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Vehicular Thermoelectrics: the New Green Technology

John W. Fairbanks
Department of Energy
Vehicle Technologies Program

Presented at the
DEER 2010
Detroit, Michigan
September 29, 2010

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

- Generate Electricity without Introducing any Additional Carbon into the Atmosphere

- Maintain Vehicle Occupant Comfort With Major Reduction of Fuel Use

- Eliminate Vehicular Use of R134a Refrigerant Gas which has 1300 times Greenhouse Gas Effect as CO_2, the Primary Greenhouse Gas

Journalism vs. Engineering

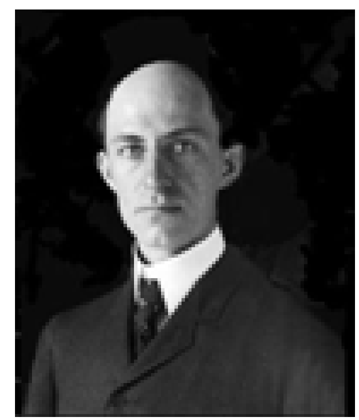
The New York Times

"The flying machine which will really fly might be evolved by the combined and continuous efforts of mathematicians and mechanicians in from one million to ten million years"

October 9, 1903

"We started assembly today"

Orville Wright's Diary
October 9, 1903



Courtesy of DARPA

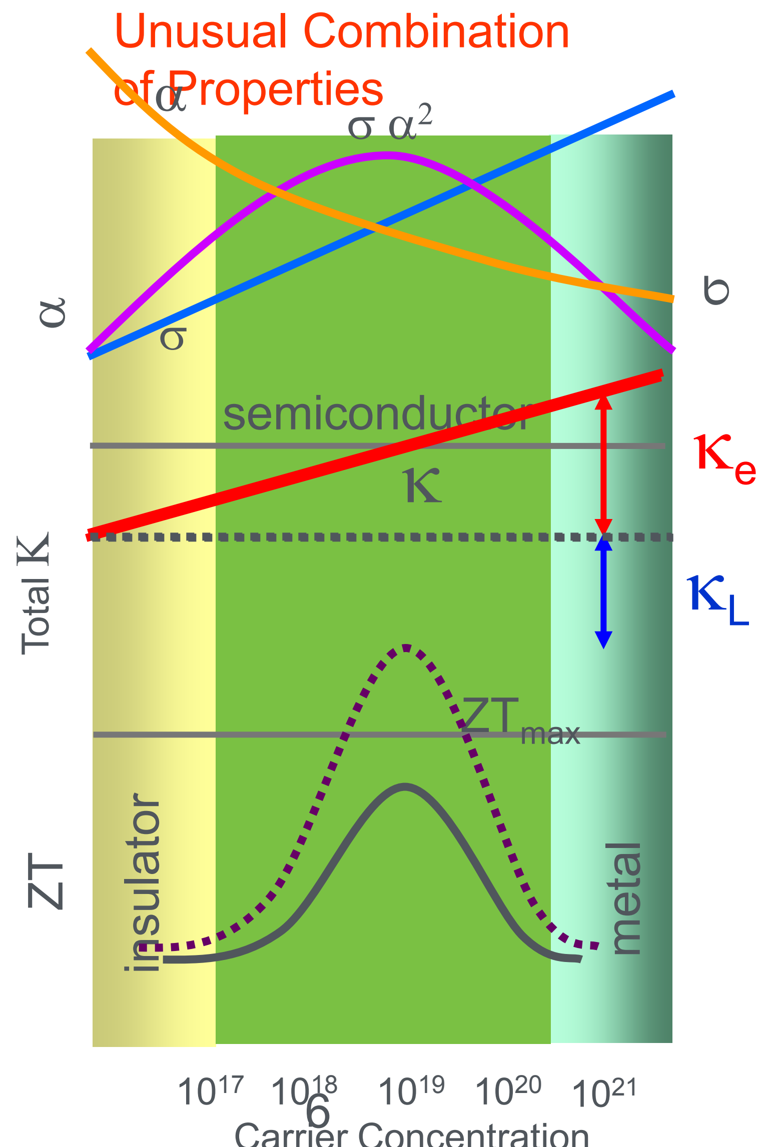
TE Materials Performance: Figure of Merit (ZT)

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

ρ = electrical resistivity

Nanoscale Effects for Thermoelectrics (courtesy Millie Dresselhaus, MIT)

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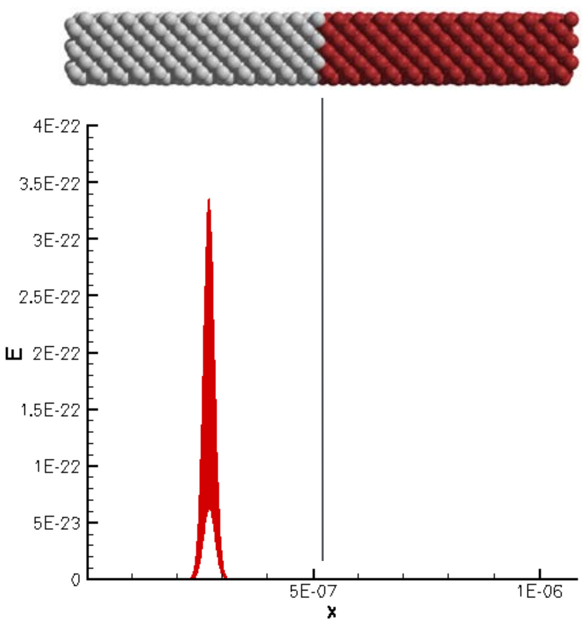
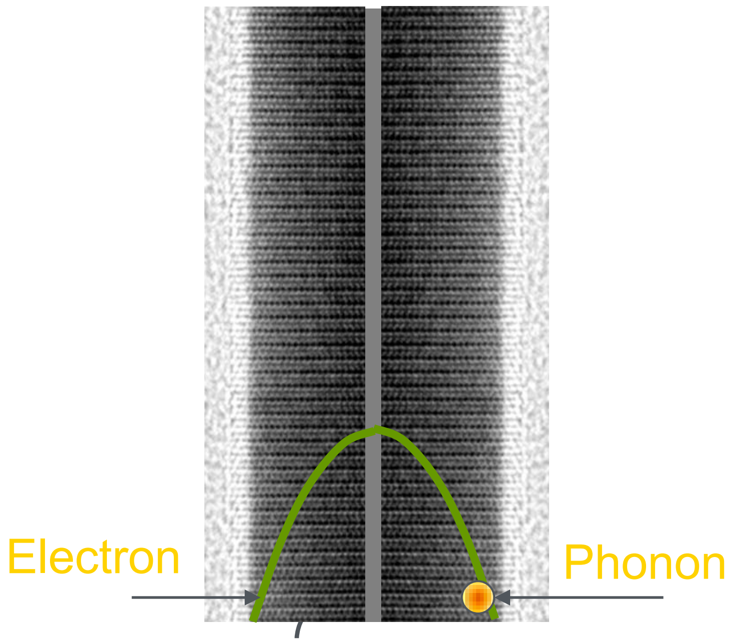
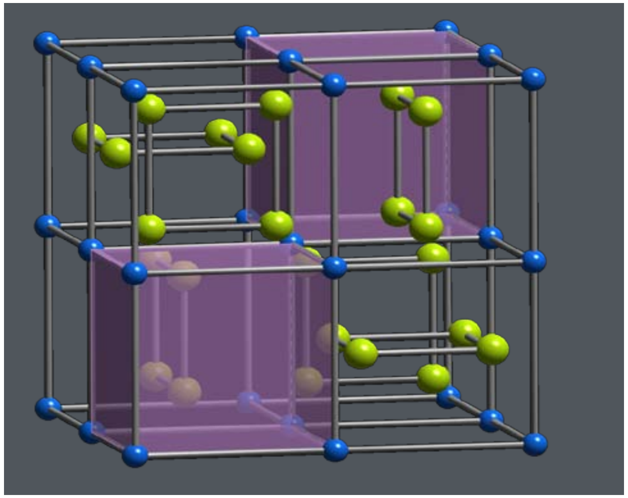
Interfaces that Scatter Phonons but not Electrons

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



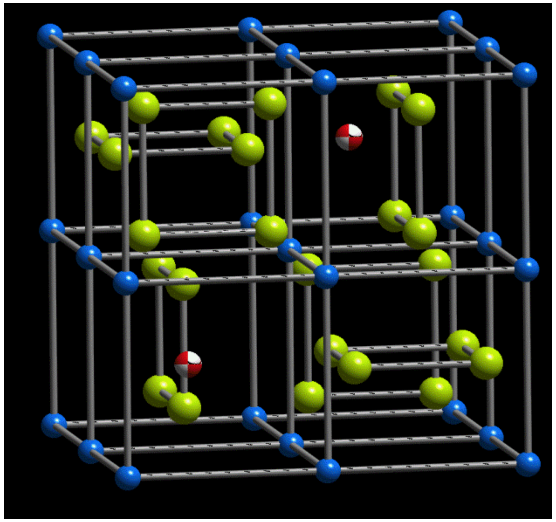


Crystal Structure of Skutterudite



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

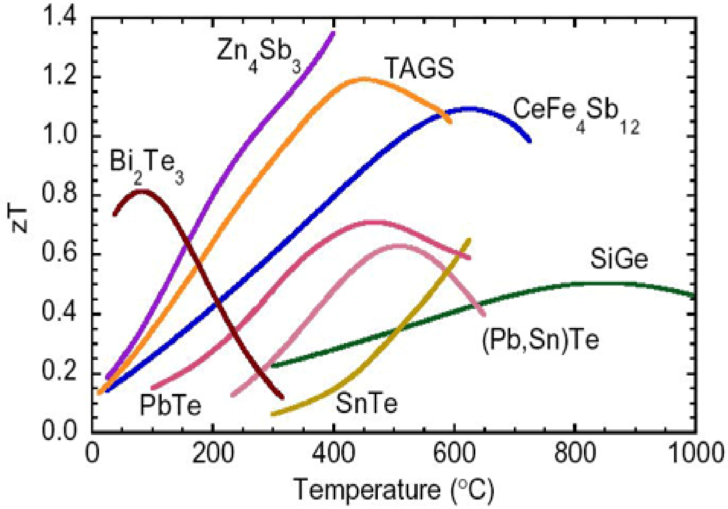
- Cobalt atoms form a *fcc* cubic lattice
- Antimony atoms are arranged as a square planar rings
- There are 8 spaces for the Sb_4 units
- 6 are filled and 2 are empty



