Vehicular Thermoelectric Applications Session DEER 2009

John W Fairbanks
Department of Energy
Vehicle Technologies
Washington, D.C.

August 5, 2009
Dearborn, Michigan

Journalism vs. Engineering

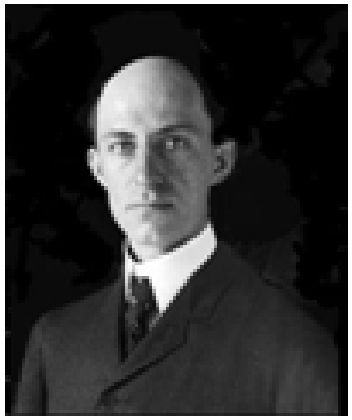
The New York Times

"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



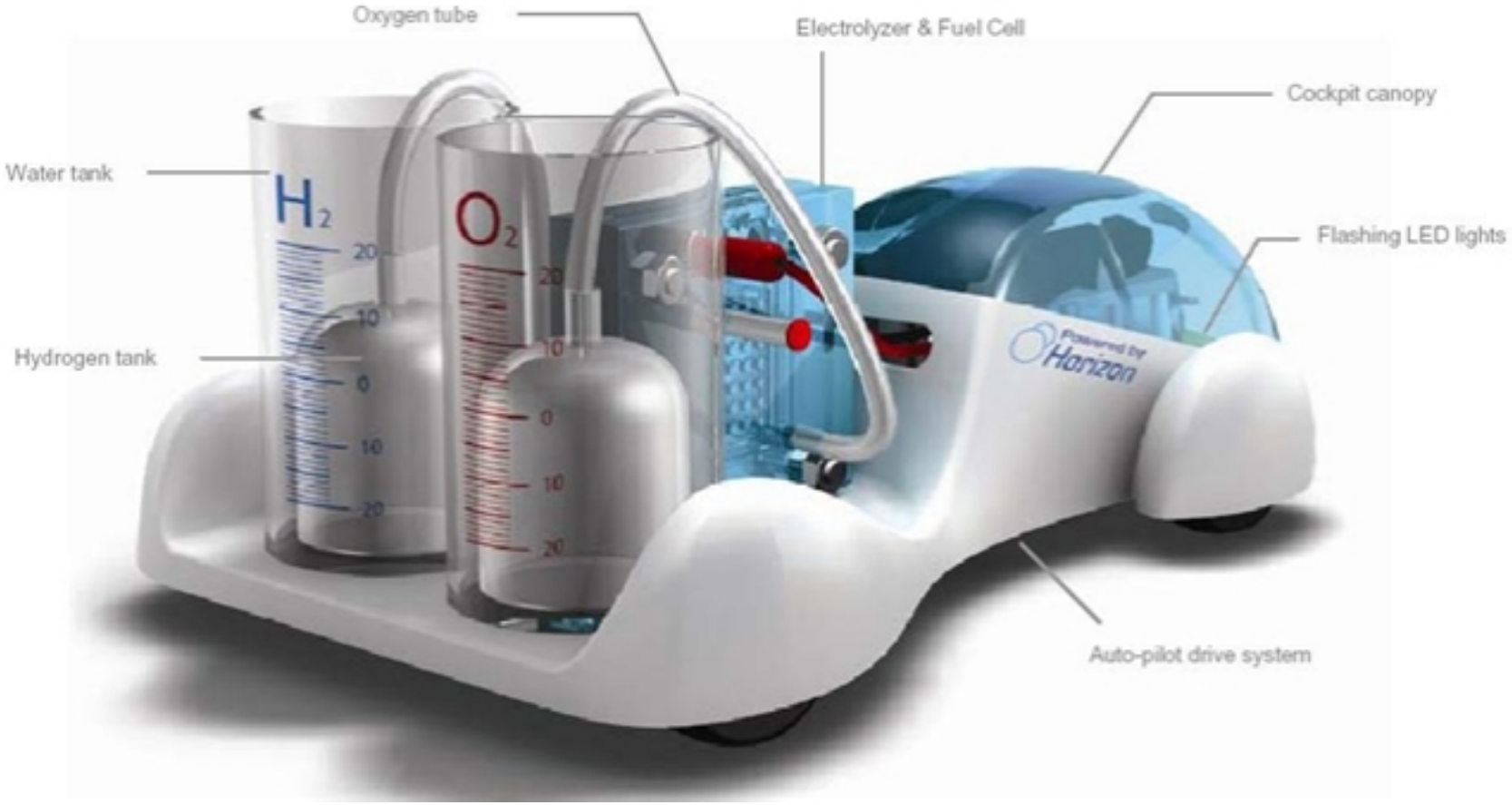
Courtesy of DARPA

Evolution of Transport

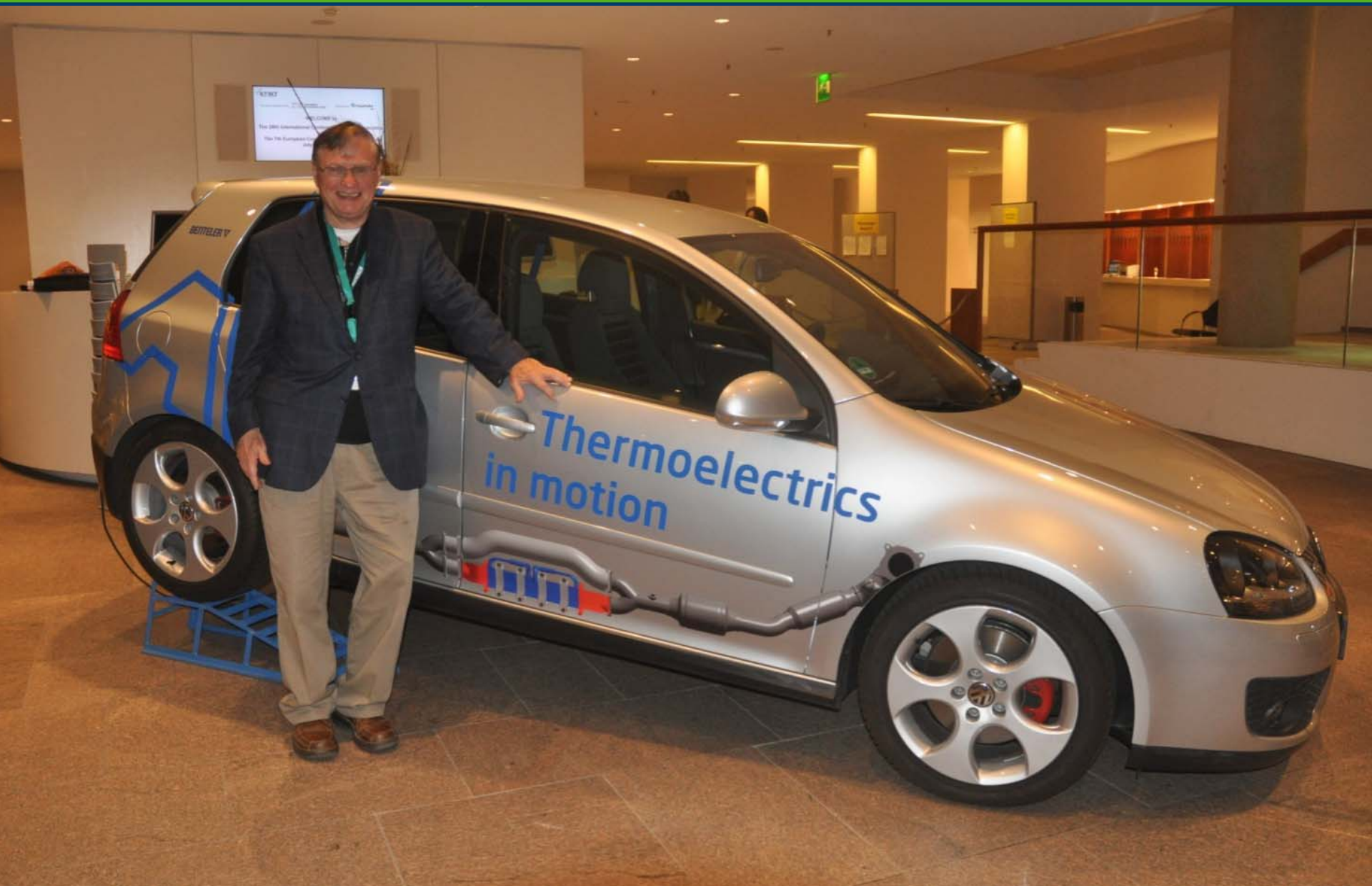
1903

2003

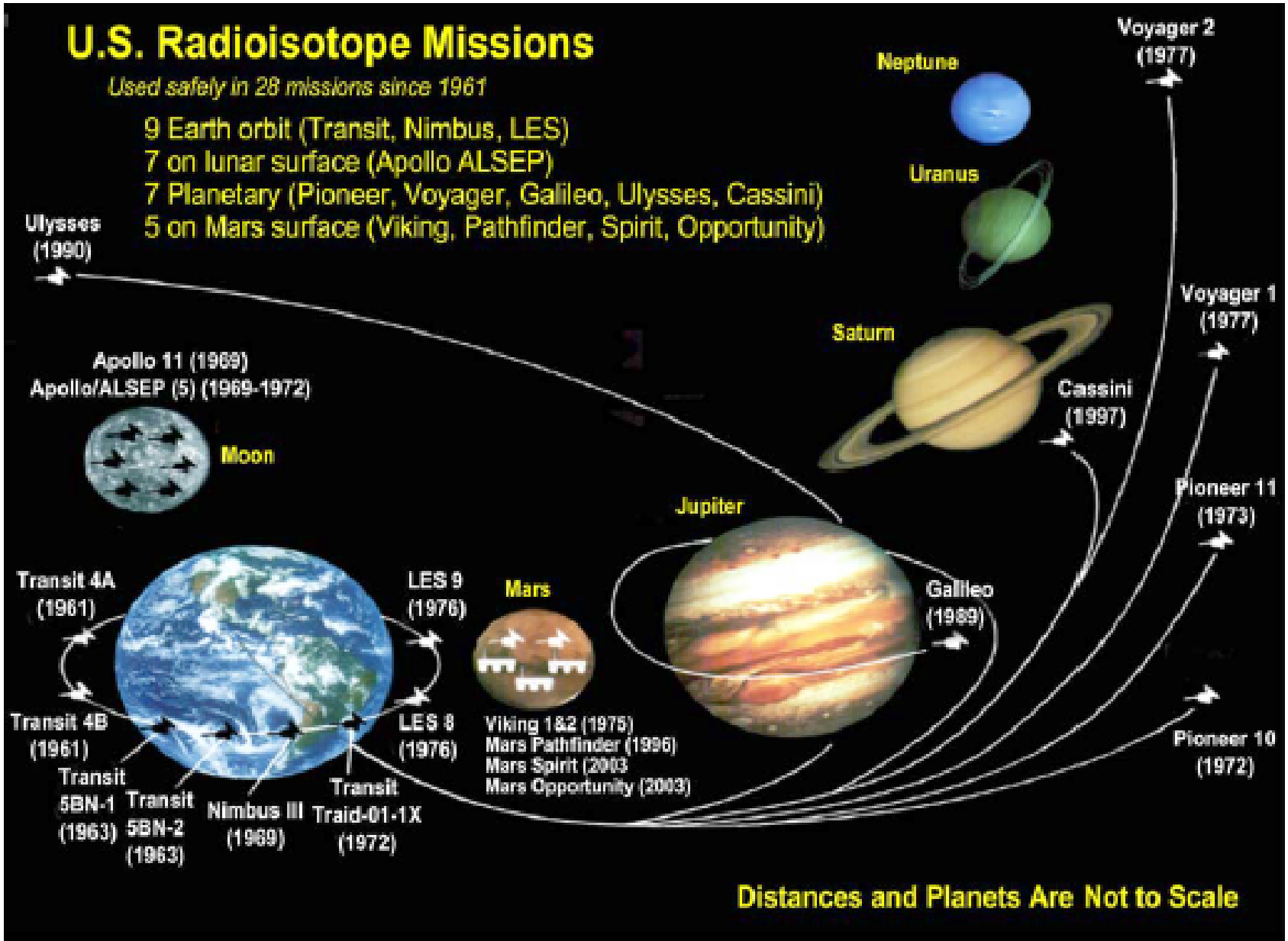
Car of the Future?



