantity of thermoelectric materials
- Historically, semiconductor costs decrease with volume; thermoelectrics should follow this trend
- Automotive industry continually wants “new and improved” technology
- Increasing gasoline/diesel prices
- Fuel economy requirements and emissions regulations

Volt Battery Location

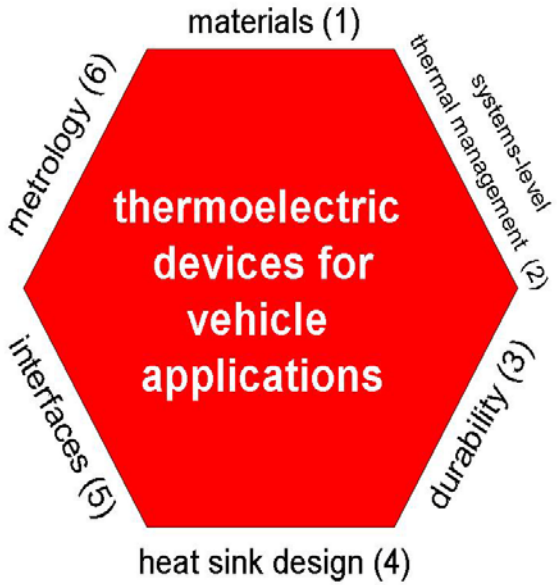


Li-Ion Battery Pack for Chevy Volt

Chevy Volt Battery Thermal Fins



University/industry collaboration, $9M/yr over 3 years
LOIs were due May 21, 2010
Proposals due June 22, 2010



Key Element 1: Materials.
Key Element 2: Thermal management.
Key Element 3: Durability.
Key Element 4: Interfaces
Key Element 5: Heat sink design.
Key Element 6: Metrology.

Advanced Combustion Engine R&D Budget by Activities

Major Activities	FY 2008 Appropriation ($000)	FY 2009 Appropriation ($000)	FY 2010 Appropriation ($000)	FY 2011 Request ($000)
Advanced Combustion Engine R&D	**$44,591**	**$40,800**	**$57,600**	**$57,600**
Combustion and Emission Control	38,815	35,089	47,239	47,239
Solid State Energy Conversion	*4,527*	*4,568*	*8,748*	*8,748*
SBIR/STTR	1,248	1,143	1,613	1,613

Summary

- DOE initiated the development of thermoelectrics for vehicular applications to enhance transportation energy efficiency.
- Thermoelectric generators and zonal passenger heating/cooling with thermoelectrics are two applications that could enable at least a 10 percent improvement in fuel economy.
- Unique Federal laboratory expertise and facilities could be utilized to improve the conversion efficiency of thermoelectric materials.
- The combination of enhanced thermoelectric materials, more stringent CAFE standards, and market forces would improve the commercialization potential of vehicular thermoelectrics.

THERMOELECTRICS: THE NEW GREEN AUTOMOTIVE TECHNOLOGY

Thank You!

http://www1.eere.energy.gov/vehiclesandfuels/technologies/engines/index.html

The 3rd Thermoelectric Applications Workshop (2011)

- Castine, ME?