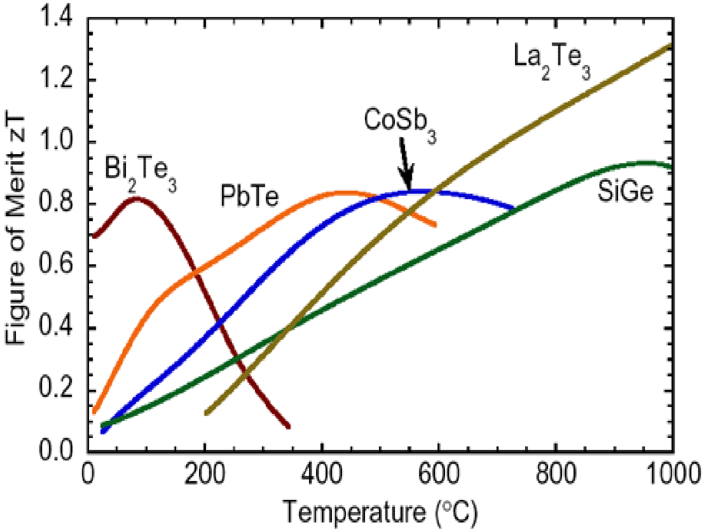
R_xCoSb_3

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

Current TE Materials



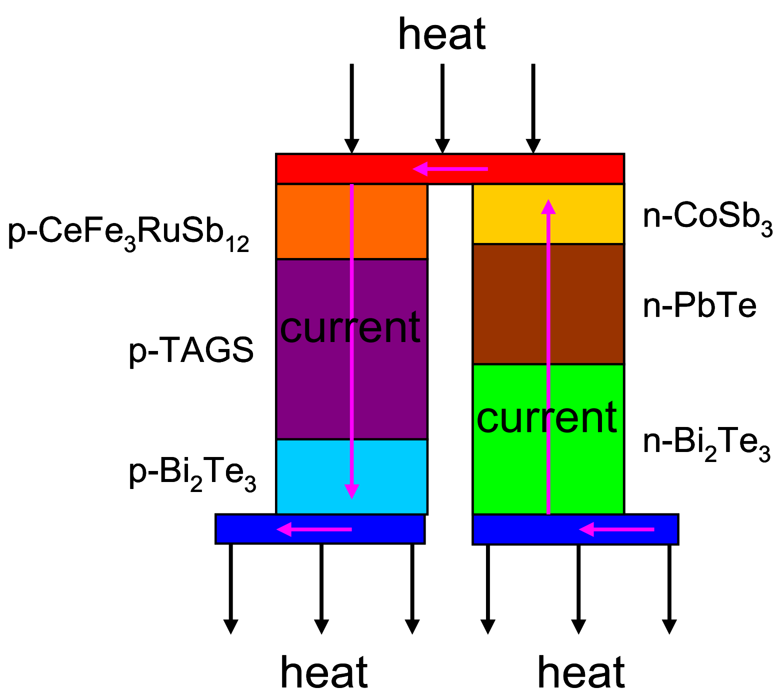
P-type TE material



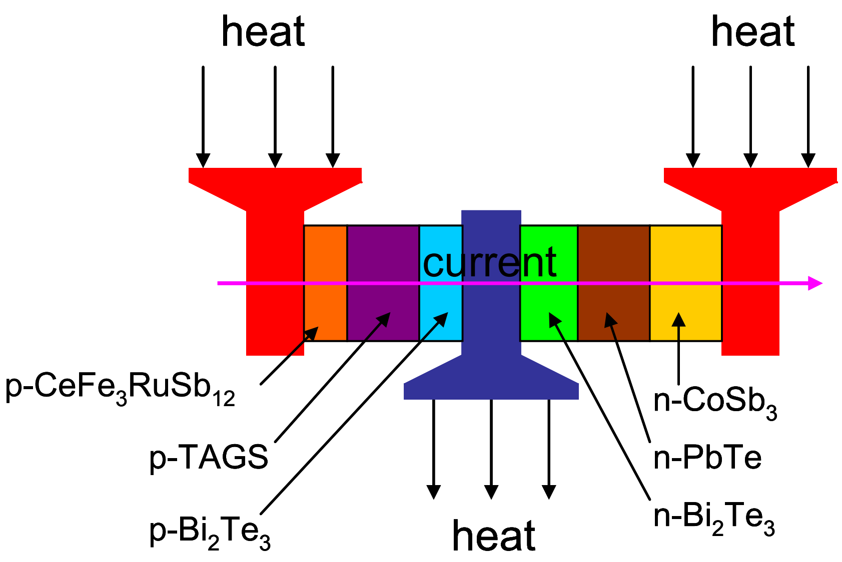
N-type TE material

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

BSST Y Segmented TE Configuration

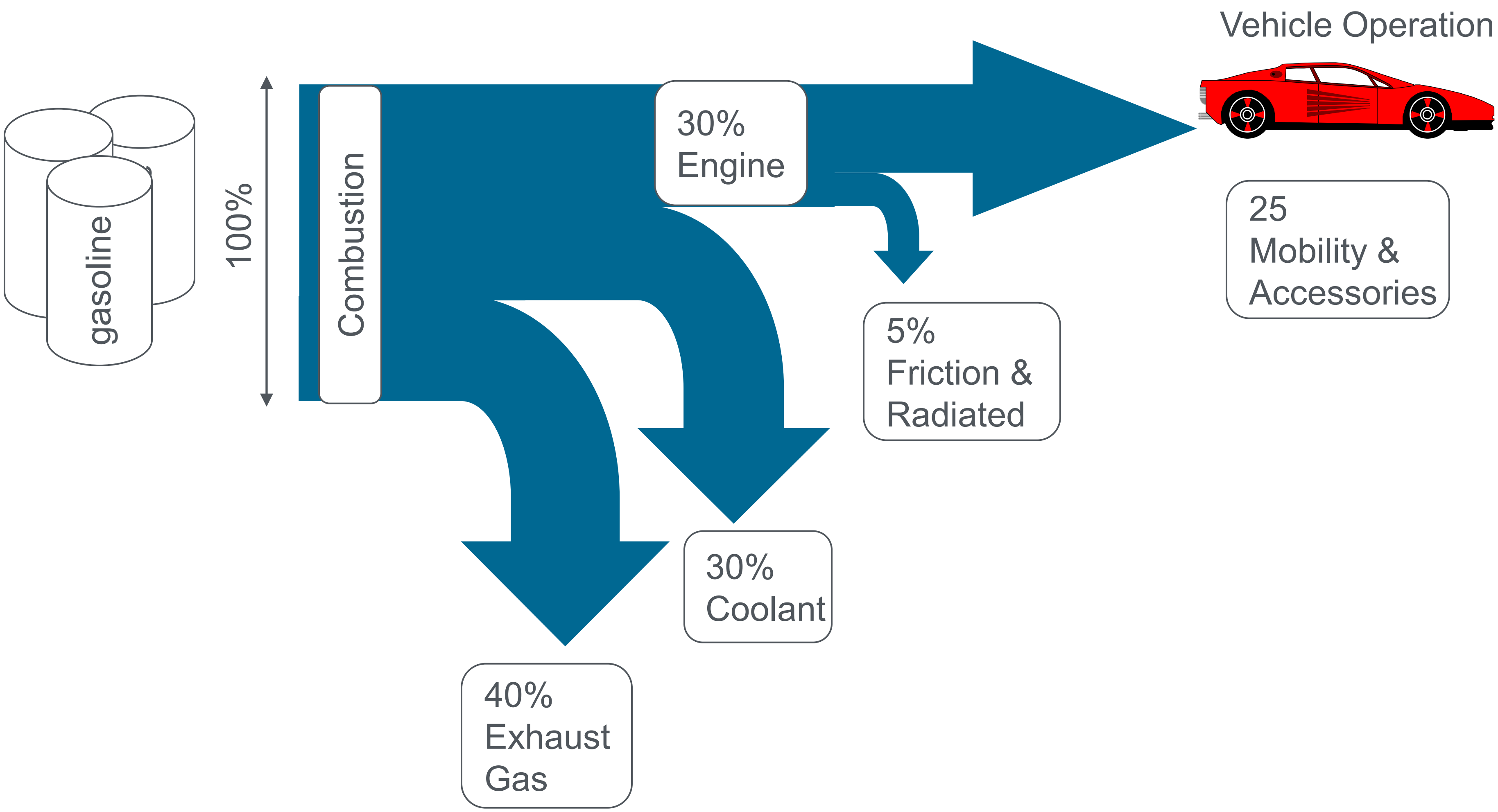


- Traditional configuration



- BSST “Y” configuration

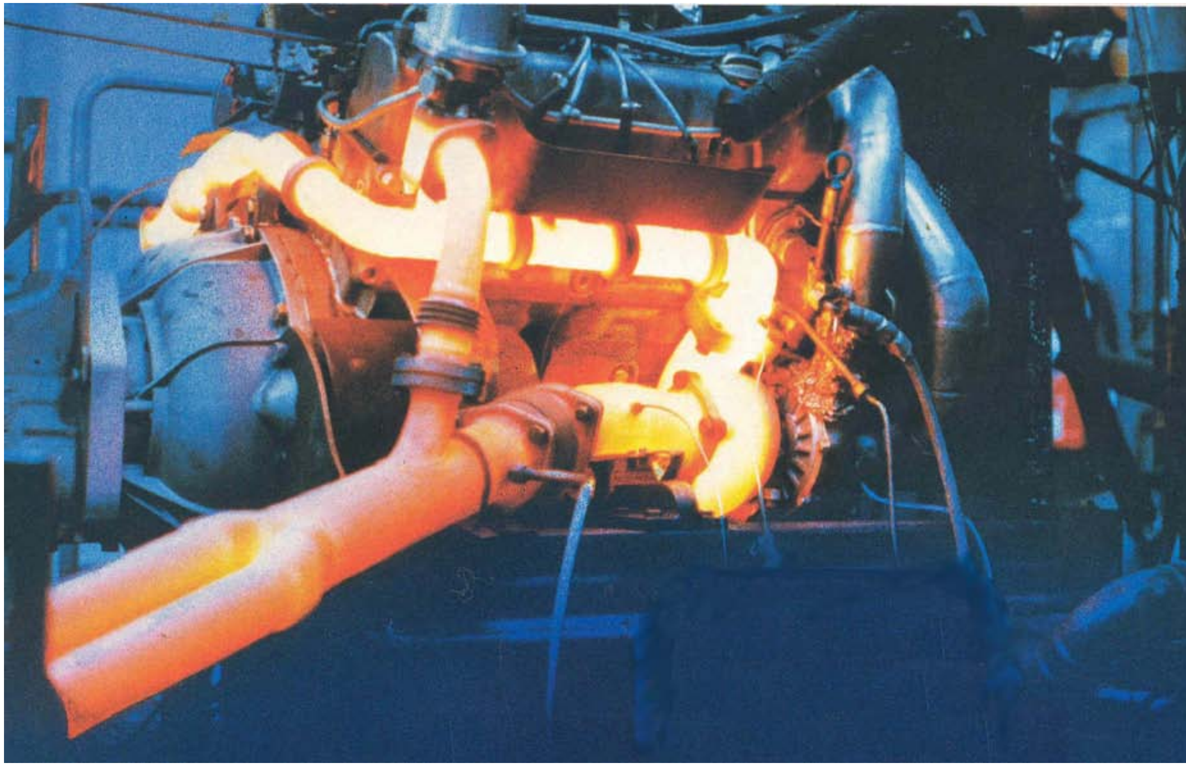
Typical Waste Heat from Gasoline Engine Mid Size Sedan



Thermoelectrics (Seebeck)

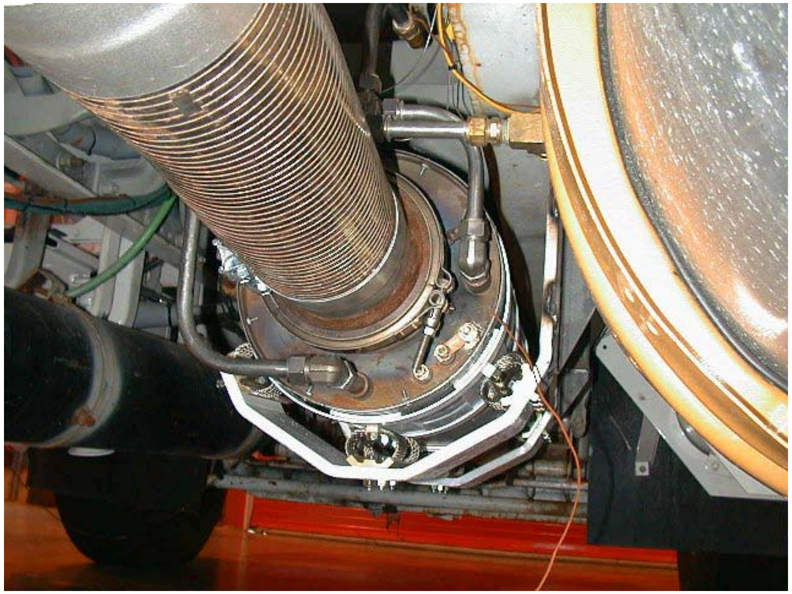
- Waste Heat Direct Conversion to Electricity
  Potential Applications;

Vehicles
Industrial Processes
Power Stations
Marine Propulsion
Off Highway
Locomotives
Aircraft Gas Turbine Engines
Geothermal
Department of Defense



Installed Thermoelectric Generator on Heavy Duty Truck circa 1994

Front View



Rear View

550 HP Heavy-Duty Truck with TEG (1994)

Engine – Caterpillar 3406E, 550 HP
PACCAR's 50 to 1 Test Truck
Heavily Loaded (over 75,000 lbs)
TEG Installed under the Cab

Competitive Award Selections (March 2004 RFP)

Awardees	Additional Team Members
High Efficiency Thermoelectric	
General Motor Corporation and General Electric	University of Michigan, University of South Florida, Oak Ridge National Laboratory, and RTI International, Marlow Industries
BSST, LLC.	Visteon, BMW-NA, Ford, ZT Plus
Michigan State University	NASA Jet Propulsion Laboratory Cummins Engine Company Tellurex, Iowa State