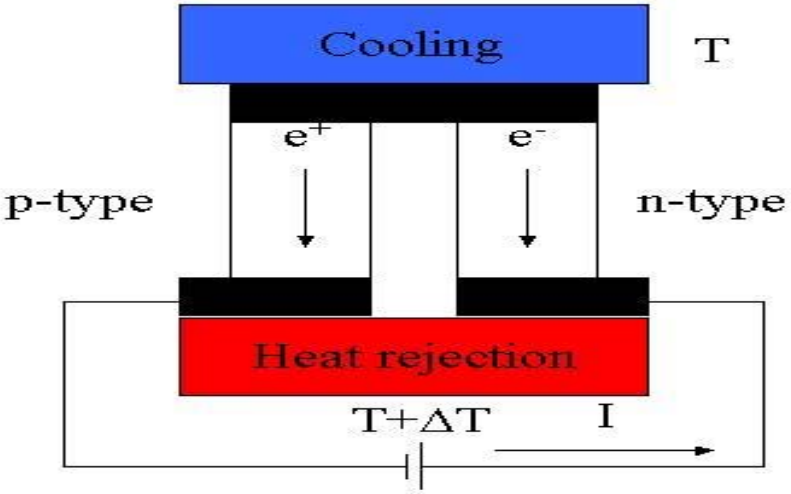
International Thermoelectric Conference 2009 – Frieburg, Germany



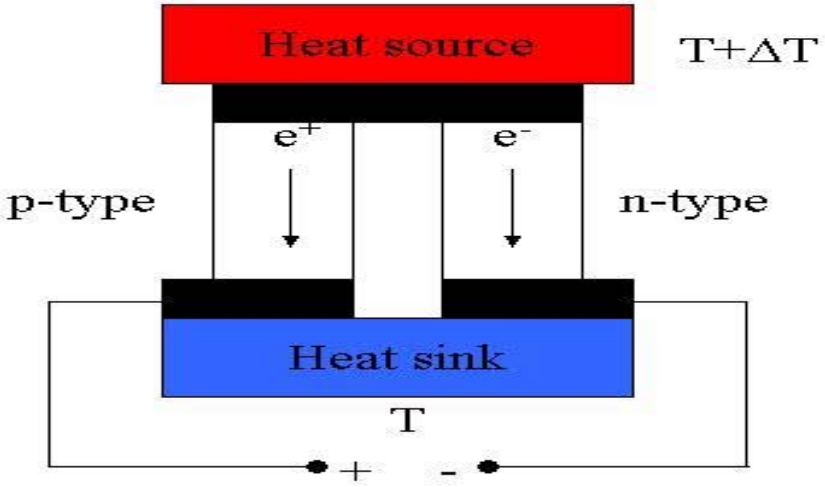
U.S. Spacecraft using Radioisotope Thermoelectric Power Generators



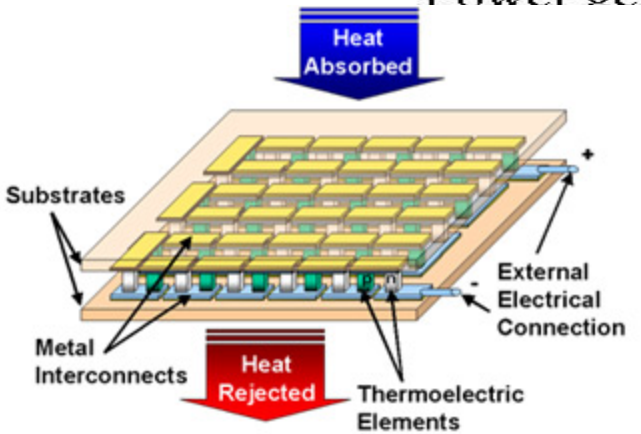
Thermoelectric Generator and HVAC



Refrigeration



Power generation



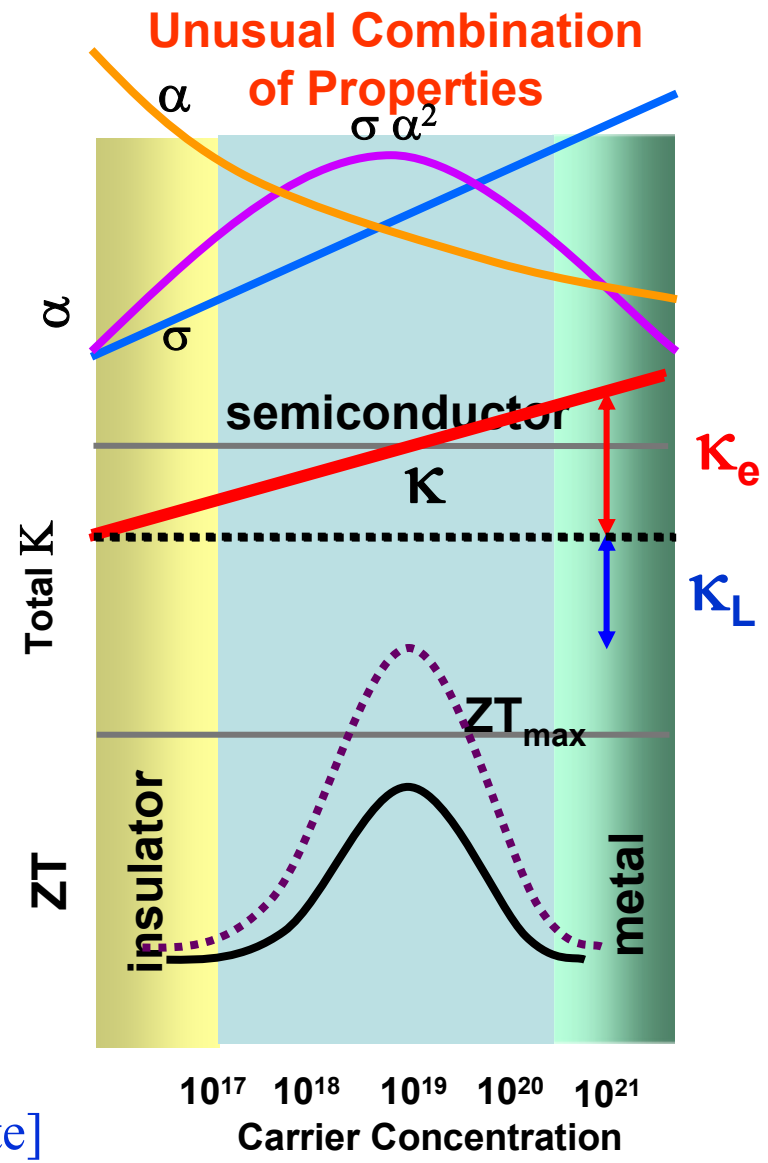
TE materials performance: Figure of Merit (ZT)

Electrical conductivity

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

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

Total thermal conductivity



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

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

ρ = **electrical resistivity**

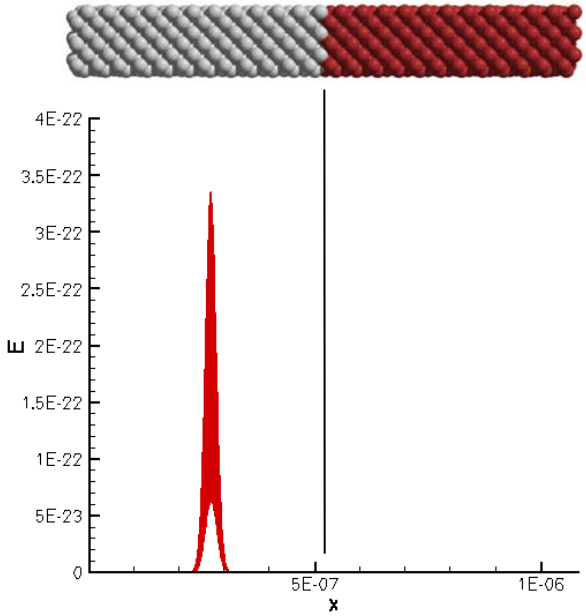
[courtesy Oregon State]

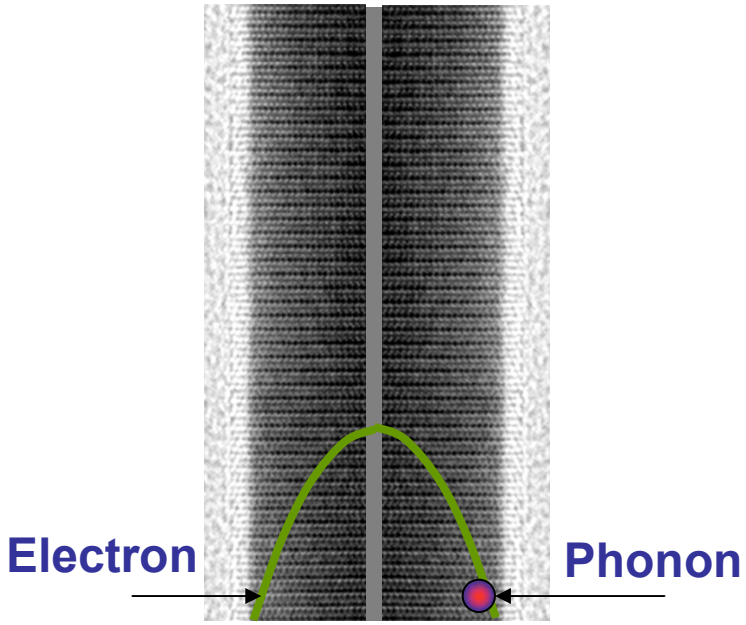
Nanoscale Effects for Thermoelectrics

Interfaces that Scatter Phonons but not Electrons

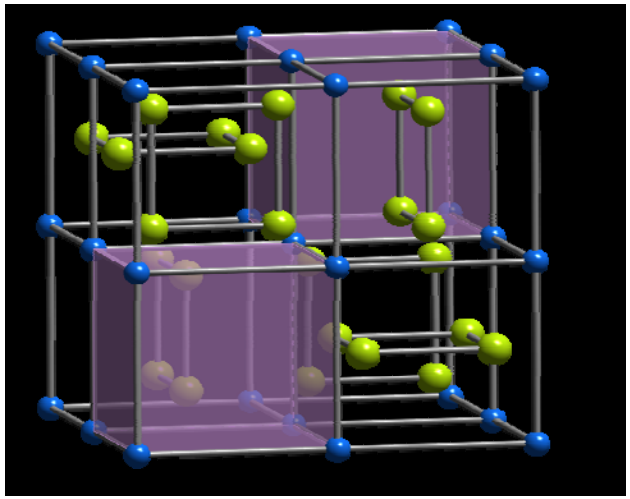
[courtesy: Millie Dresselhaus, MIT]