SI Engine Waste Heat Recovery Thermoelectric Generator Positioning

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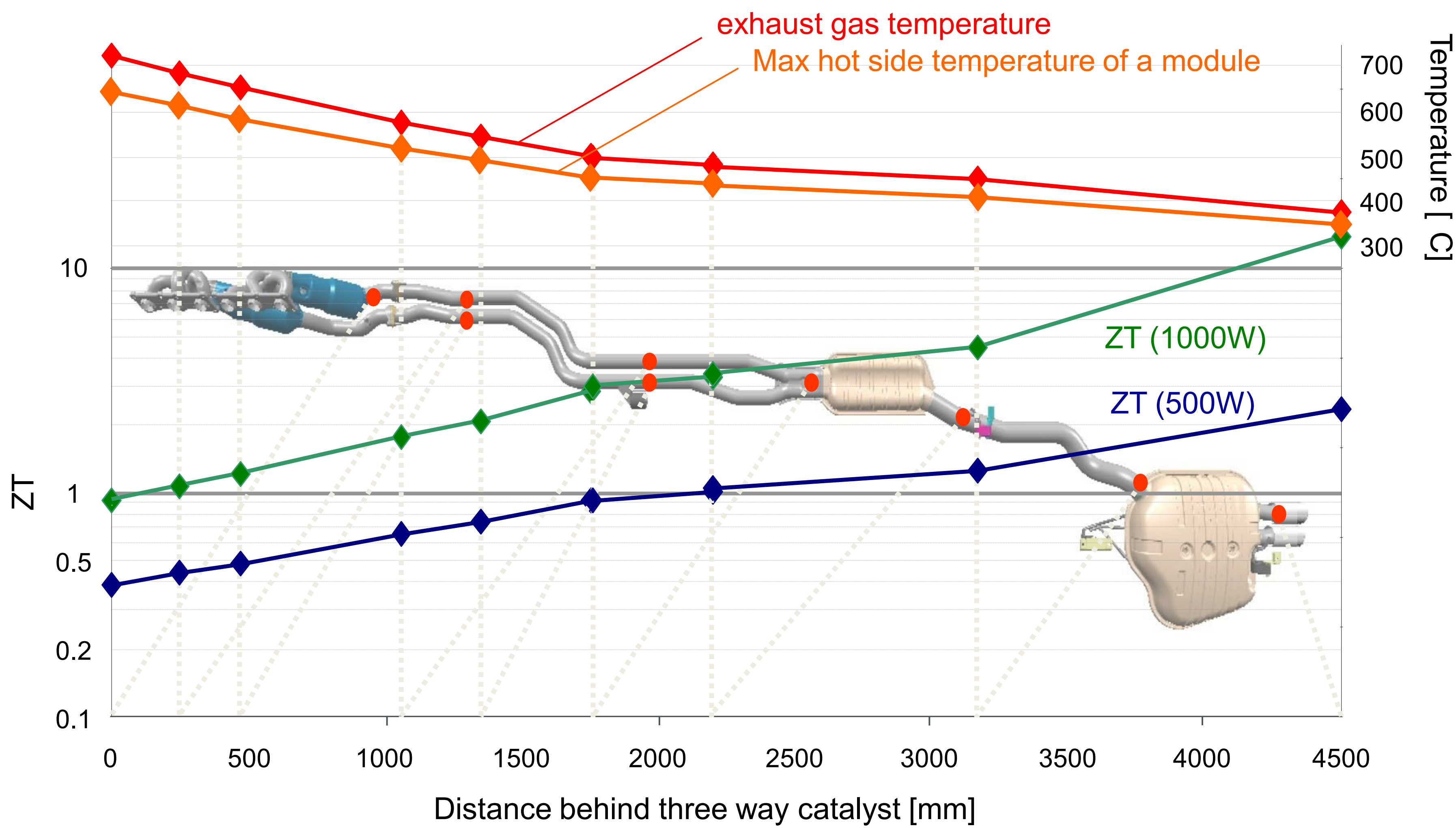
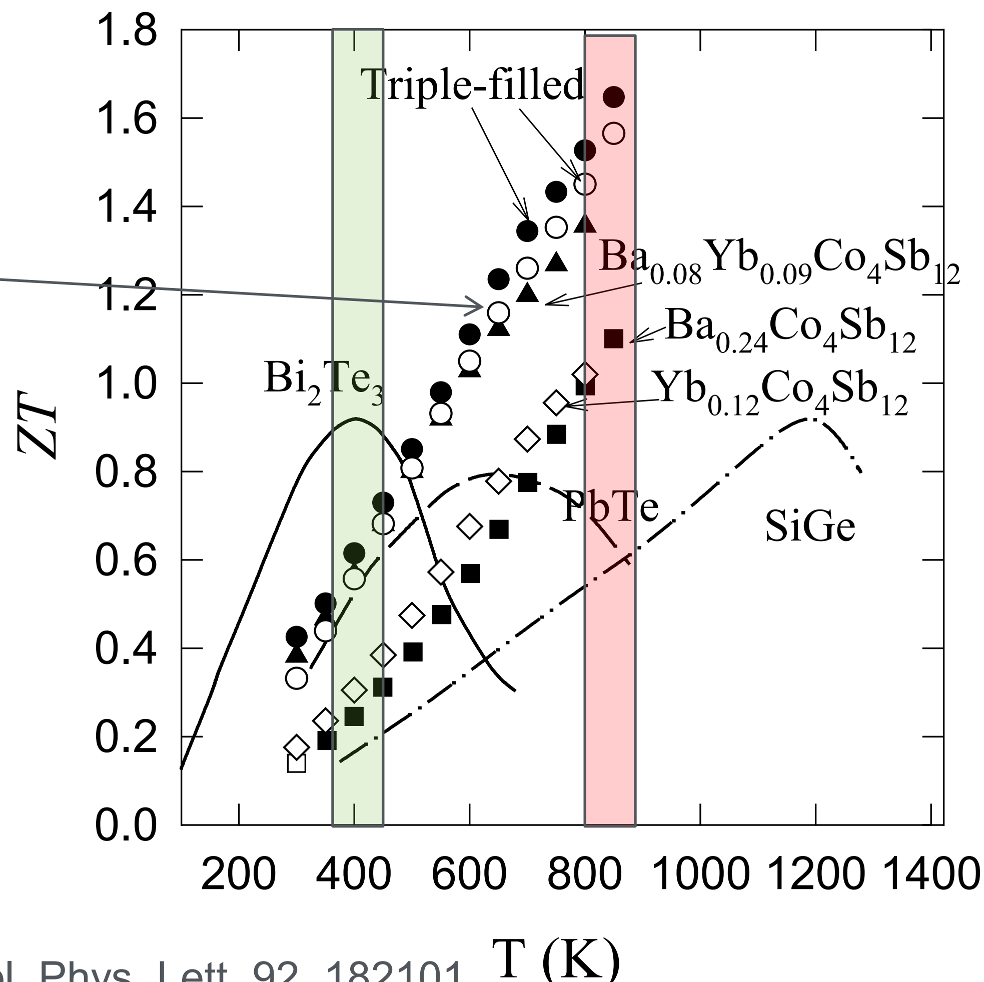


BMW 530iA at 130 km/h, Exhaust gas back pressure limited to 30mbar at 130km/h

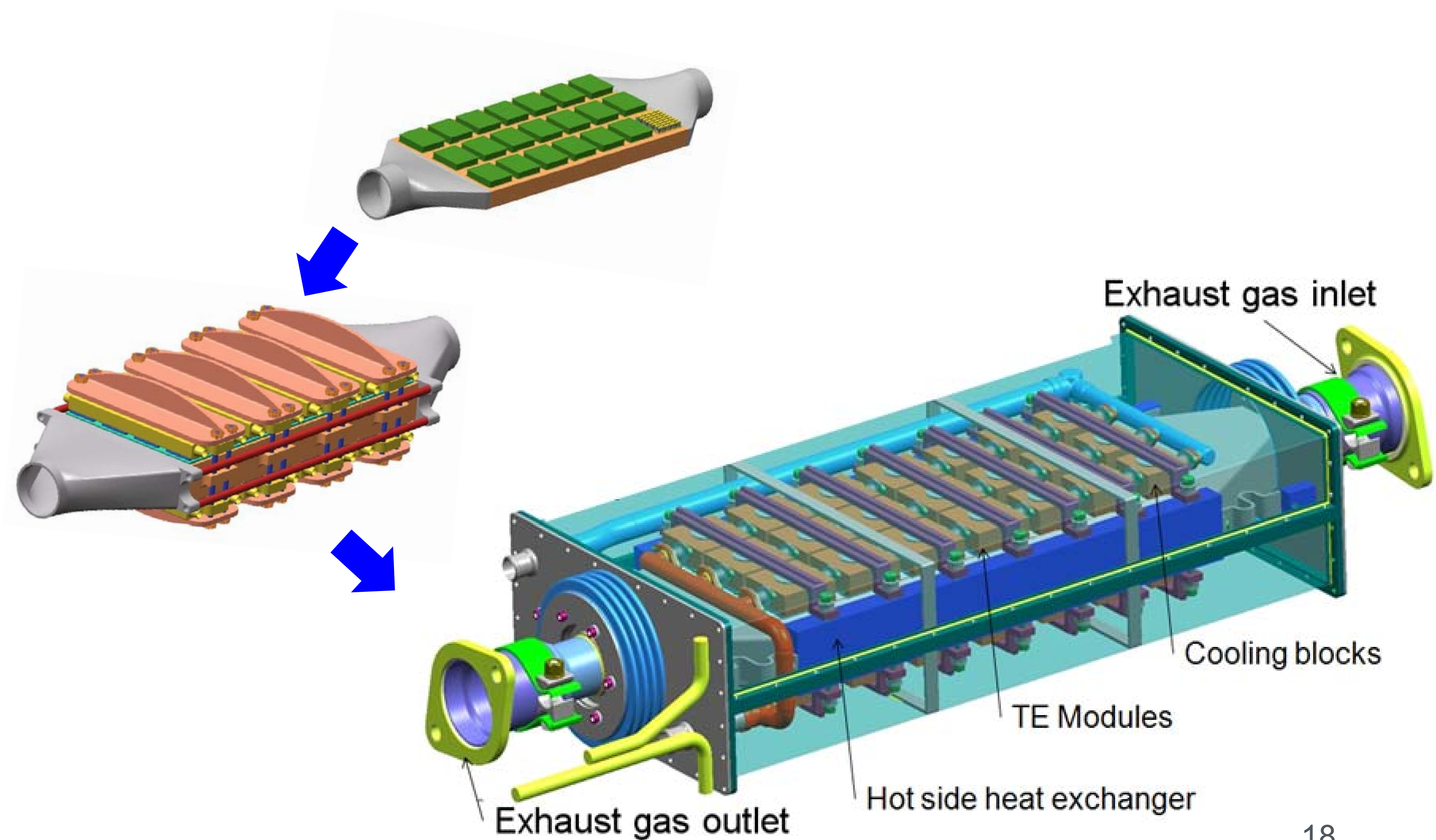
Highest ZT Achieved with Triple-filled Skutterudites

$ZT_{ave} = 1.2$

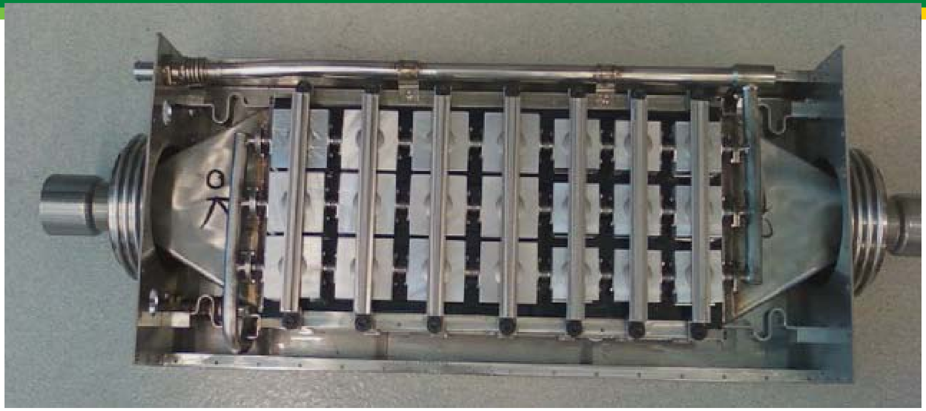


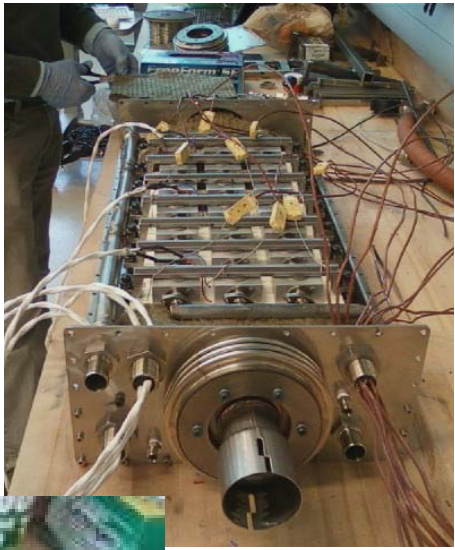
1. X. Shi, et al. Appl. Phys. Lett. 92, 182101 (2008)
2. X. Shi, et al., submitted (2009)

Iterative Designs of GM Prototype TEG

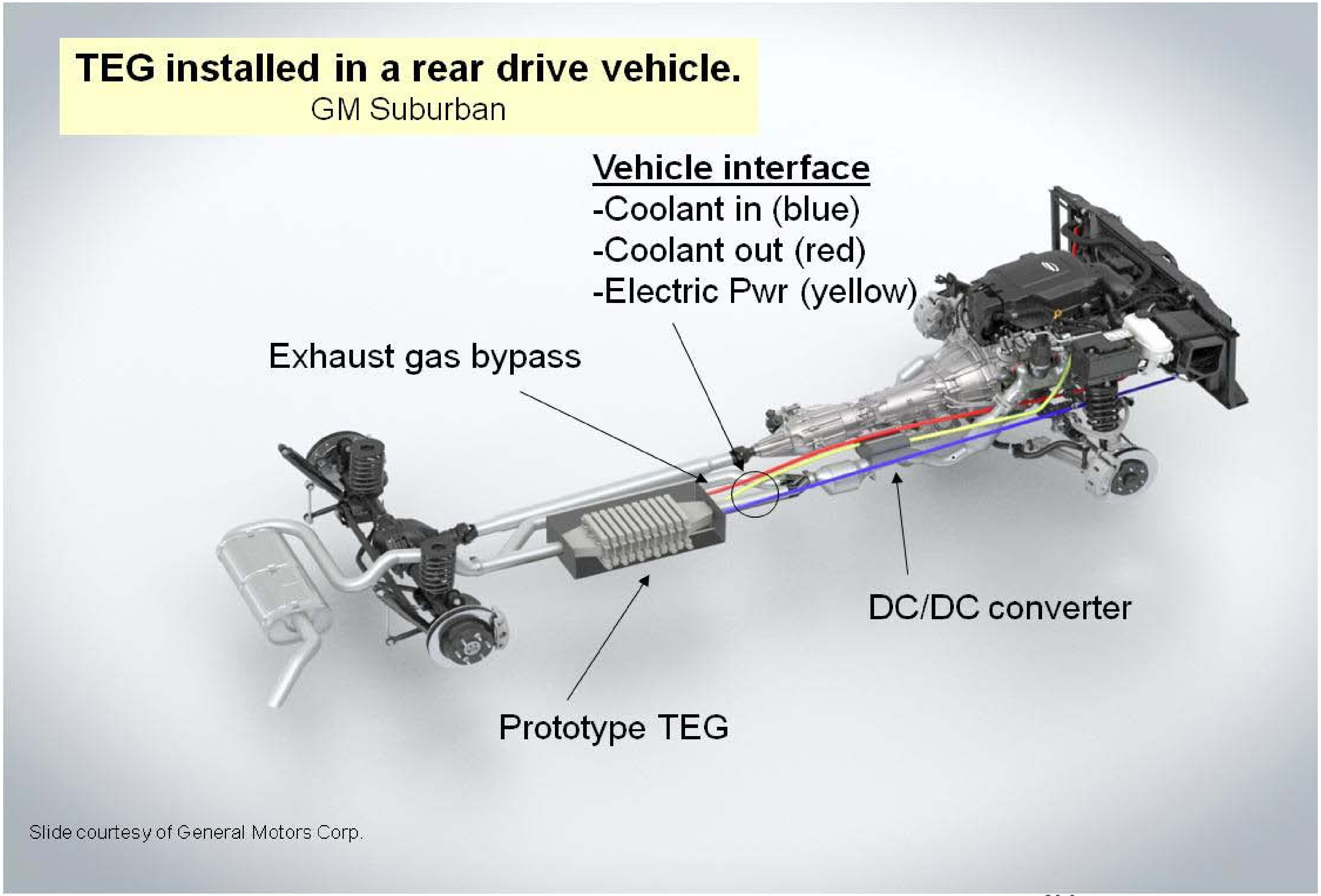


GM Production Prototype TEG

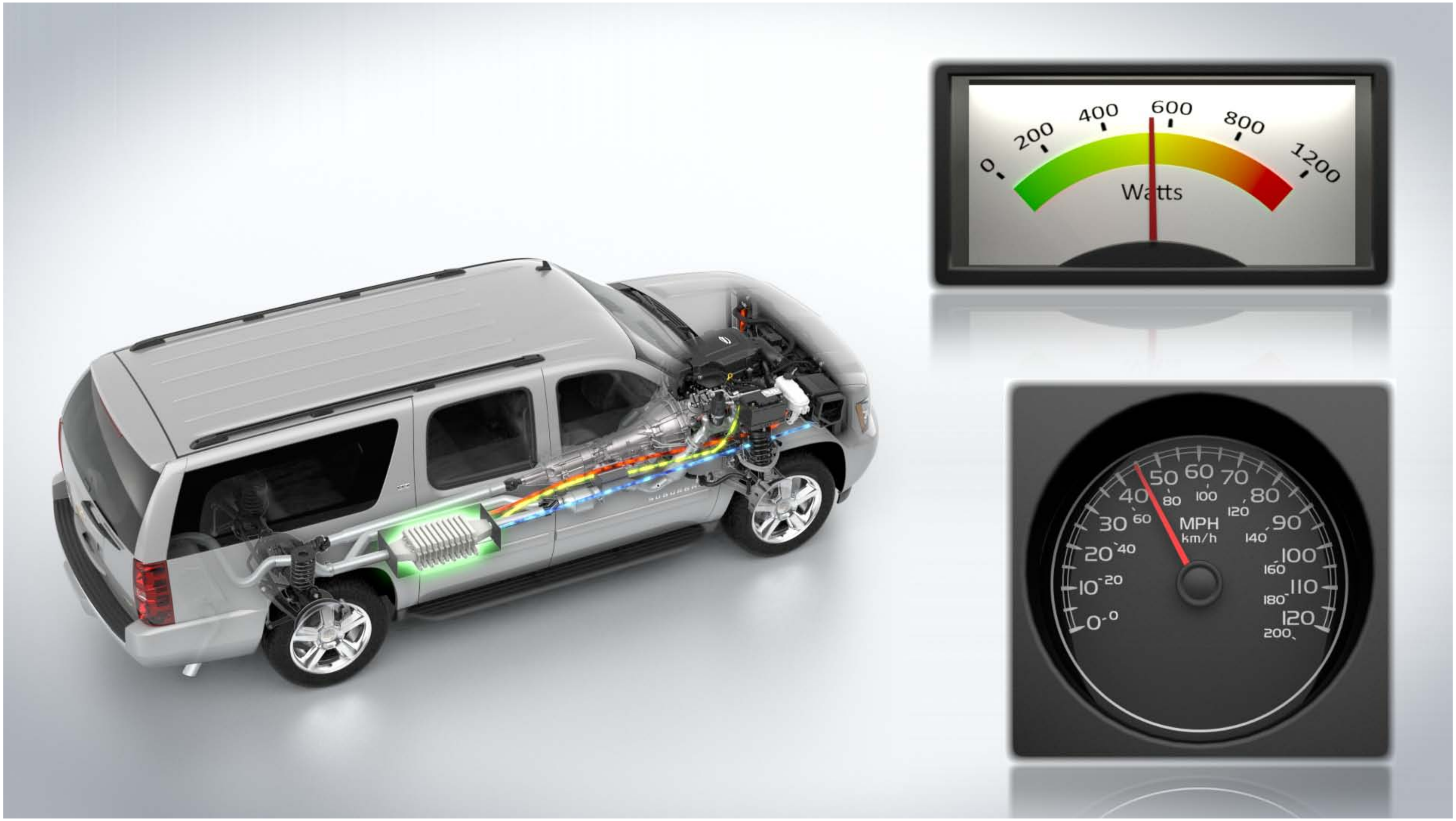




GM TE Generator on a Chevy Suburban Chassis



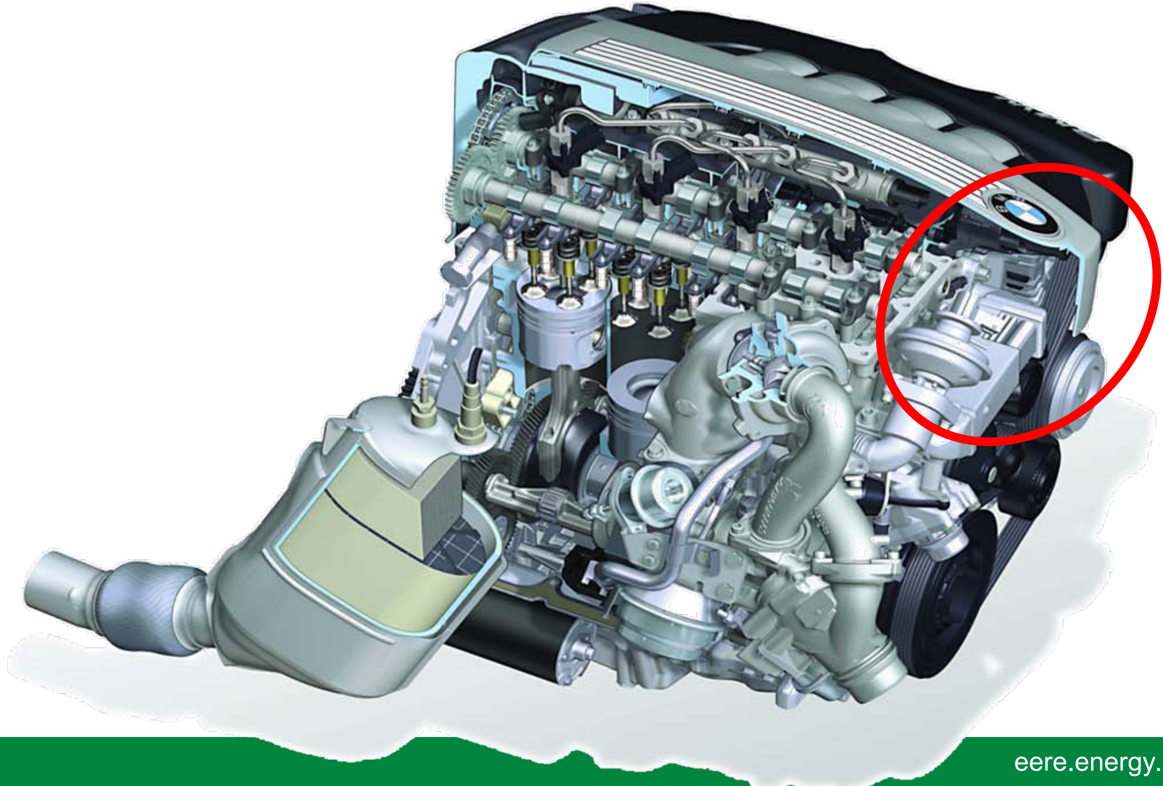
TEG installation in Chevy Suburban



BMW Exhaust Gas Recirculation (EGR)-TEG

BMW integrating a TEG with the EGR cooler of a Diesel engine.

The infrastructure for a TEG (water cooling, by-pass, exhaust-flap) is available in today's EGR coolers



Source: BMW Group

BMW Diesel Engine EGR TEG.