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

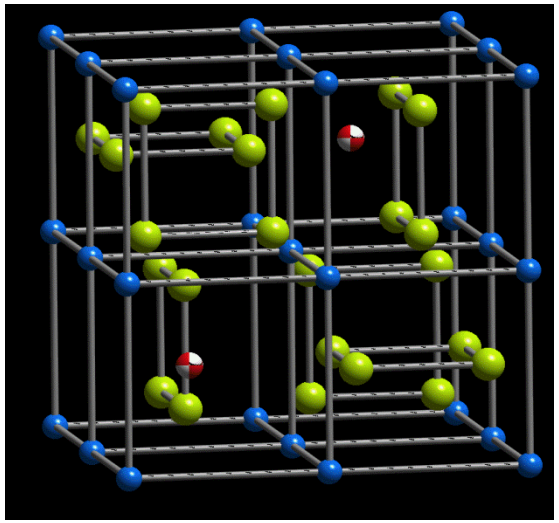




Crystal Structure of Skutterudites



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



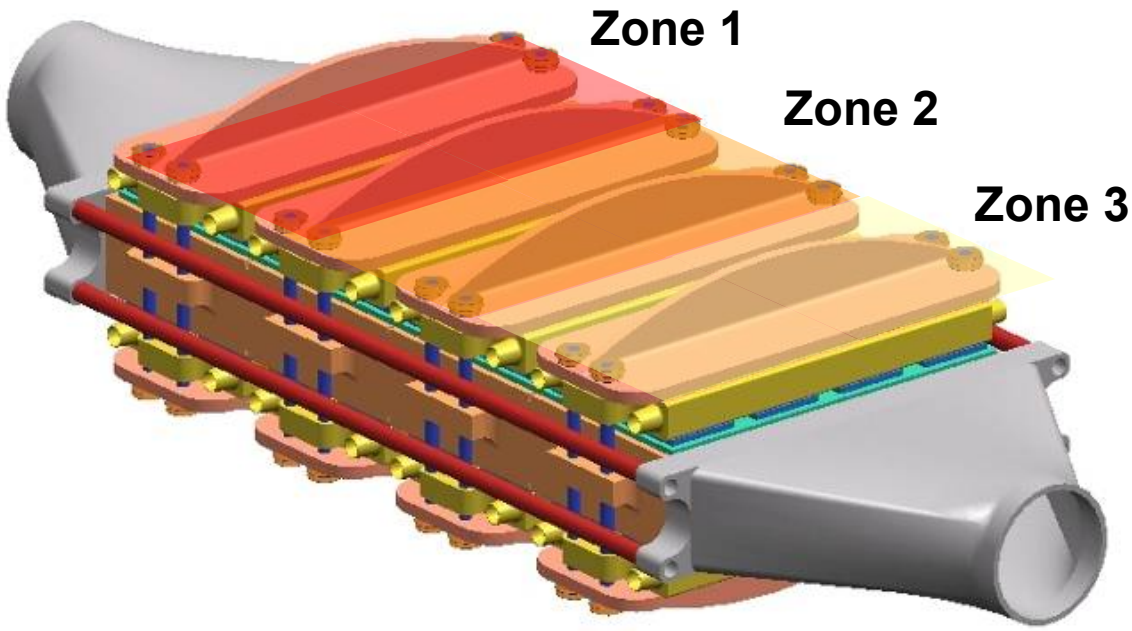
R_xCoSb_3

- 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

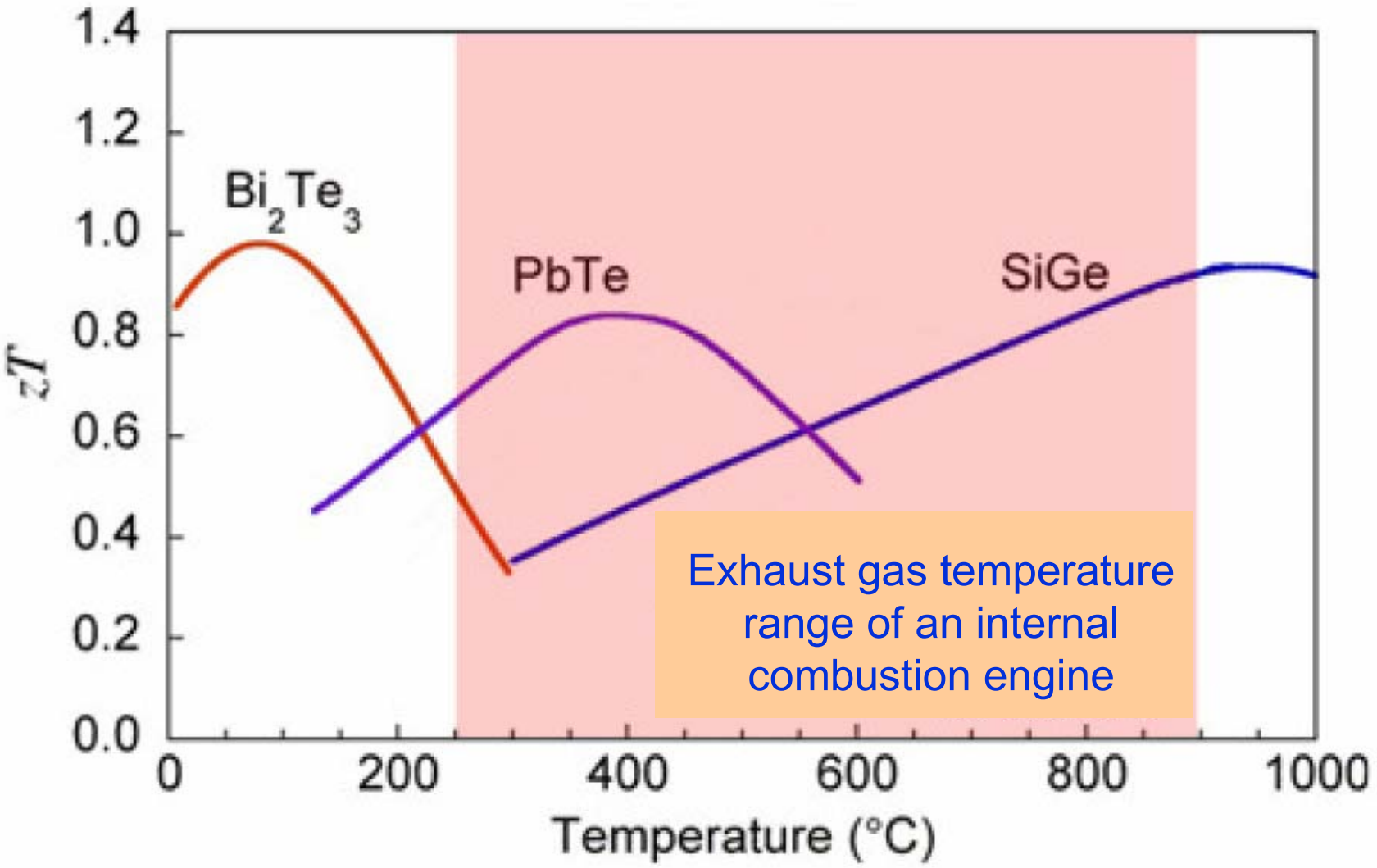
Atoms can be inserted into empty sites. Atoms can "rattle" in these sites – scatter phonons and lower the lattice thermal conductivity.

[courtesy: Oregon State]

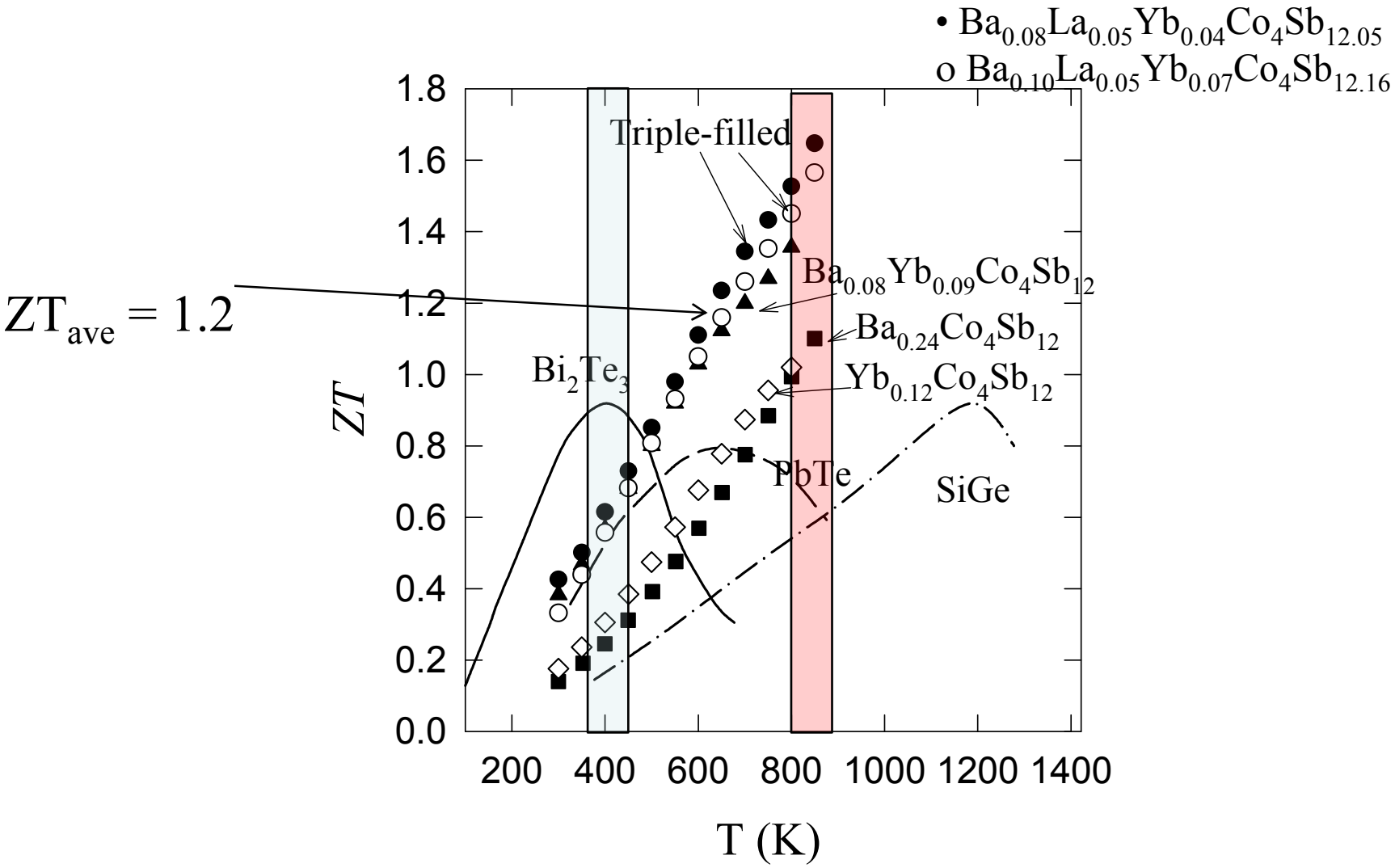
Thermoelectric Modules optimized for Thermal Zones



TEG Candidate Materials – 2005

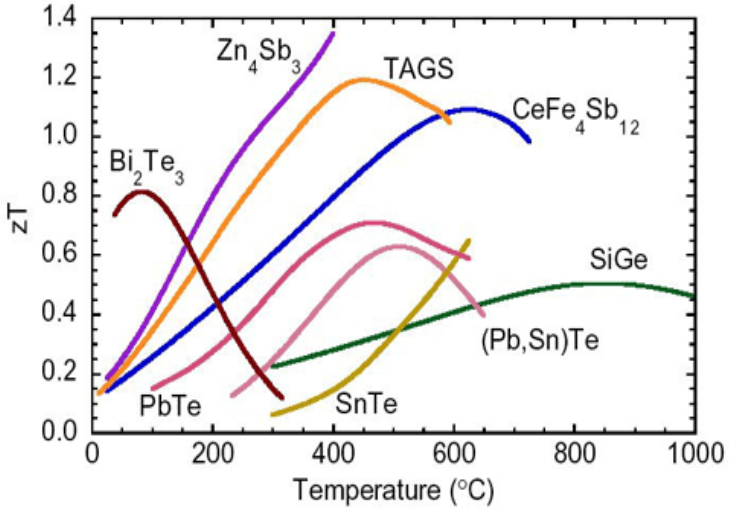


Highest ZT Achieved in Triple-filled Skutterudites

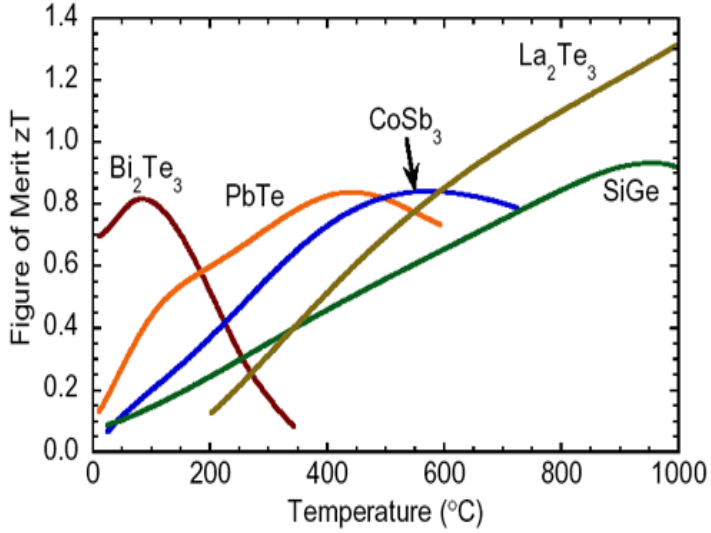


1. X. Shi, et al. Appl. Phys. Lett. **92**, 182101 (2008)
2. X. Shi, et al., submitted (2009)

Current TE Materials



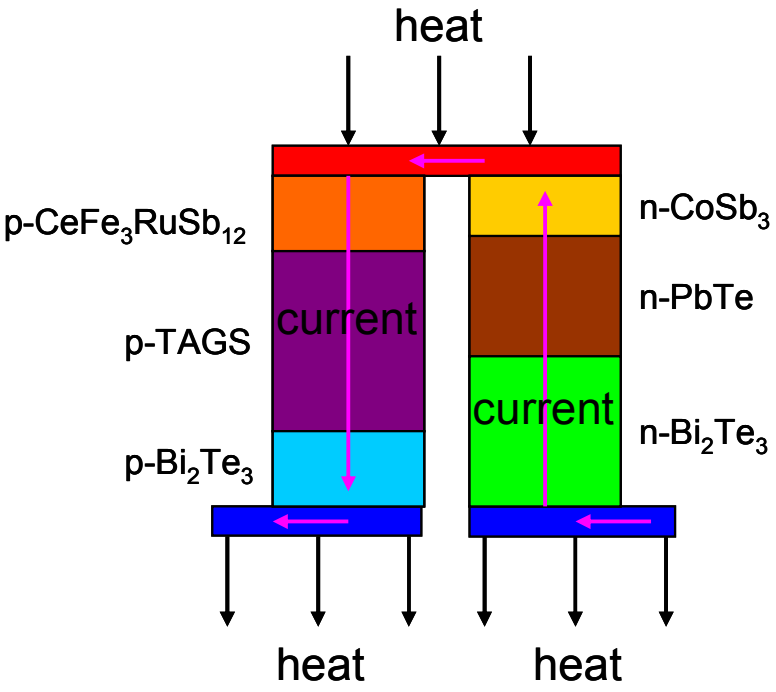
P-type TE material



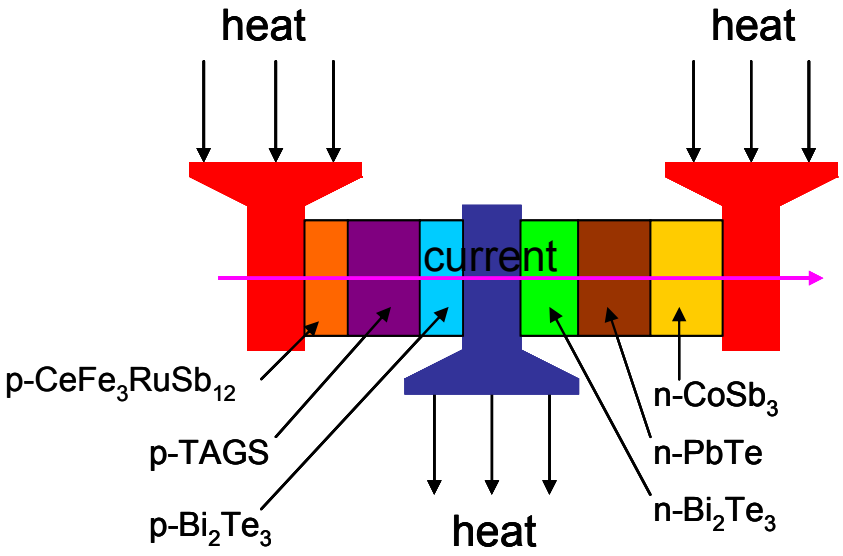
N-type TE material

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

BSST Y Segmented TE Configuration

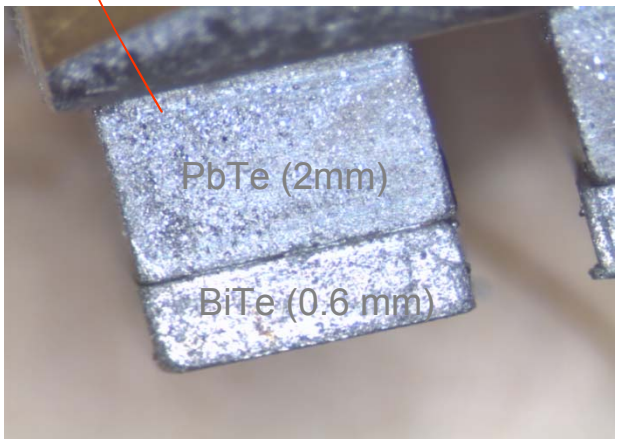


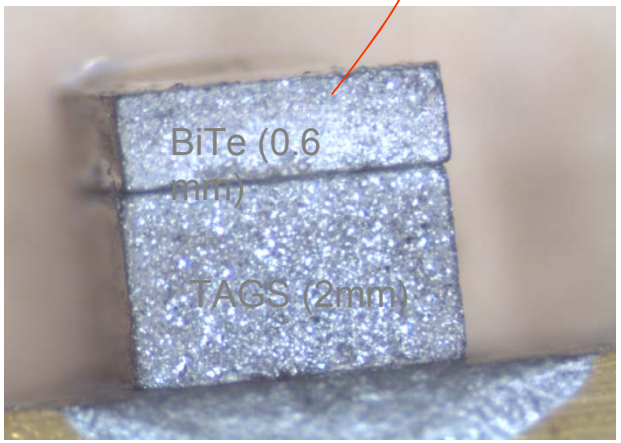
- Traditional configuration



- BSST “Y” configuration

Segmented Couple TAGS/PbTe-Bi_2Te_3





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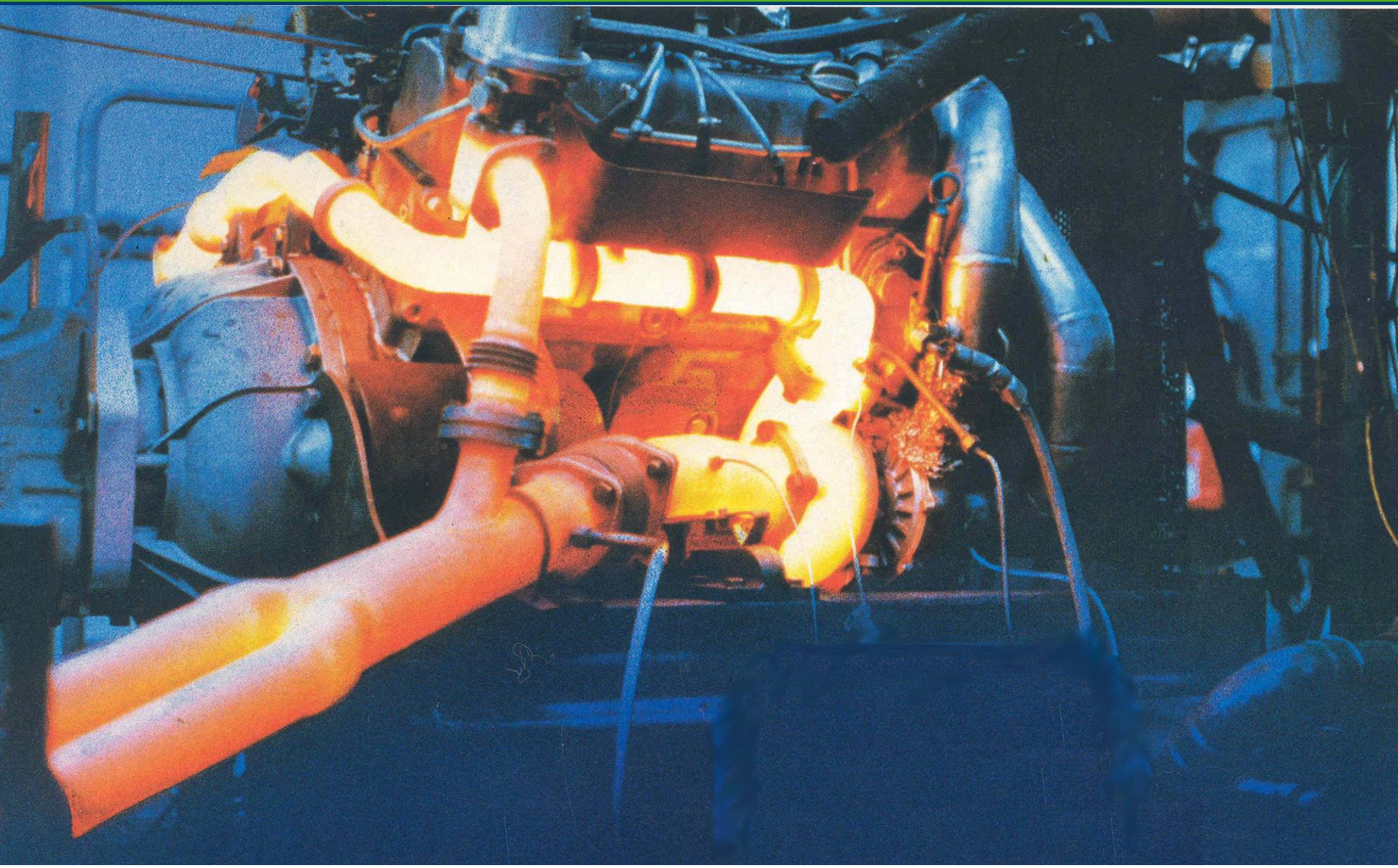
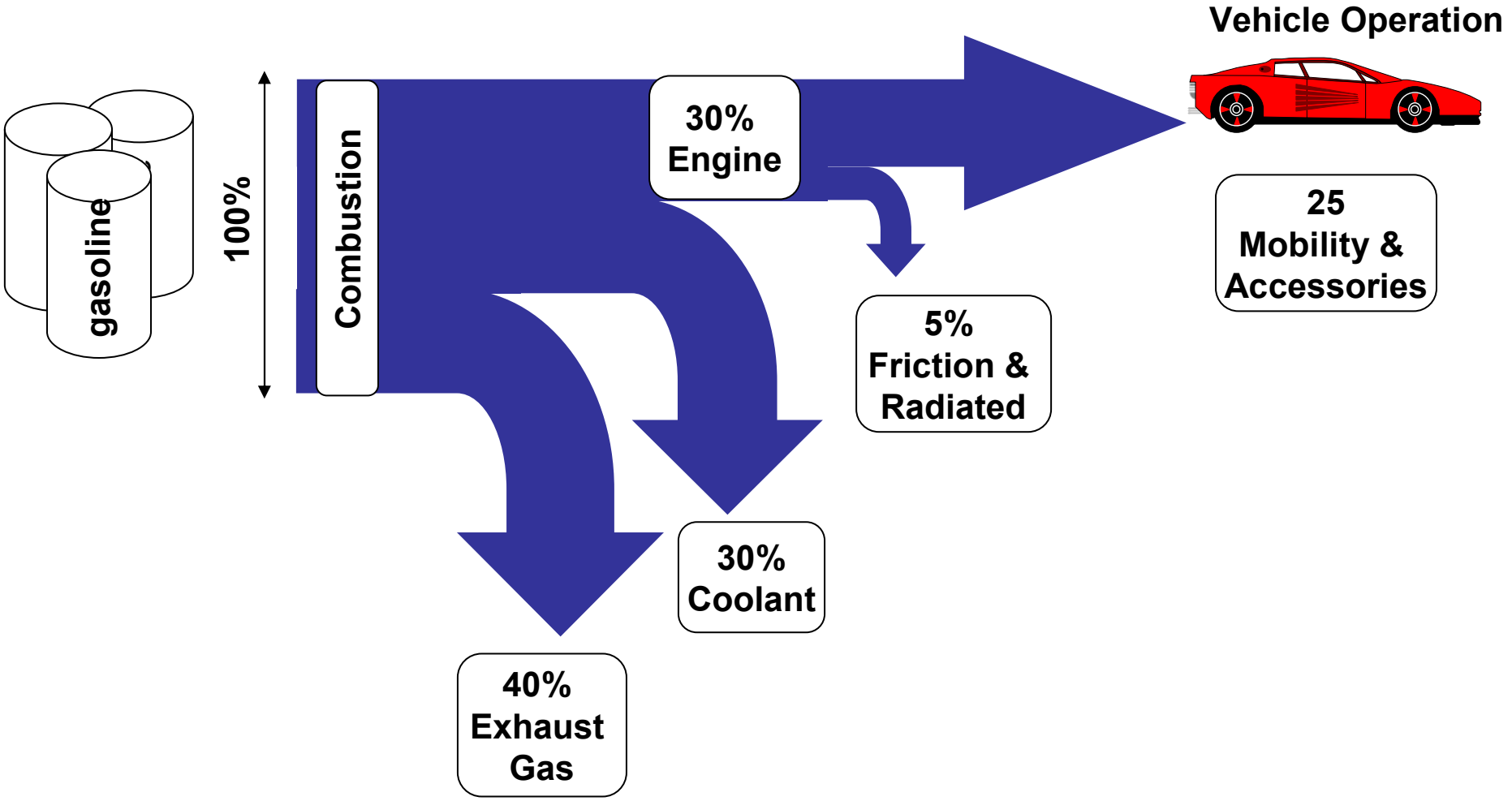
Available Energy in Auto Engine Exhaust

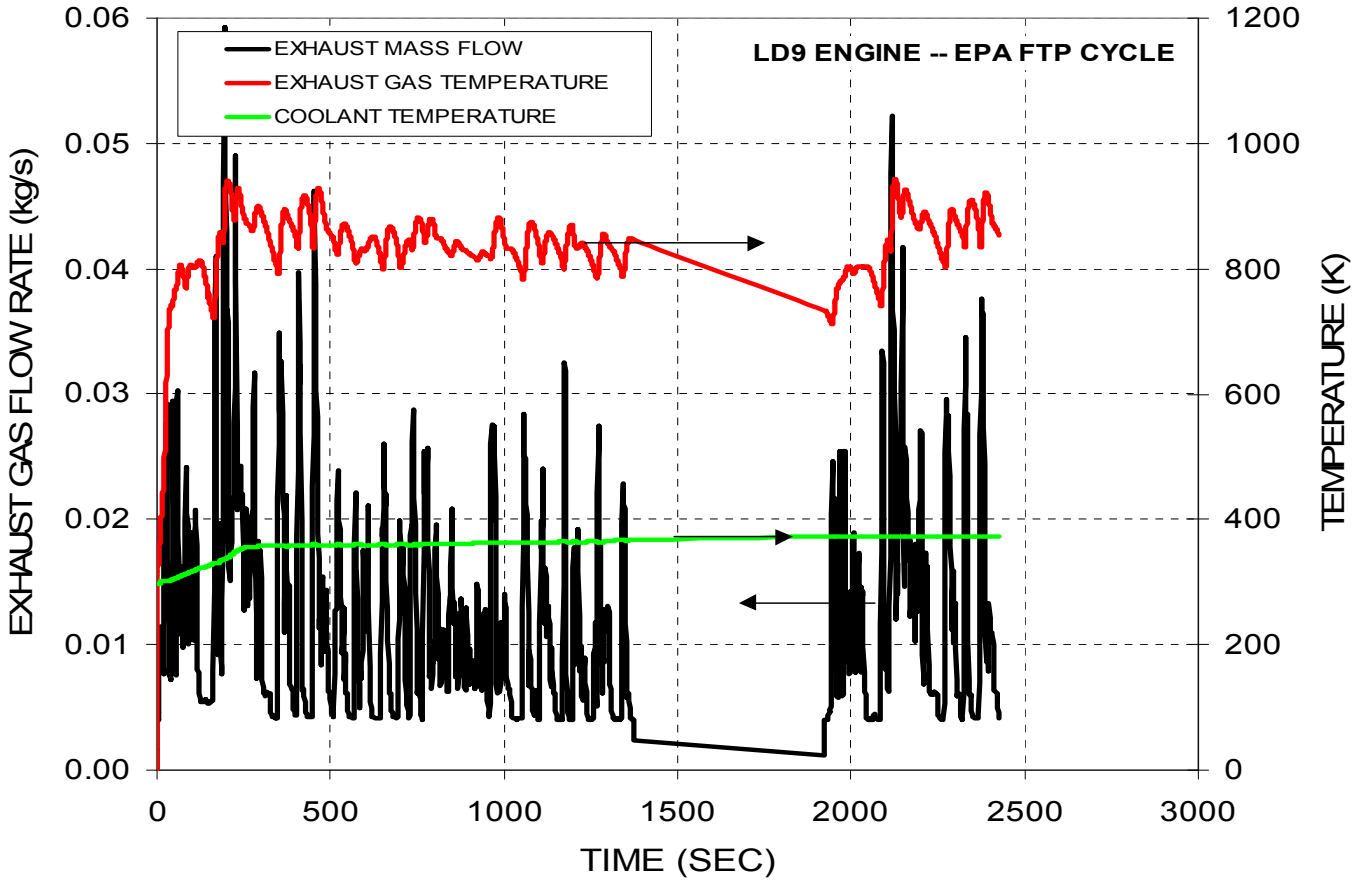


Potential Thermoelectric Heat Sources



Spark Assisted Gasoline internal Combustion Engine (Light Truck or Passenger Vehicle)