Source: BMW Group

BMW EGR-TEG

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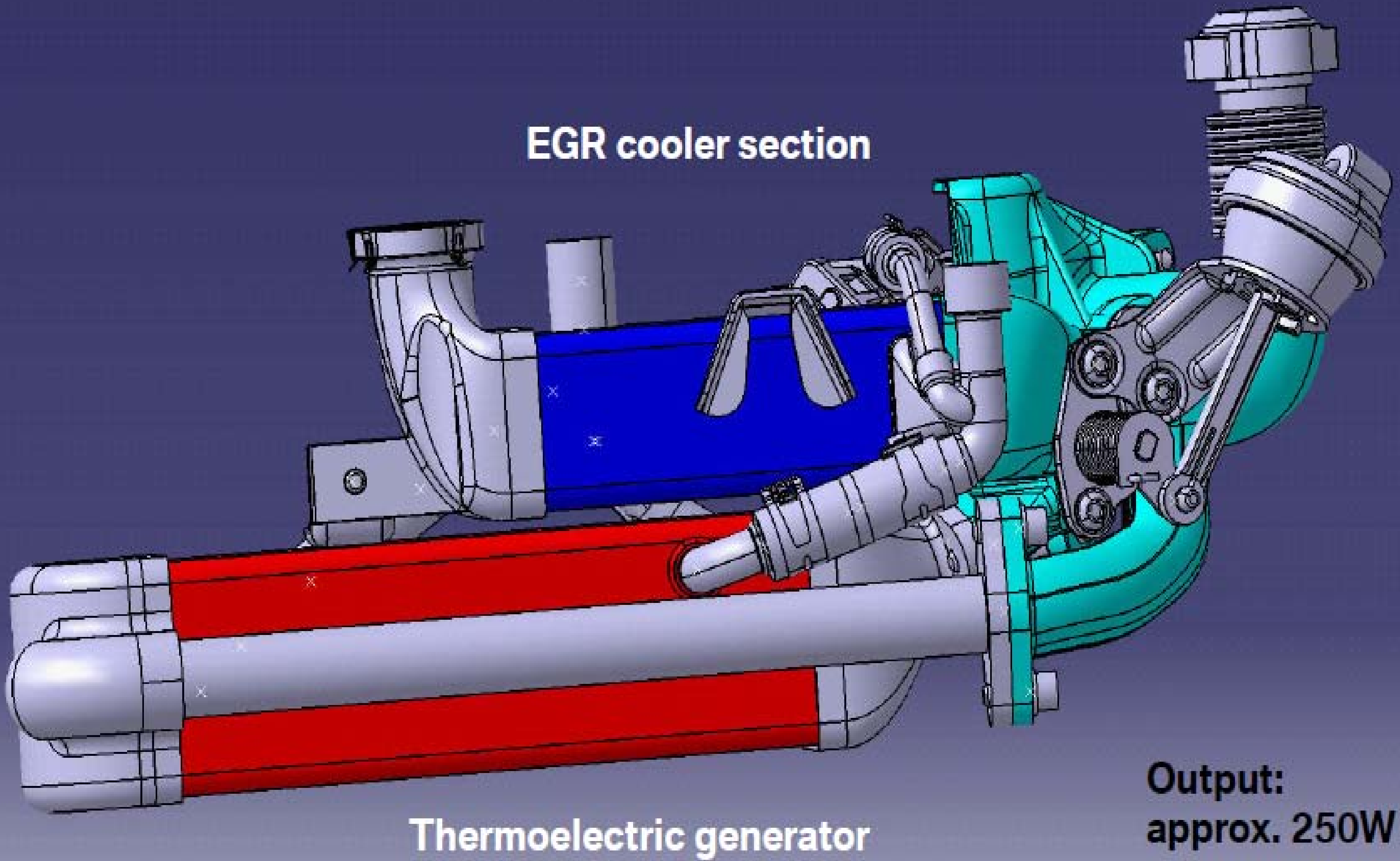
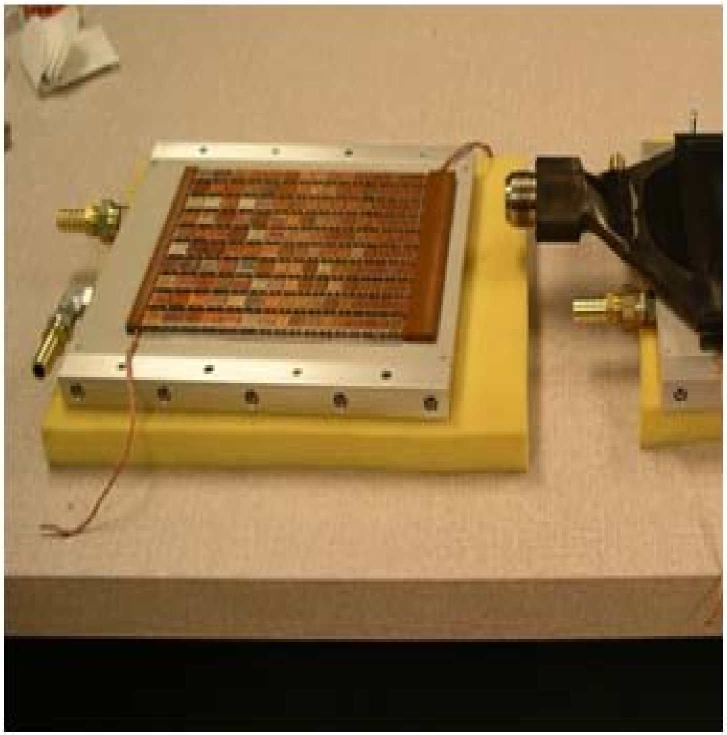
Source: BMW Group

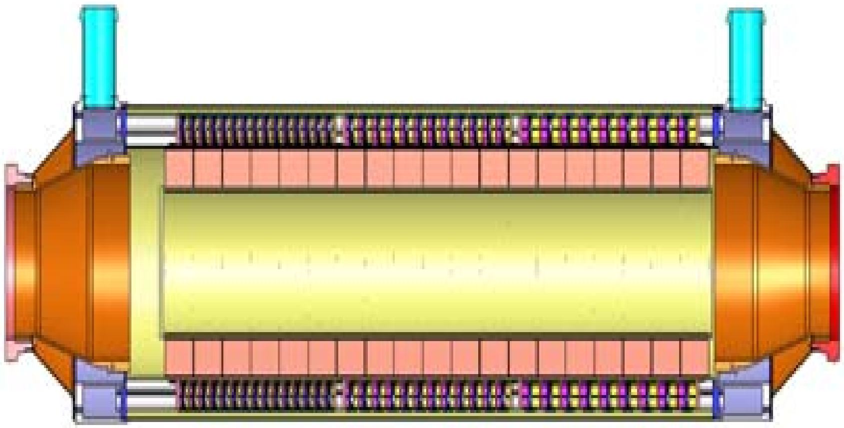
BMW EGR-TEG



Source: BMW Group

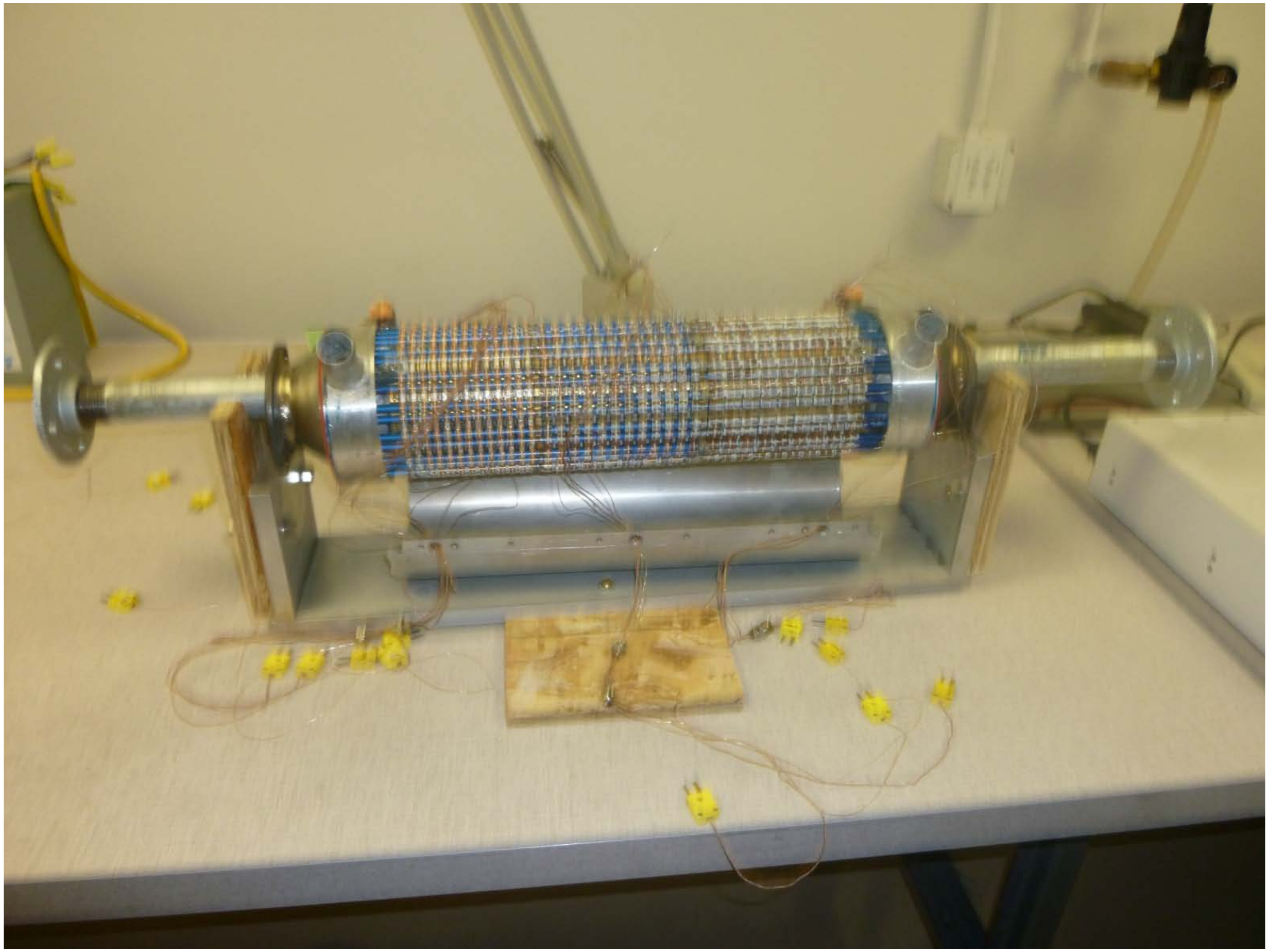
BSST 2D to 3D Design Iteration for Ford and BMW