Exhaust Flow and Temperatures for a 4- Cylinder Engine



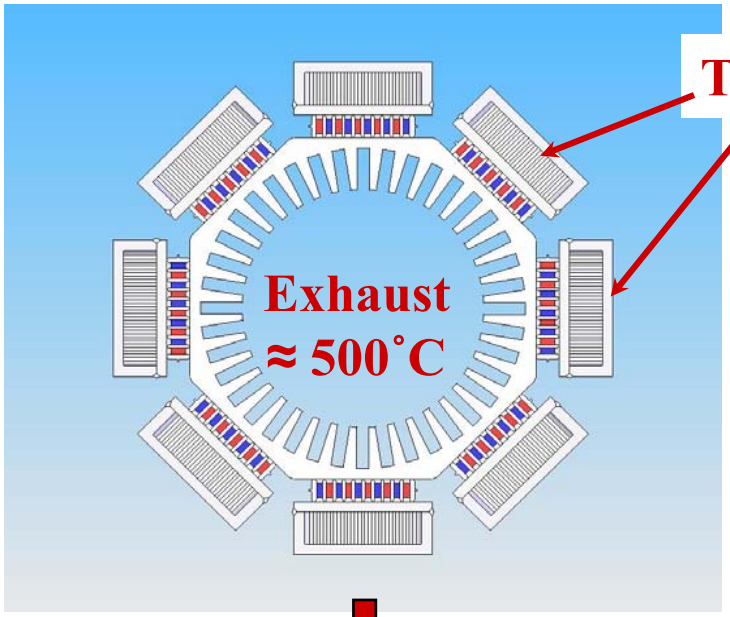
There are tens of kW heat energy in the exhaust & coolant

TE Power Generation from Engine Waste Heat

Heat Rejection
Waste Heat > 60%

$T_H \approx 500^\circ C$

$T_C \approx 110^\circ C$



Carnot Efficiency

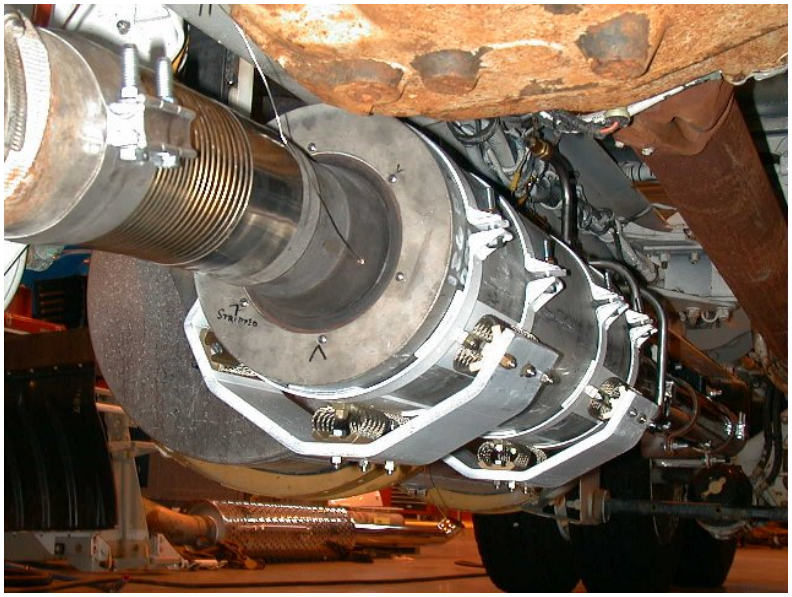
$$\eta_C = \frac{T_H - T_C}{T_H}$$

TE Efficiency

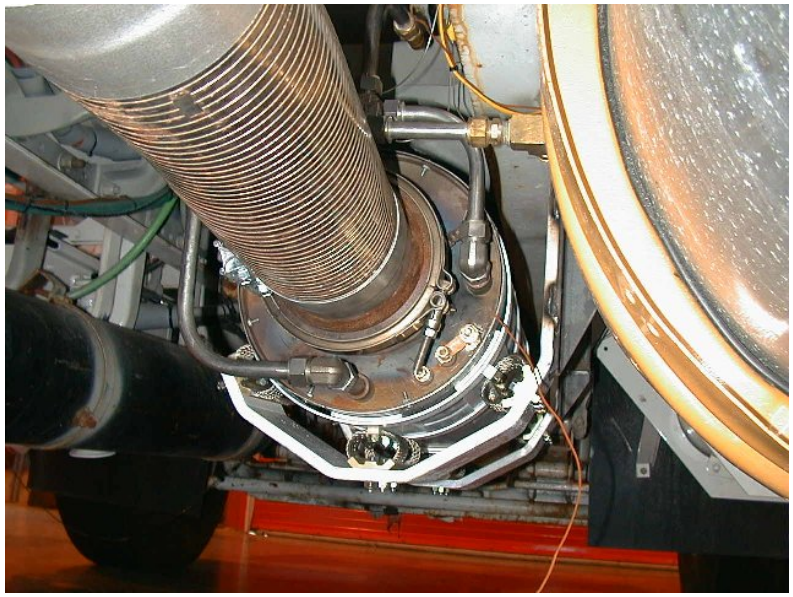
$$\eta = \left(\frac{T_H - T_C}{T_H}\right)\left(\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}}\right)$$

Waste Heat Recovery
Goal > 10% Increase in fuel economy

Installed Thermoelectric Generator on Heavy Duty Truck



Front View



Rear View

550 HP Truck Equipped With the TEG

Engine – Caterpillar 3406E, 550 HP
PACCAR's 50 to 1 Test Track
(Note Speed Bumps and Hill)
Standard Test Protocols Used or Each Evaluation
Heavy Loaded (over 75,000 lbs)
TEG Installed Under the Cabin

DOE Vehicular Thermoelectric Generator Projects

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
BSST, LLC.	Visteon, BMW-NA, Ford, Marlow Industries
Michigan State University	NASA Jet Propulsion Laboratory Cummins Engine Company Tellurex, Iowa State

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Beltless or More Electric Engine

Truck Electrification

Electrify accessories
decouple them from engine
Match power demand to real time need
Enable use of alternative power sources

Modular HVAC

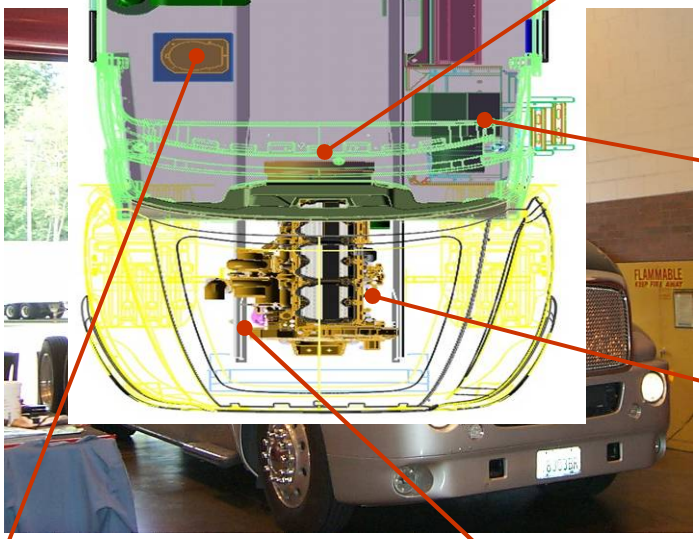
Variable speed compressor more efficient and serviceable
3X more reliable compressor no belts, no valves, no hoses leak-proof refrigerant lines instant electric heat

Shore Power and Inverter

Supplies DC Bus Voltage from 120/240 Vac 50/60 Hz Input Supplies 120 Vac outlets from battery or generator power

Down Converter

Supplies 12 V Battery from DC Bus



Compressed Air Module

Supplies compressed air for brakes and ride control

Electric Water Pump

Higher reliability variable speed faster warm-up less white smoke lower cold weather emissions

Starter Generator Motor

Beltless engine product differentiation improve systems design flexibility more efficient & reliable accessories

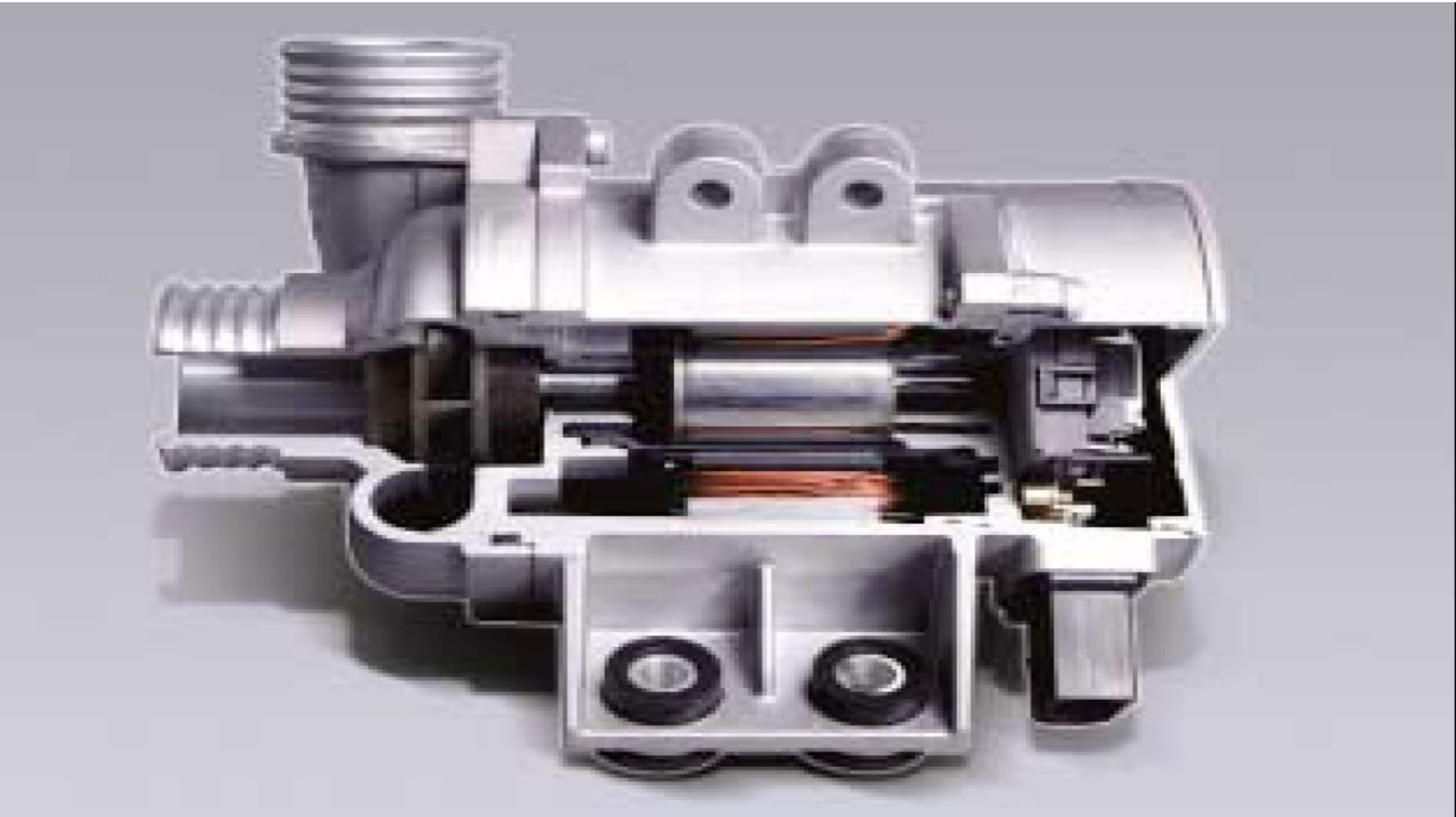
Auxiliary Power Unit

Supplies DC Bus Voltage when engine is not running - fulfills hotel loads without idling main engine overnight