Cross Sectional View of Preproduction Waste Heat Recovery TEG

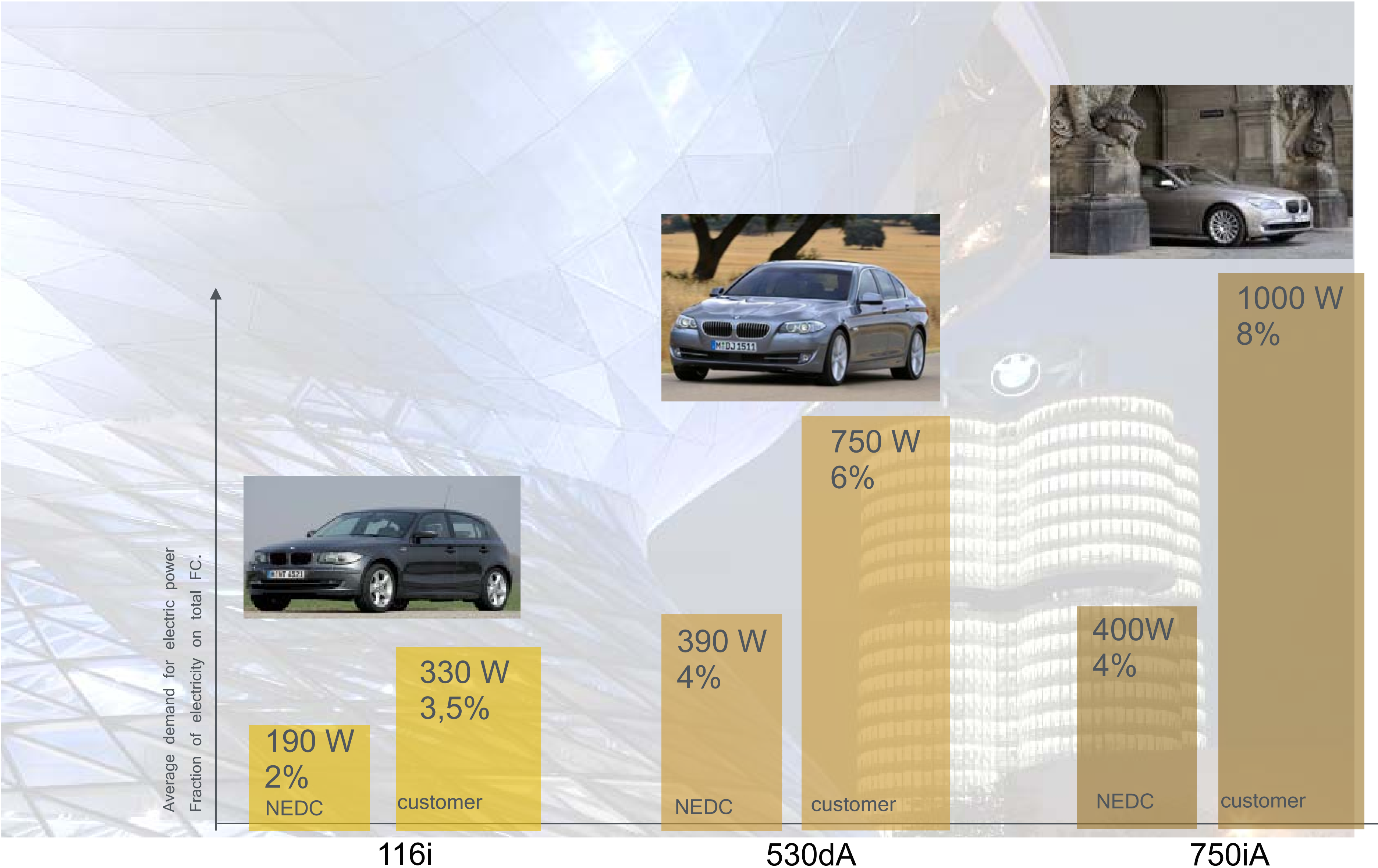
TEG for Ford Fusion and BMW X6



Fusion V-6 TEG Packaging

Demonstration TEGs In Ford Fusion, BMW X6 and Chevy Suburban

Thermoelectric Generators – BMW Accelerating to Achieve CO_2 Reductions



International Thermoelectric Conference 2009 – Frieburg, Germany

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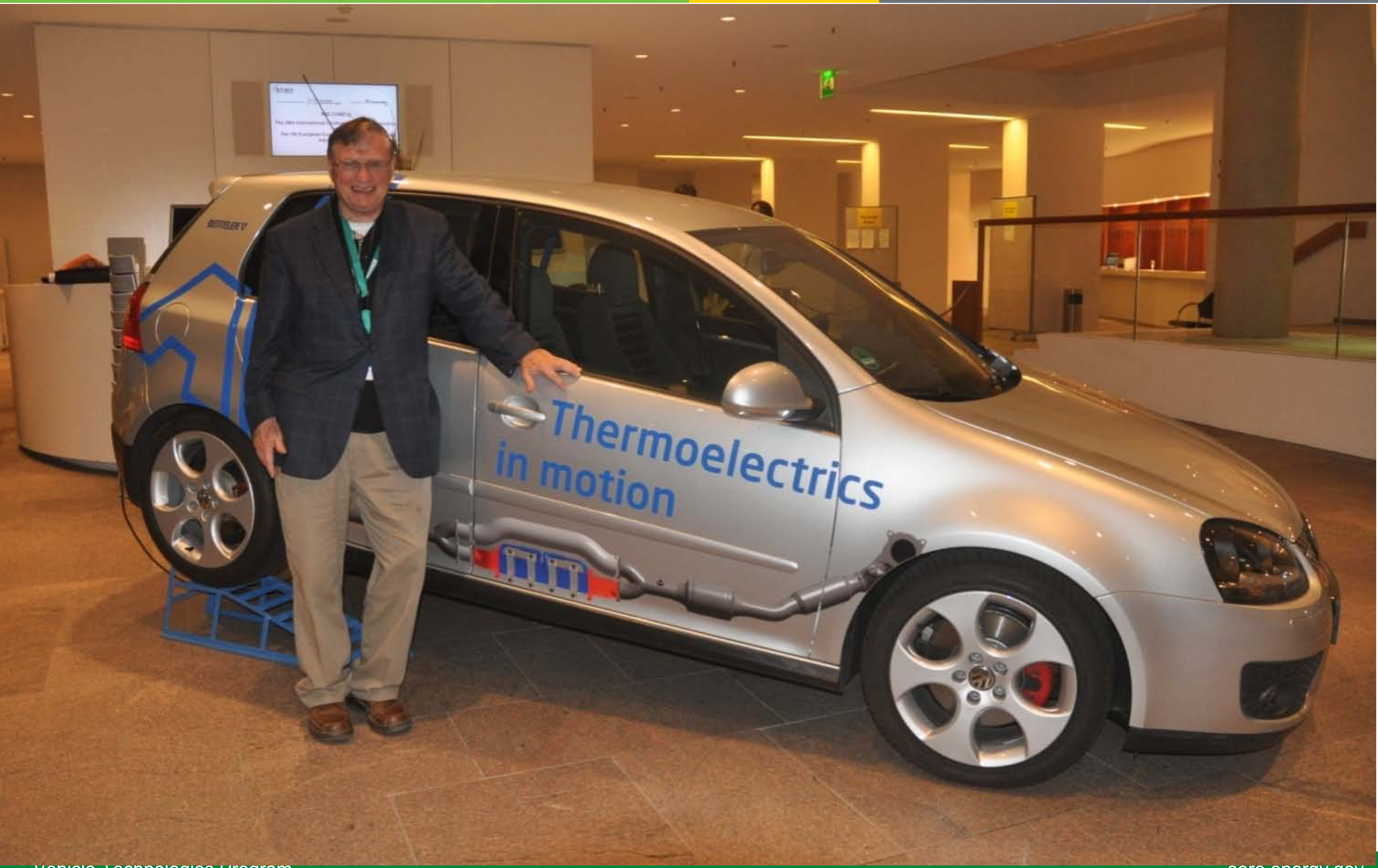
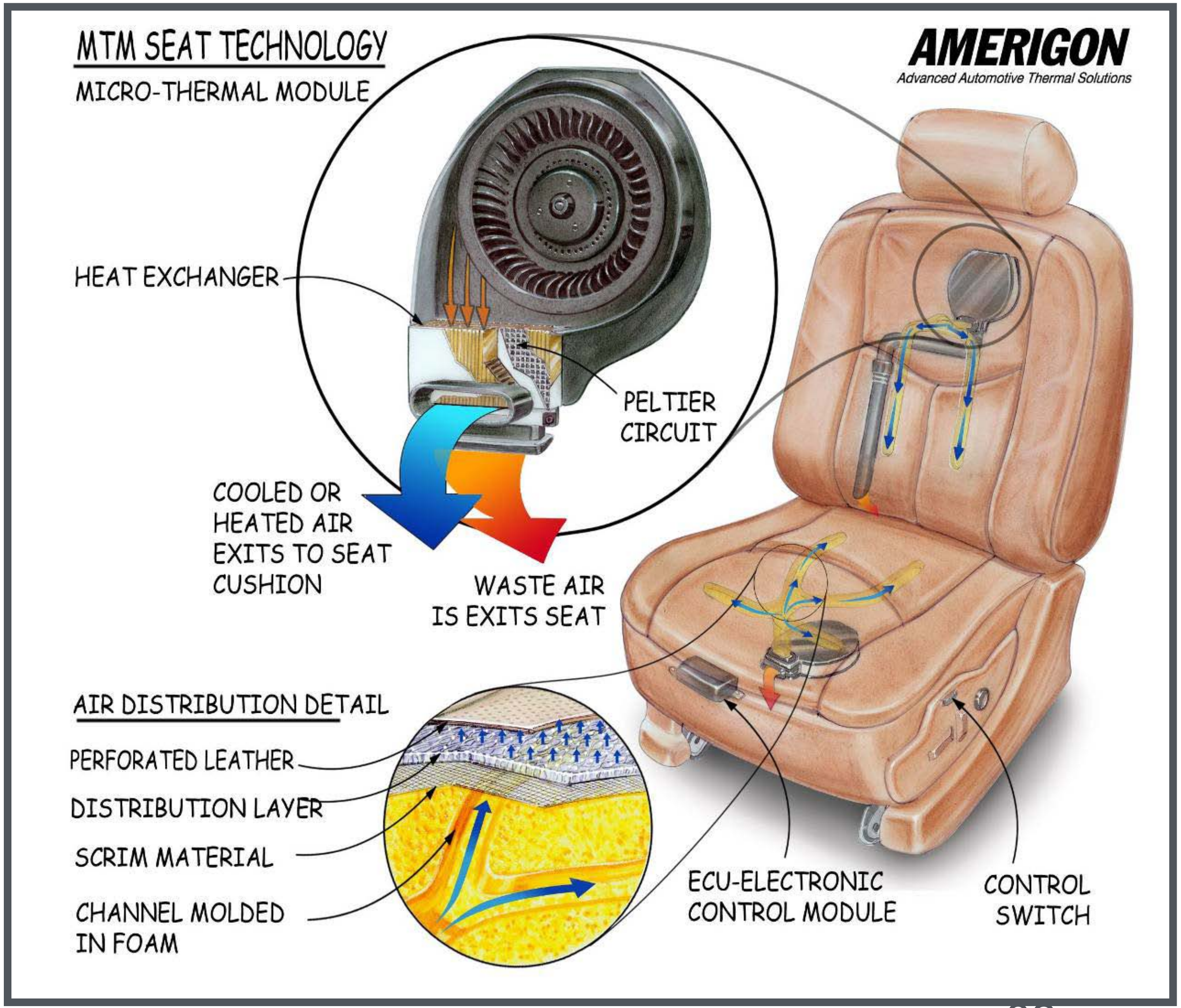


Climate Control Seat™



Automotive (TE HVAC) Thermoelectric Heating Ventilation and Air Conditioning

- Competitive Awards to Ford and GM
- Co-Funded with the California Energy Commission
- Develop TE Zonal or Distributed Cooling/Heating System
- Maintain Occupant Comfort without Cooling Entire Cabin
- Reduce Energy used in Automotive HVAC's by 50%
- Eliminate all Toxic, Greenhouse and Flammable Gases Associated with Automotive HVAC

Accelerate Deployment of Zonal TE HVAC in Light-Duty Vehicles

Program Objectives: Ford Team's Vehicular TE HVAC

Develop TE HVAC to optimize occupant comfort and reduce fuel consumption

Reduce energy use by A/C compressor by 1/3

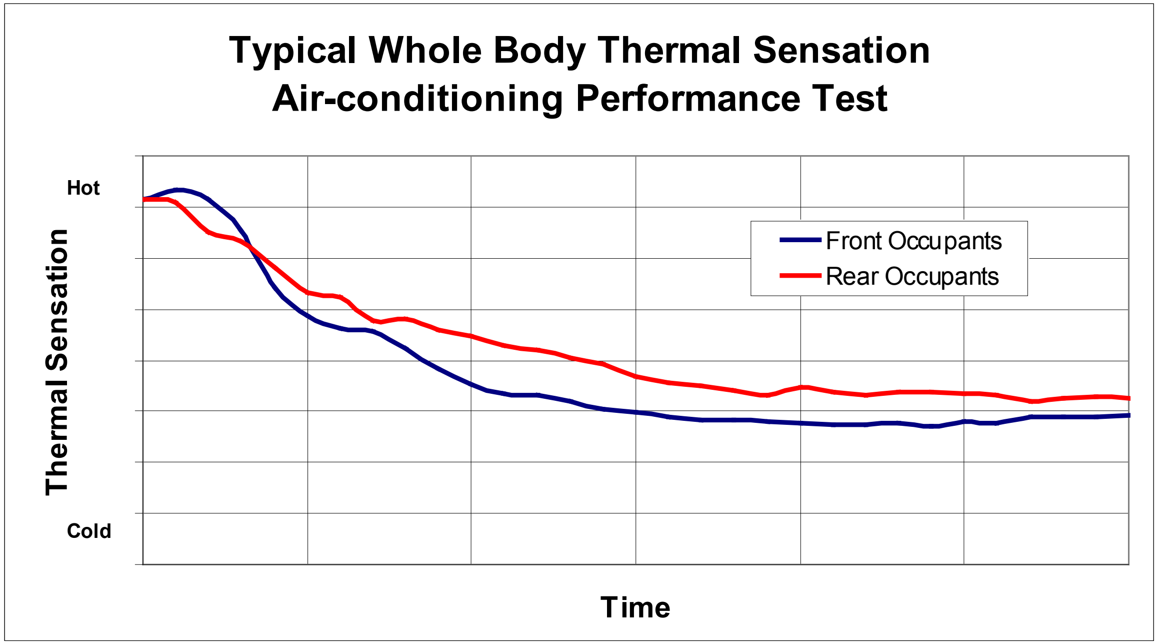
TE HVAC achieves COP cooling > 1.3 and COP heating > 2.3