Electric Oil Pump

Variable speed
Higher efficiency

BMW's Electric Water Pump Improves Fuel Economy 1.5 to 2.0 %



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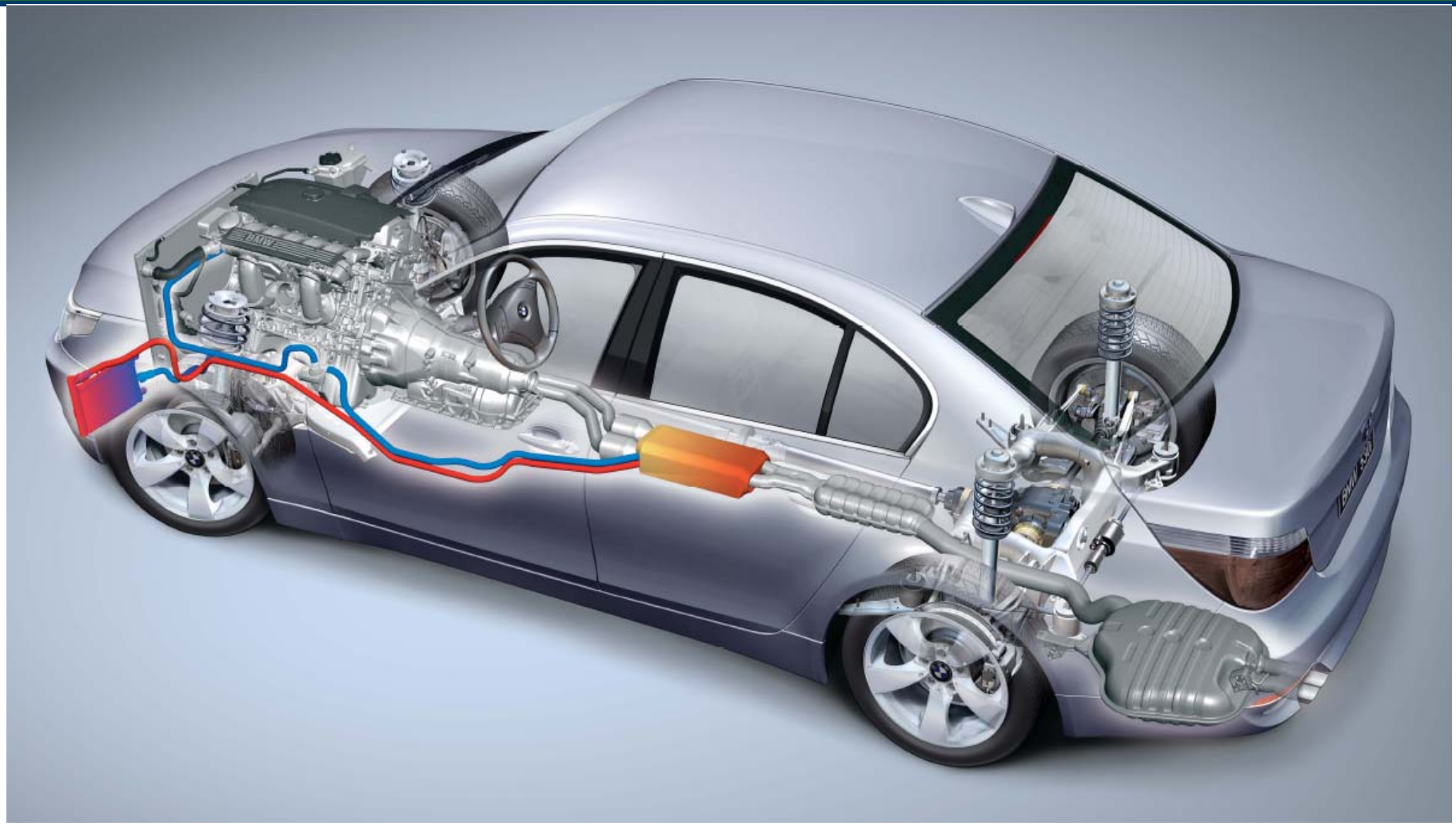
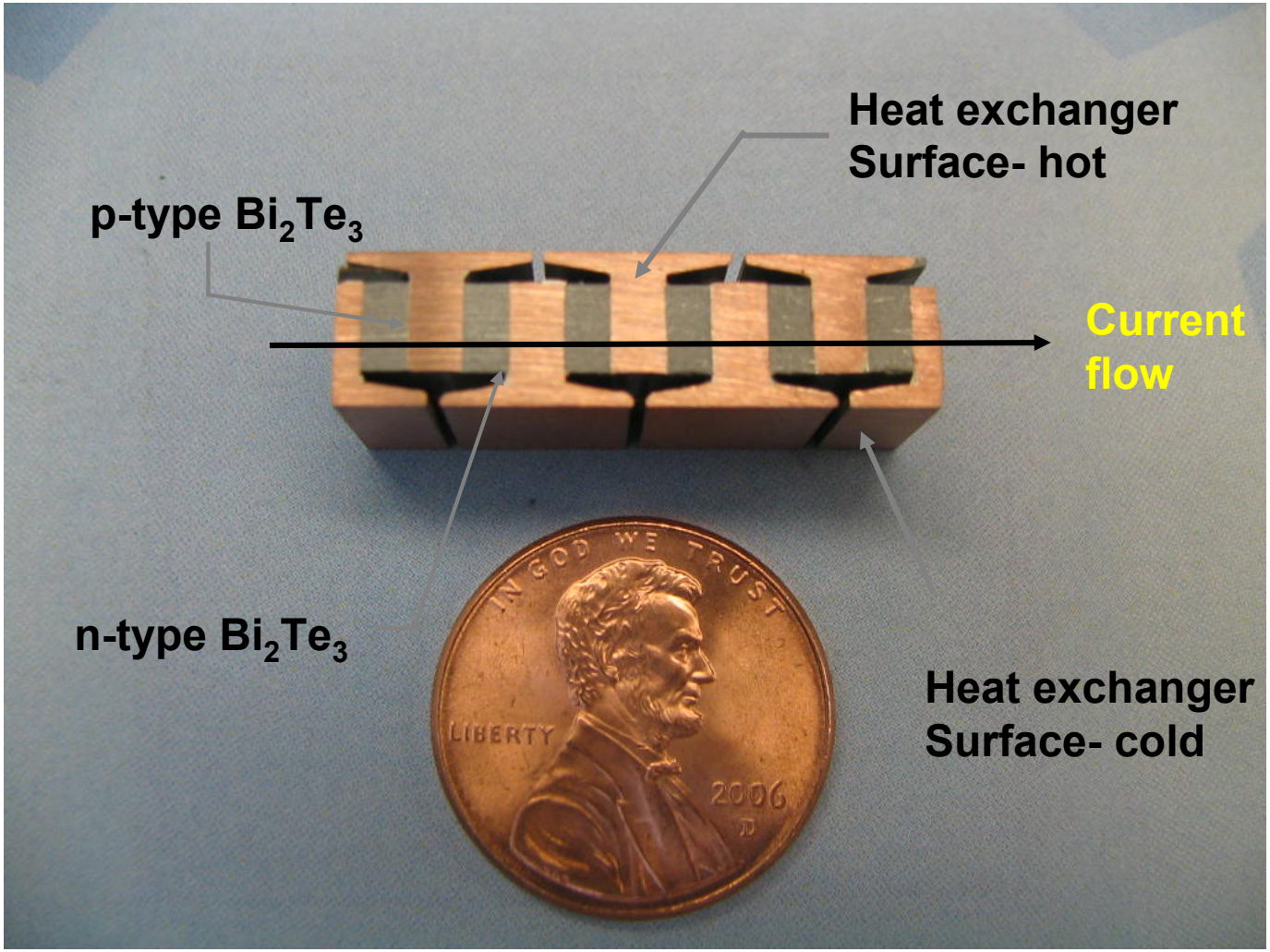
BMW Series 5 , Model Year 2011, 3.0 Liter Gasoline Engine w/ Thermoelectric Generator

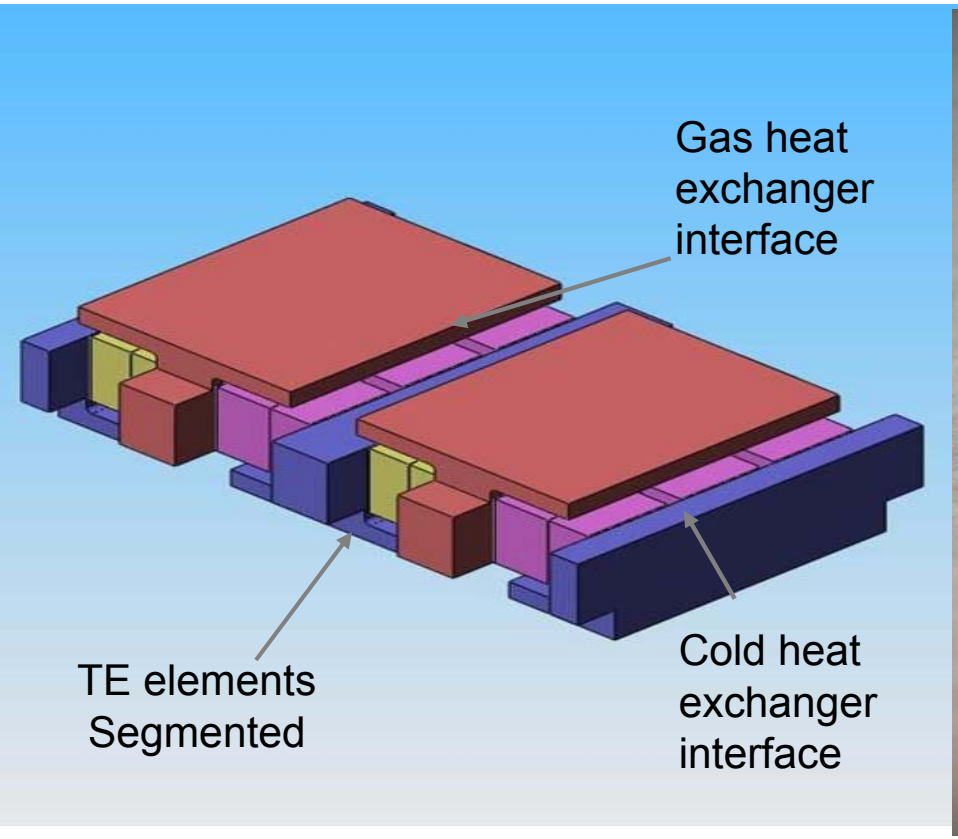


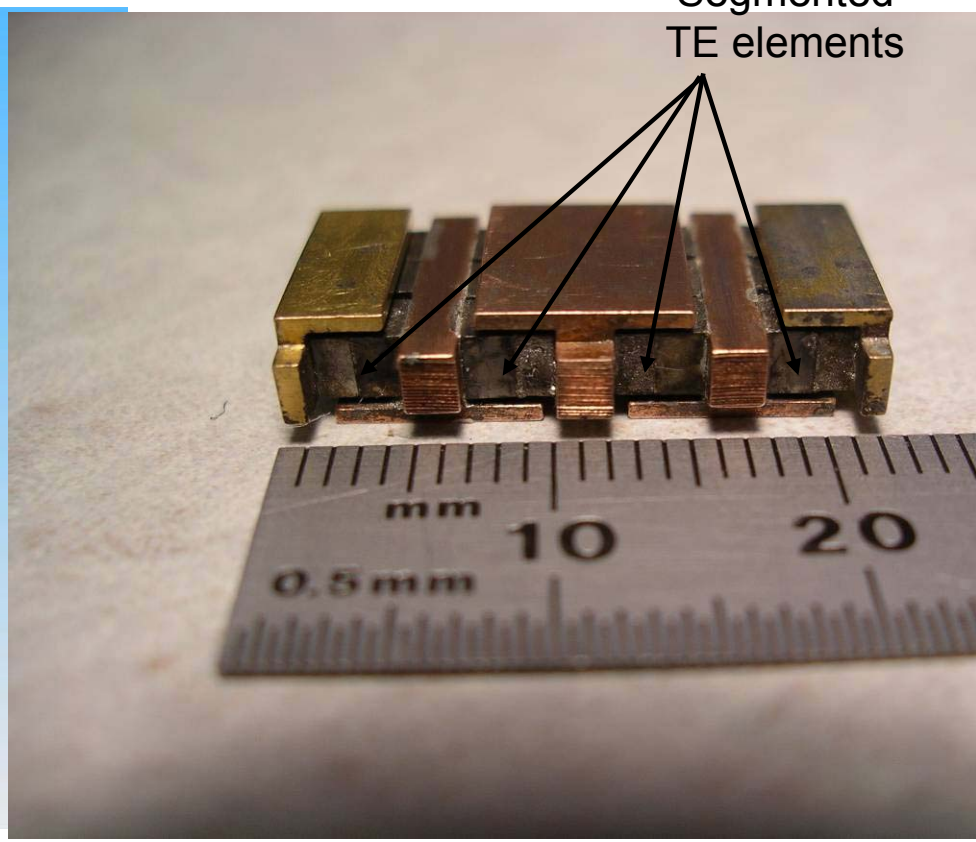
FreedomCAR Fuel Partnership
Visteon
BSST innovative solutions in temperature control
BMW
MINI

2nd Generation Bi_2Te_3 Subassembly



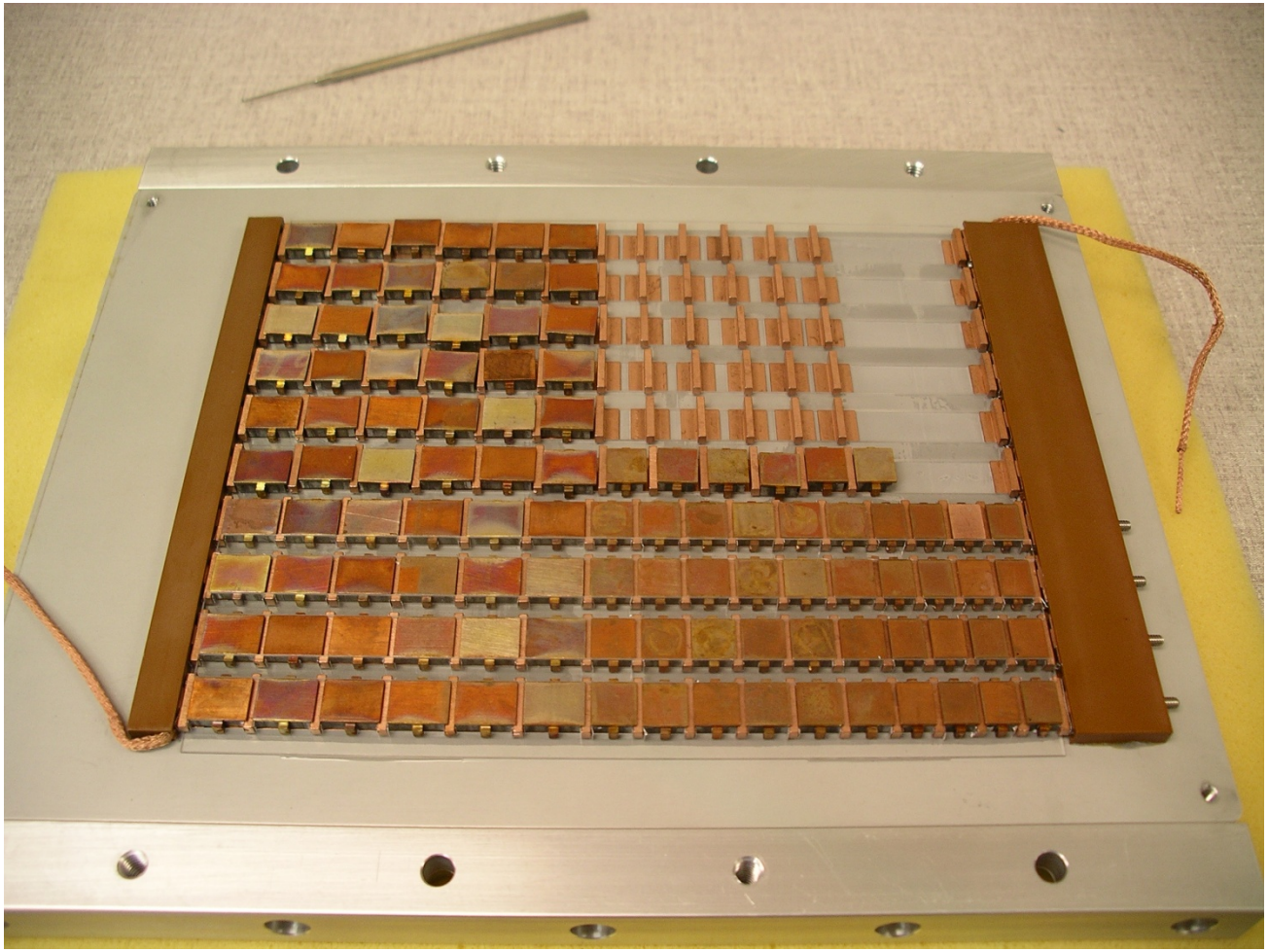
High Temperature 2nd-Stage Segmented Element Subassembly