Demonstrate a TE HVAC system for light-duty vehicles

Develop a commercialization pathway for a TE HVAC

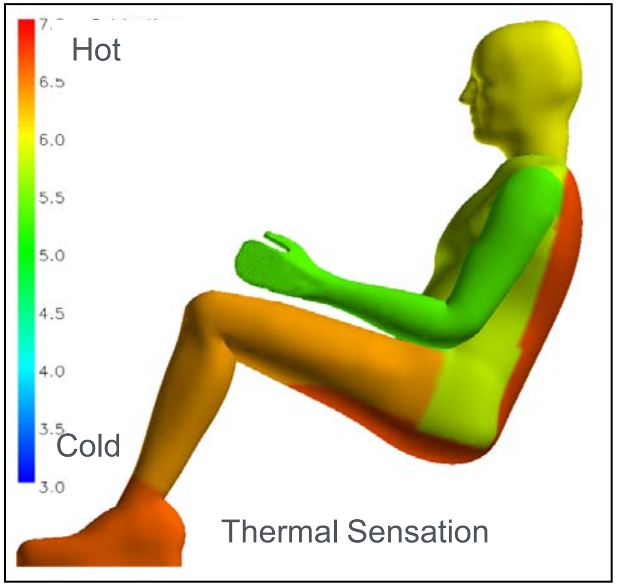
Integrate, test, and deliver a TE HVAC in a 5-passenger vehicle

CFD Data Converted to Transient Occupant: Thermal Sensation Predictions



Occupant Thermal Sensation Predictions are a Function of:

- Temperature
- Velocity
- Solar Load
- Surface Radiation
- Humidity



2010 Ford Fusion HEV Selected for TE HVAC Demonstration Program

- Electric A/C Compressor
- EATC Climate System
- High-Voltage Electrical System
- Flexible 12-V Architecture
- Existing CAD / CAE / Test Data

Fusion HEV is a flexible and relevant platform to demonstrate the TE HVAC concept

- Current Vehicular Air Conditioner (A/C) uses Compressed R134-a Refrigerant Gas

-- Vehicles leak 110 g/year R134-a

-- R134-a Has 1300 times the "Greenhouse Gas Effect" as Carbon Dioxide (CO2)

-- That is 143 kg/year CO2 equivalent per vehicle/year or

34 Million Metric Tons of CO2 equivalents/year frompersonal vehicles in the US from operating air conditioners

Plus additional 11Million Metric tons of CO2 equivalents/year released to atmosphere from vehicle accidents in the US

Total of 45 Million Metric Tons of CO2 equivalents/year from regular and irregular leakage in the US enter the ambiance

-- EU is proscribing use of R134-a

Vehicular Thermoelectric HVAC

- No substance release
  - Therefore no Ozone Depletion, Greenhouse Gases, Toxicity or Flammability problems
  - No moving parts other than fan and coolant recirculation pump
    - Minimal maintenance cost
    - Fuel Consumption
      - Zonal Concept cools/heats each occupant independently, not whole cabin
      - 680 Watts to cool single occupant
      - Current A/C's 3500 to 4500 watts cool entire cabin
      - 73 percent of personal vehicle miles driven with driver only
      - Lighter weight
      - First Approximation – Cost competitive
  - Converts to Heater by reversing polarity of DC current

Zonal Thermoelectric Air Conditioner/ Heater (HVAC) Concept

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

Thermoelectric HVAC Advantages for Plug-in Hybrids

- ❑ Occupant Heating During Battery Propulsion (No Engine Heat)
  - ➢ Resistance Heating Inefficient

Occupant Cooling

- ➢ Electric Compressor Refrigerant Gases
  - > Need R134-a Replacement

Thermoelectric HVAC Zonal Concept

- > Cooling COP 1.5
  - Augment or Replace Compressed Gas Unit
- > Heating COP 2.5
  - Replace Resistive Heaters
    - Typical COP 1.0

-- While TE HVAC is beneficial to all vehicles, it is especially advantageous for Plug-in Hybrids, Hybrids, Electric Cars, Fuel Cell Powered Vehicles and vehicles with small high efficiency, low temperature exhaust engines

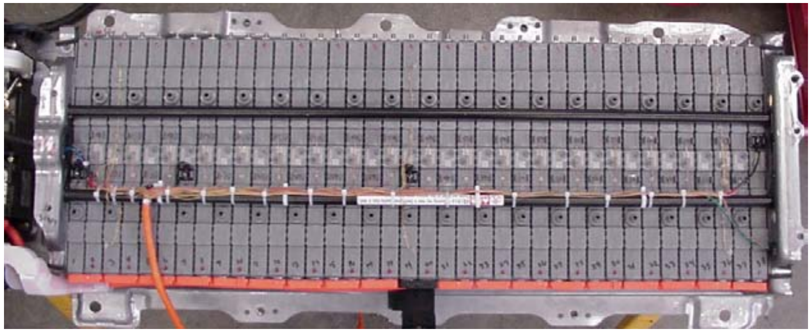
Temperature affects battery operation

> Round trip efficiency and charge acceptance

> Power and energy

> Safety and reliability

> Life and life cycle cost



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

Sea-water/ambient air temperature difference enables 24/7 TEG Battery Charging

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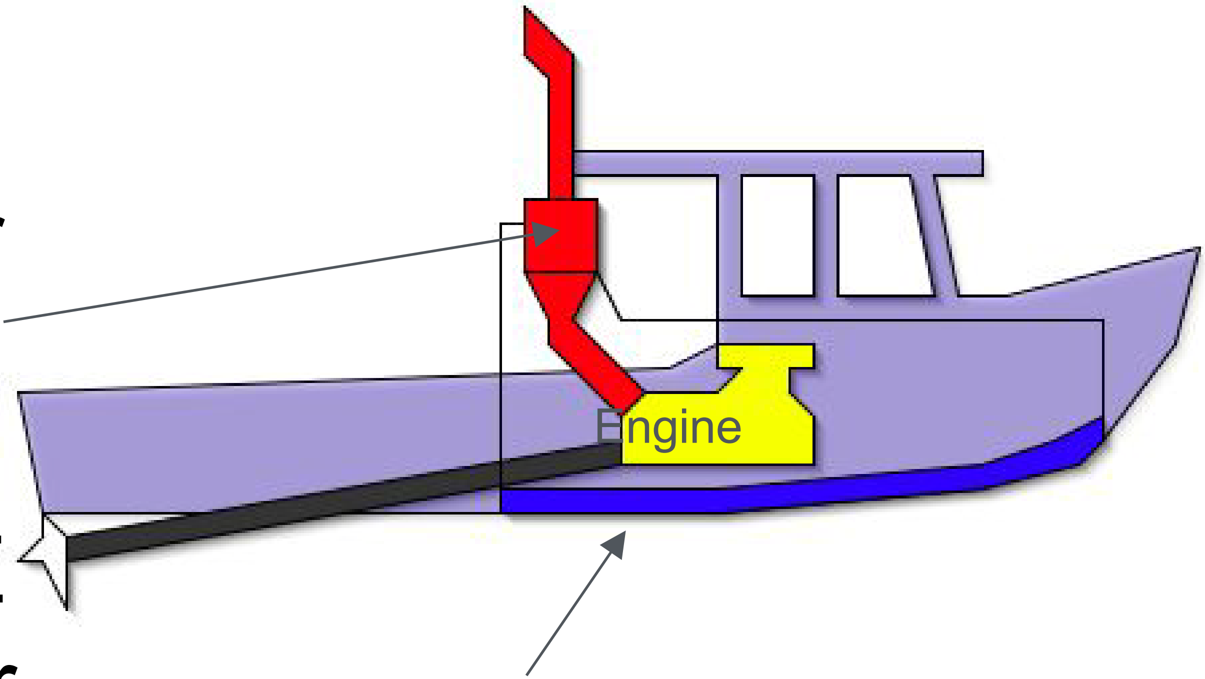
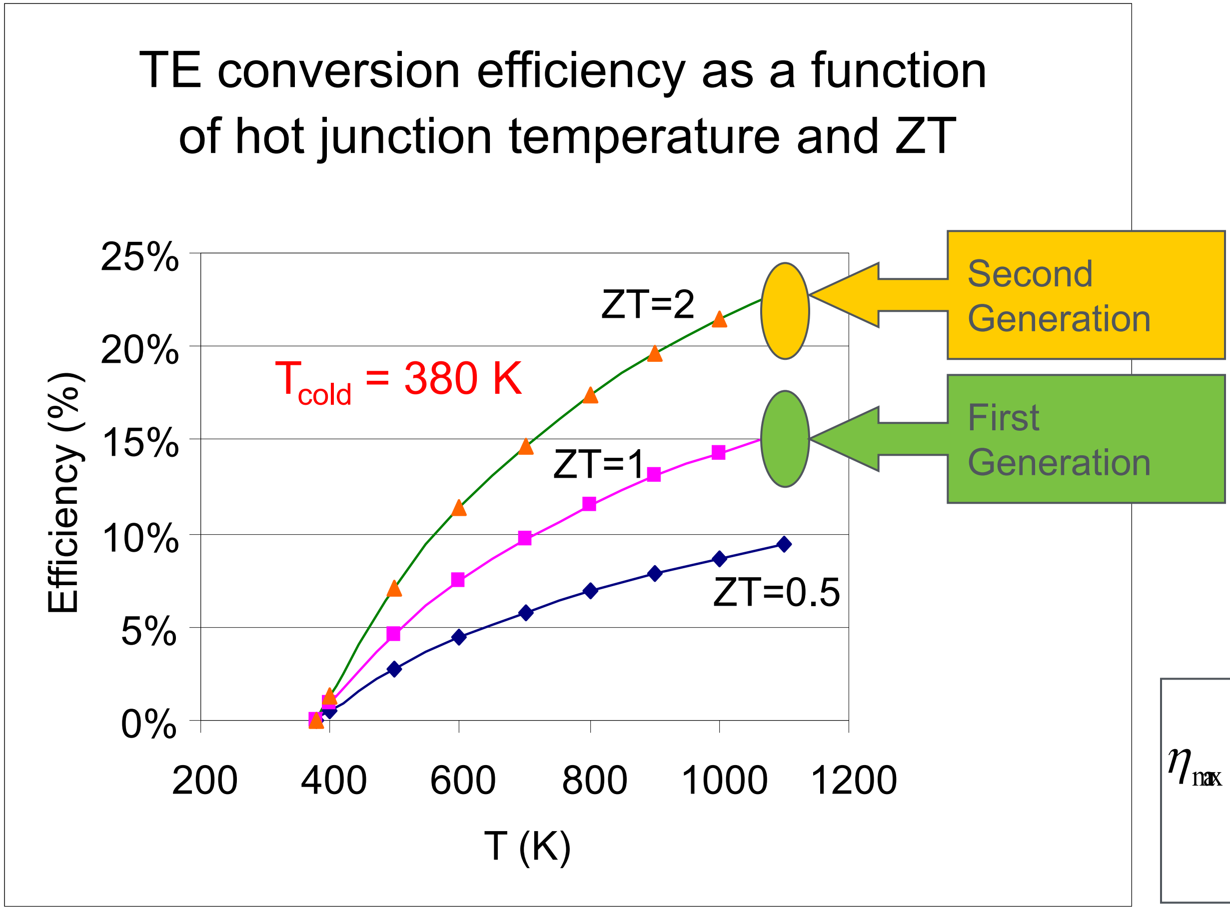
Seawater Cooled Exhaust Stack TE Generator



Keel Coolers

Maine Maritime Academy's "Fishing Vessel" R/V Friendship 47 Feet LOA

TE Materials Performance Objective



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

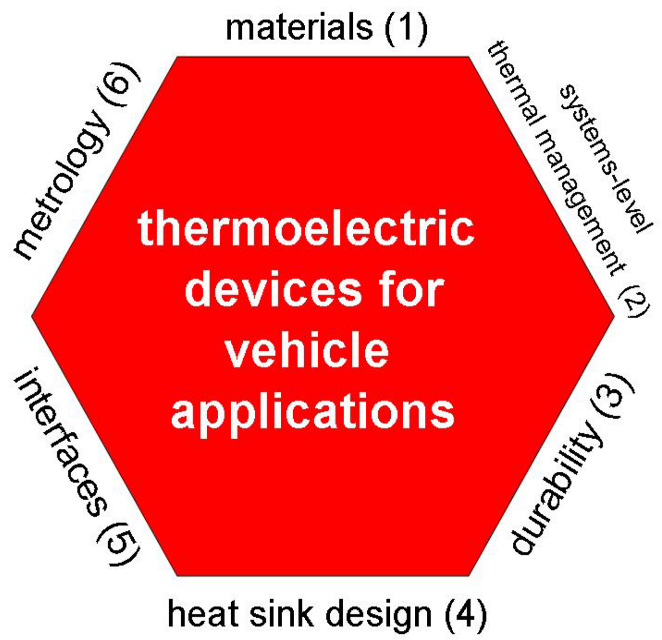
NSF/DOE Partnership on Thermoelectric Devices for Vehicle Applications - 2010 Solicitation

Vehicle Technologies Program

Thermal Transport Processes Program (within Engineering Directorate)

Purpose: Enable broad application of thermoelectric waste heat recovery devices at scale commensurate with the global vehicle manufacturing enterprise.

Areas Targeted:



Funding available:
$9M over three years ($4.5M from DOE; $4.5M from NSF)

Timeline:

*Letters of intent due: May 21, 2010

*Proposals due: June 22, 2010

*Panel Review (administered by NSF): August 2,3 2010
(decisions jointly agreed upon by DOE and NSF)

*Awards Made:September 23, 2010

Response:
*64 letters of intent;
*48 proposals received;
*9 awards (19%; NSF average 10% to 20%)

DOE/NSF Partnership inThermoelectrics

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An integrated approach towards efficient, scalable, and low cost thermoelectric waste heat recovery devices for vehicles
Scott T Huxtable (VPI), Srinath V Ekkad (VPI), Daniel J Inman (VPI), Andrew C Miner (Romny) , Shashank Priya (VPI)

Automotive Thermoelectric Modules with Scalable Thermo- and Electro-Mechanical Interfaces
Kenneth E Goodson(Stanford), Inna Kozinsky (Bosch), George Nolas (USF)

High-Performance Thermoelectric Devices Based on Abundant Silicide Materials for Waste Heat Recovery
Li Shi (UT-Austin), John B Goodenough (UT-Austin) , Matthew J Hall (UT-Austin), Jianshi Zhou (UT-Austin)

Inorganic-Organic Hybrid Thermoelectrics
Sreeram Vaddiraju (TAMU), Robert S Balog (TAMU), Tahir Cagin (TAMU)

High Performance Thermoelectric Waste Heat Recovery System Based on Zintl Phase Materials with Embedded Nanoparticles
Ali Shakouri (UCSC), Zhixi Bian (UCSC)

Integration of Advanced Materials, Interfaces, and Heat Transfer Augmentation Methods for Affordable and Durable Devices
Yongho Ju (UCLA), Richard B Kaner (UCLA)

Integrated Design and Manufacturing of Cost-Effective and Industrial-Scalable TEG for Vehicle Applications
Lei Zuo (Suny-Stony Brook), Baosheng Li (Suny-Stony Brook), Qiang Li(BNL), Jon P Longtin (Suny-StonyBrook), Sanjay Sampath (Suny-Stony Brook)

Project SEEBECK-Shaving Energy Effectively by Engaging in Collaborative research and sharing Knowledge
Joseph Heremans (Ohio State), Mercouri Kanatzidis (Northwestern), Guo-Quan Lu (VPI)

Thermoelectrics for Automotive Waste Heat Recovery
Xianfan Xu (Purdue), Timothy S Fisher (Purdue), Stephen D Heister (Purdue), Timothy D Sands (Purdue), Yue Wu (Purdue)

Vehicular Thermoelectric Hybrid Electric Powertrain

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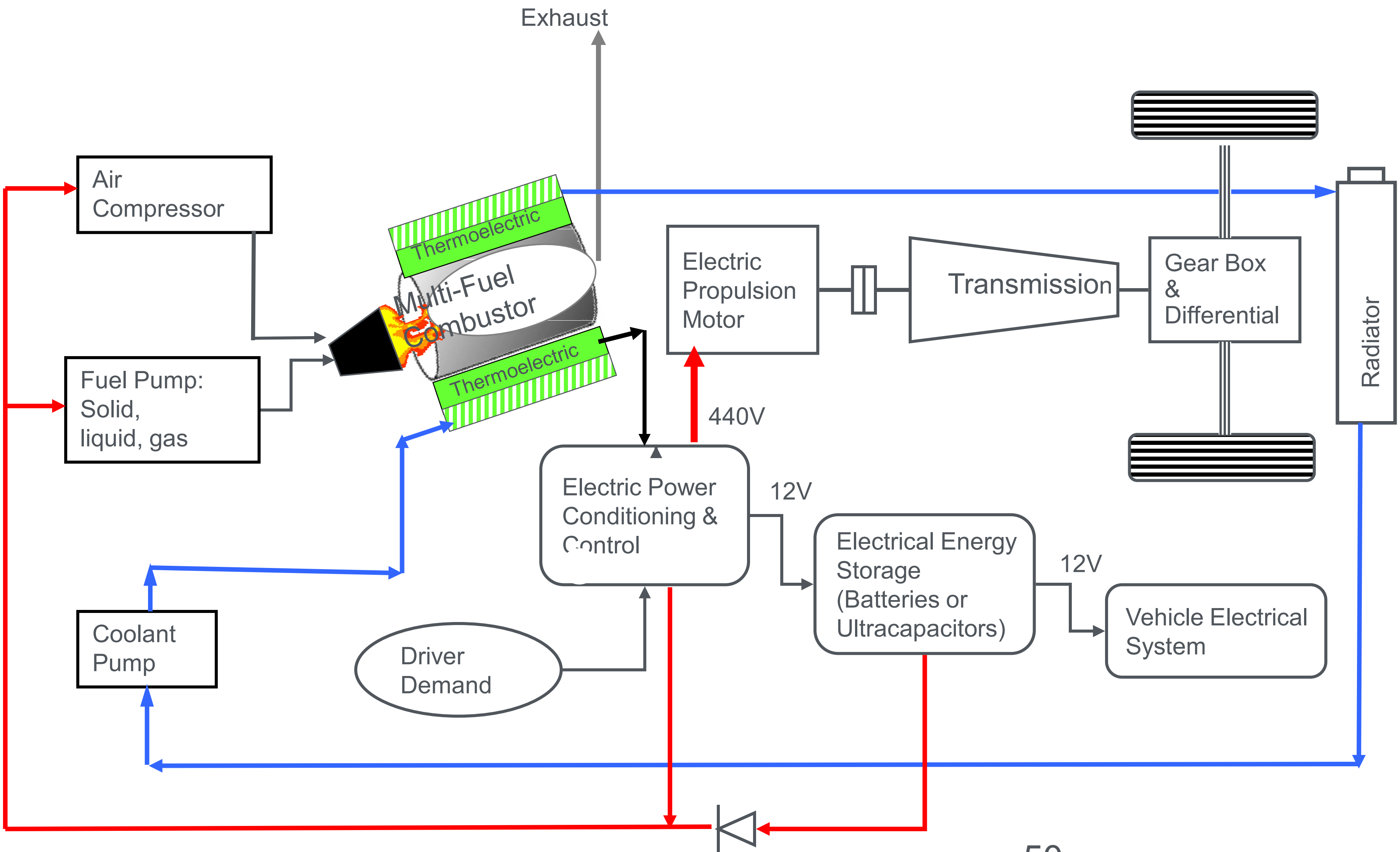

Vehicular Thermoelectric Application Possibilities

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Near Term (3-5 yrs)

- Thermoelectric Generator providing nominal 5% fuel economy gain augmenting smaller alternator
- Thermoelectric HVAC augmenting smaller A/C

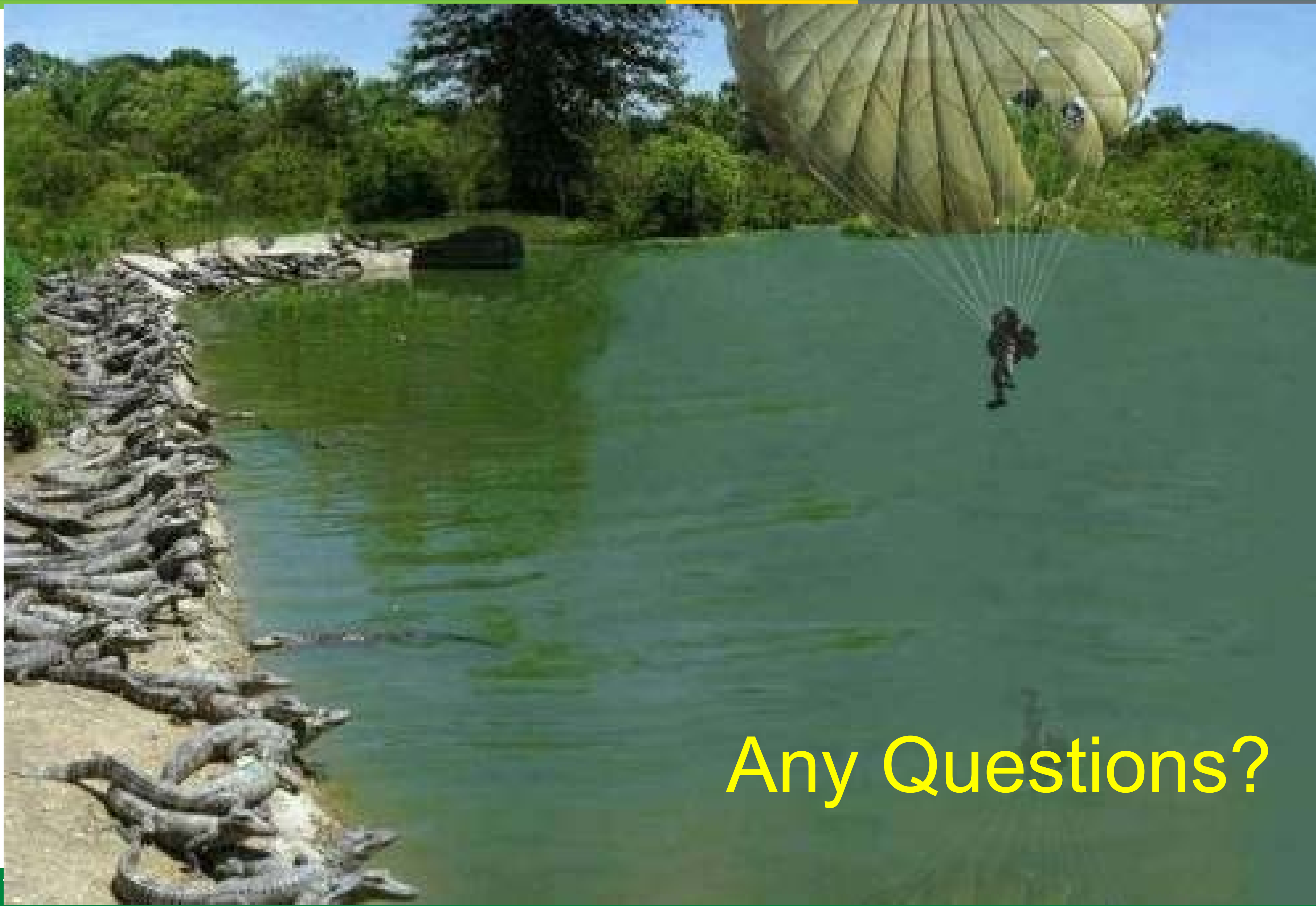
Mid Term (6-15 yrs)

- Thermoelectric Generators installed in diesel or gasoline engine exhaust
  - 55% efficient heavy duty truck engine
  - 50% efficient light truck, auto
- Thermoelectric Generators and HVAC w/o alternators or compressed gas A/C
- Aluminum/Magnesium frame & body replacing steel (Process waste heat recovery) mass market cars

Long Term (16-25 yrs)

- 35% efficient Thermoelectrics w 500 ^{0}C ΔT
  - Replace Internal Combustion Engine (ICE)
  - Dedicated combustor burns any fuel


Thank You!



Any Questions?