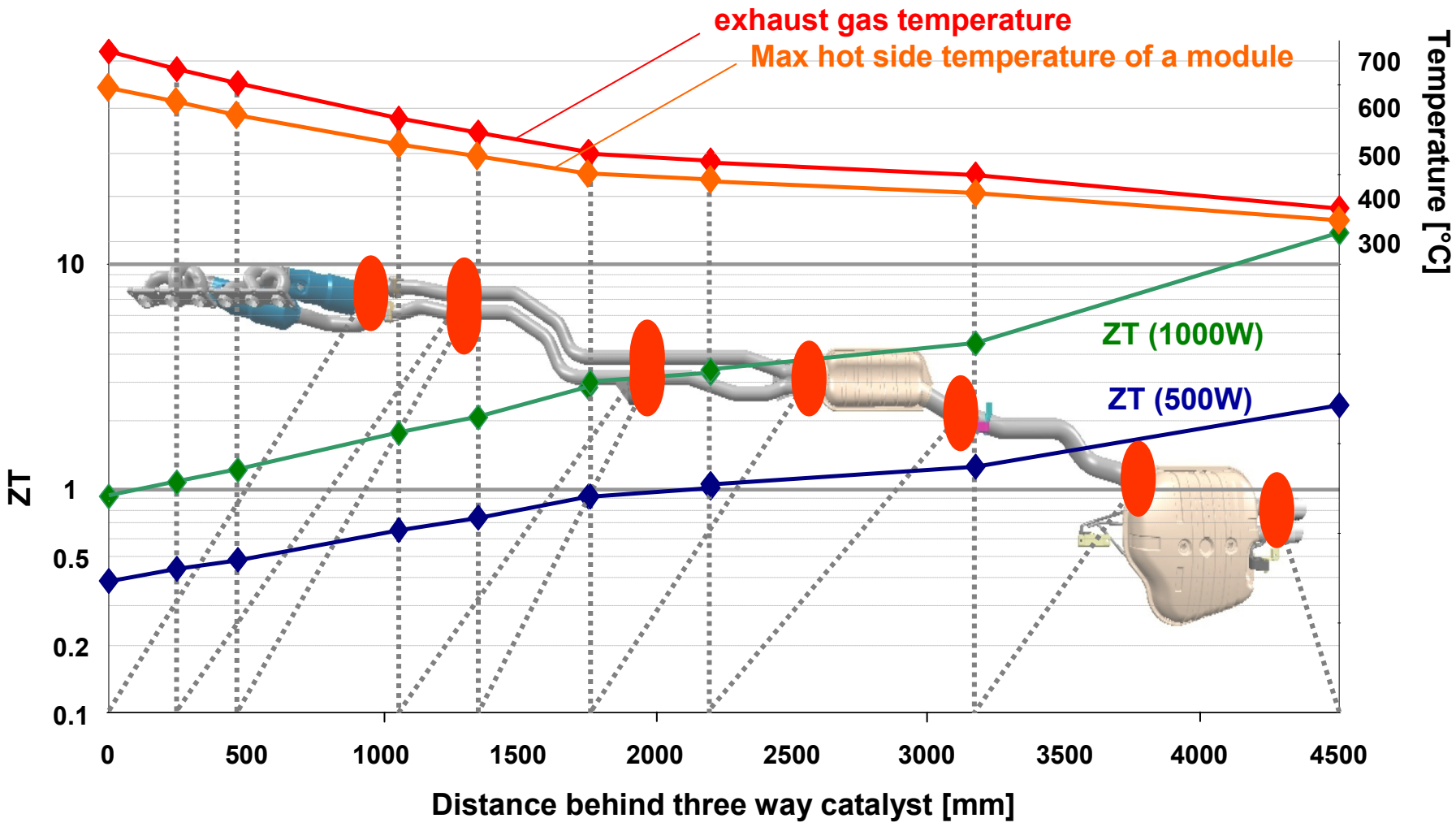


BSST 500^{0}C TEG

TE layer partially assembled on liquid heat exchanger



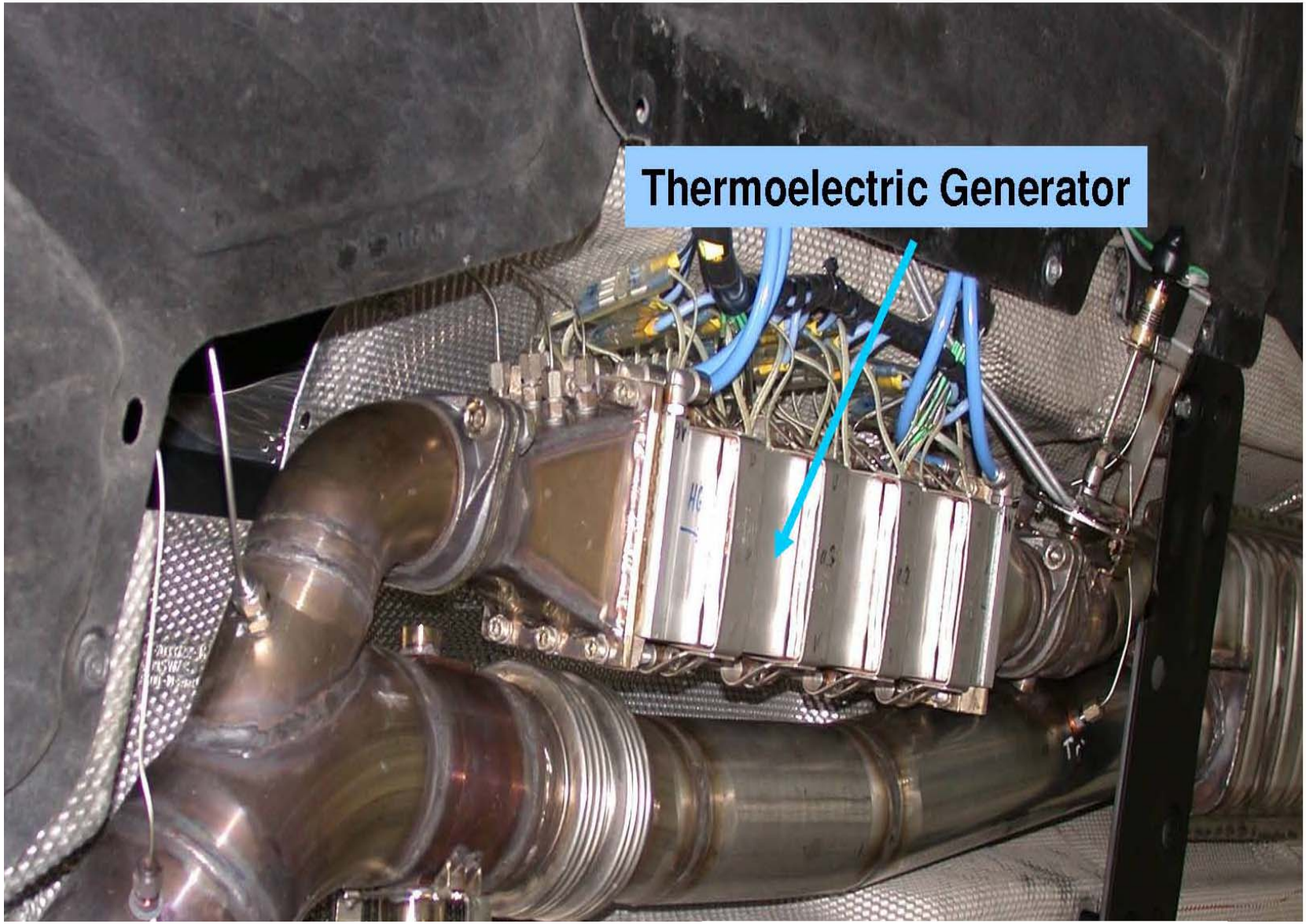
TEG SI Engine Waste Heat Recovery



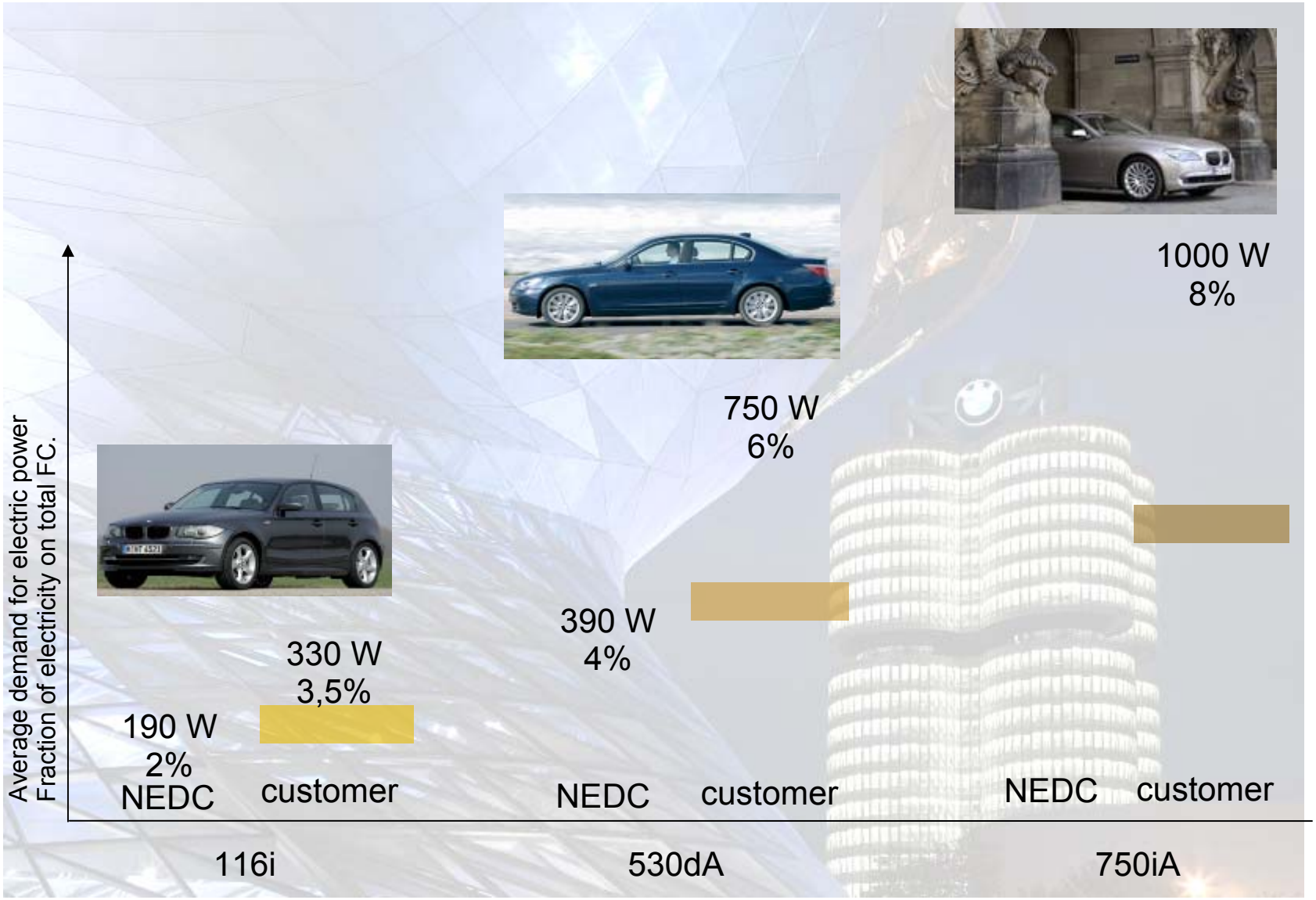
Vehicle 530iA at 130 km/h, Exhaust gas back pressure limited to 30mbar at 130km/h

Slide courtesy of BSST

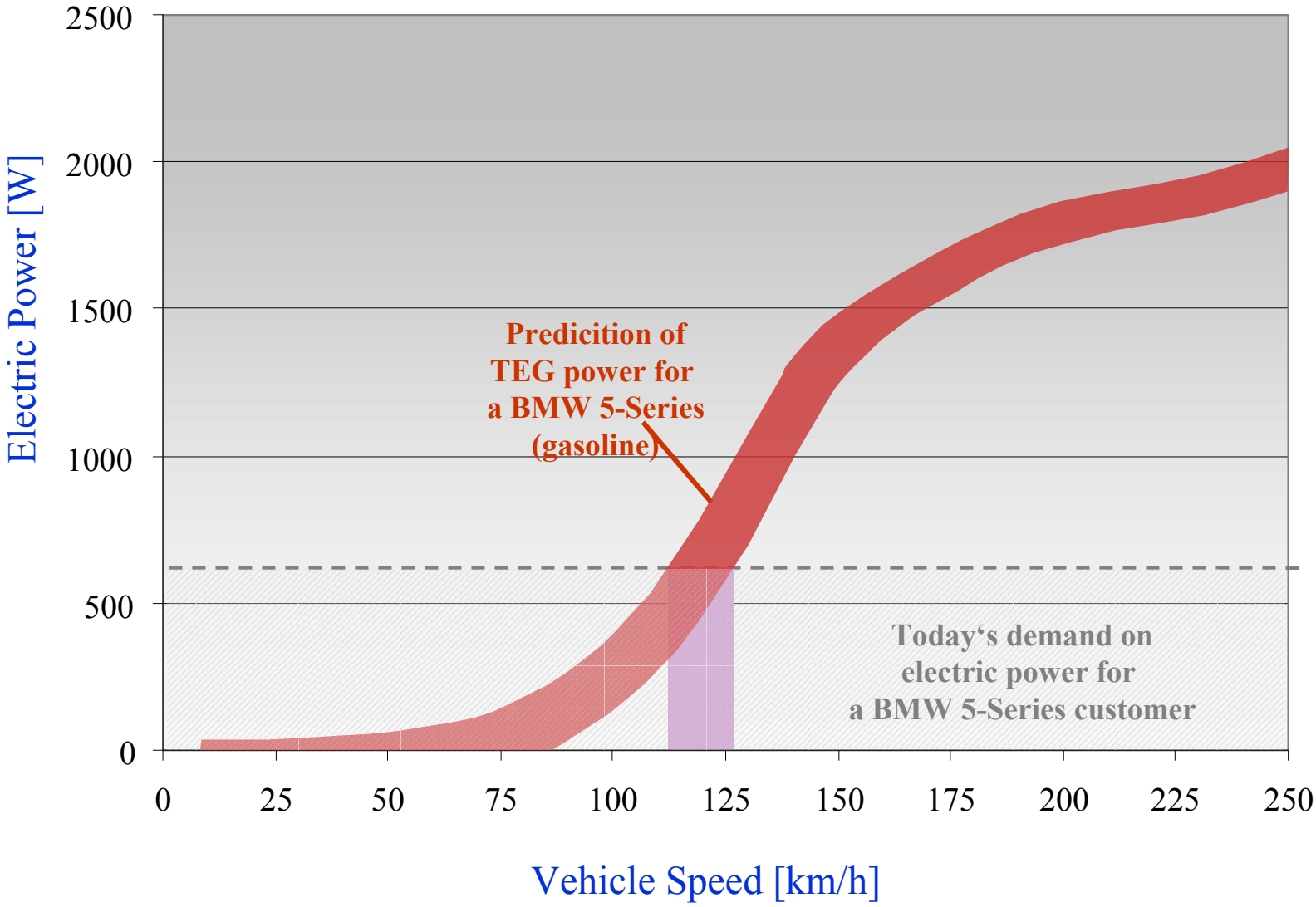
Demonstrator TEG Installed in BMW Series 5 Test Vehicle



TE Waste Heat Recovery. BMW Sedans



Slide courtesy of BSST

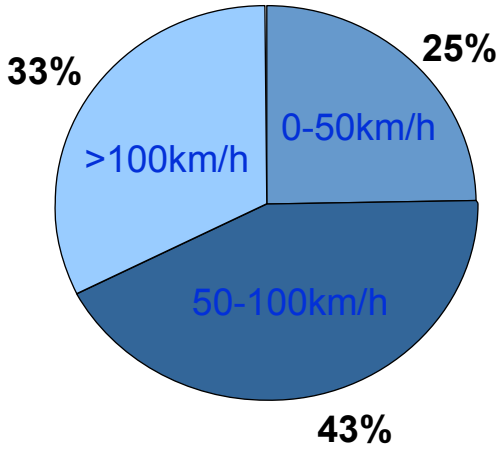

2500
2000
1500
1000
500
0
Electric Power [W]
Predicition of
TEG power for
a BMW 5-Series
(gasoline)
Today's demand on
electric power for
a BMW 5-Series customer
0
25
50
75
100
125
150
175
200
225
250
Vehicle Speed [km/h]

Efficient Dynamics, the Strategy of BMW Group.

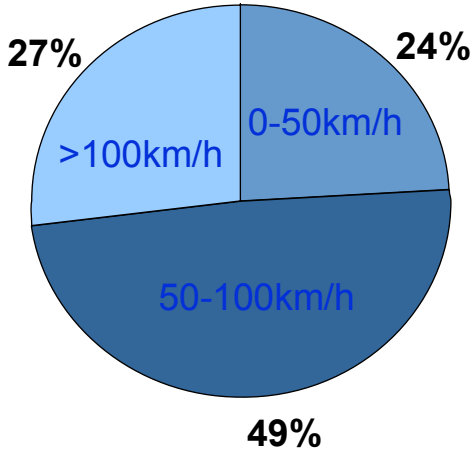
~ 130.000 trips
in ~ 25 months

~ 1.000.000 km

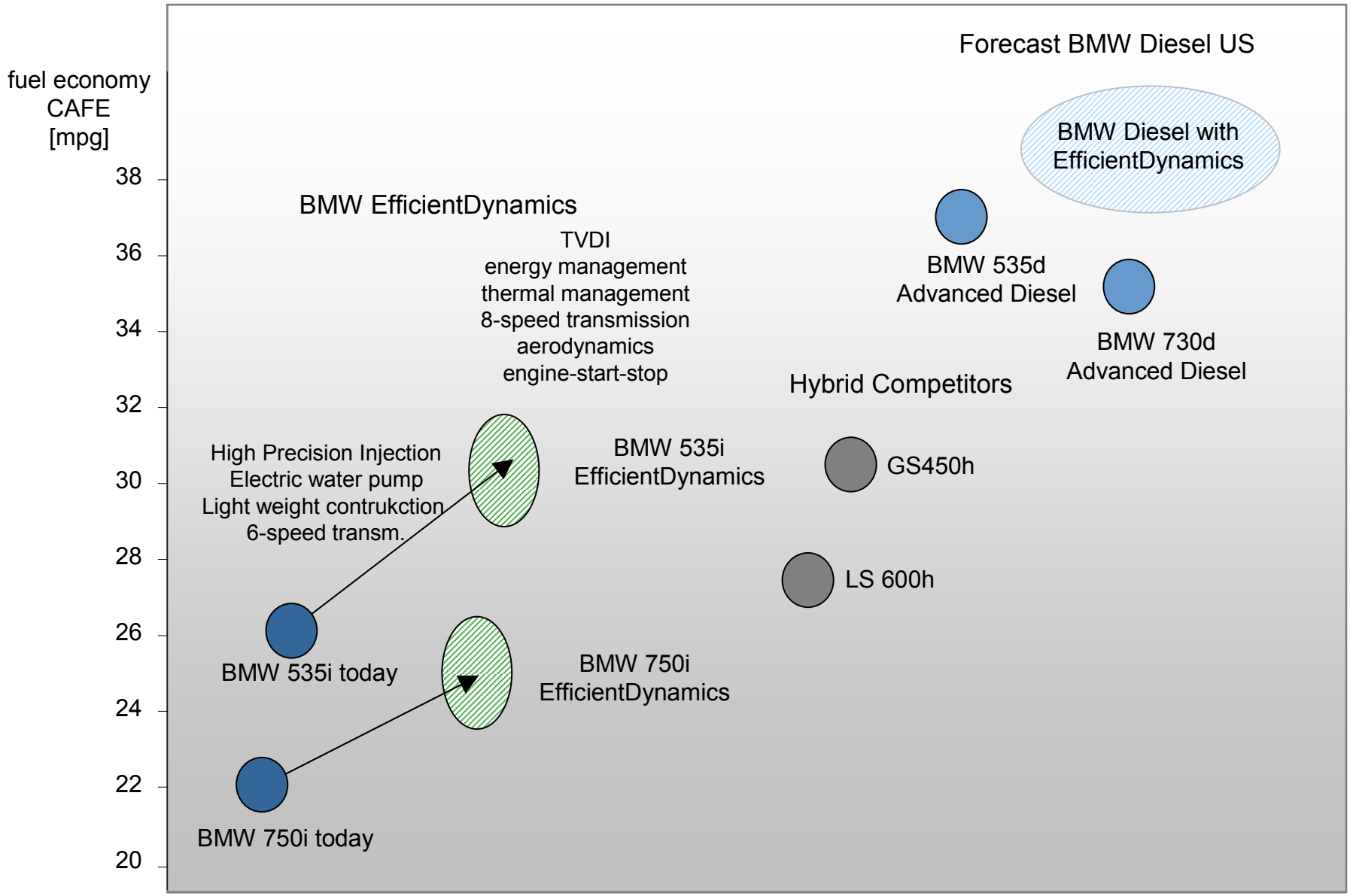
Customer Profile Germany (e.g. BMW 320i)



Customer Profile USA (e.g. BMW 328i)



Efficient Dynamics, the Strategy of BMW Group



Efficient Dynamics, the Strategy of the BMW Group

Power train

- High Precision Injection
- DI lean stratified
- Common Rail Injection
- Components with reduces friction
- Map-controlled oil and cooling pumps

Driving Resistance

- Active cooling flap system
- Tires with reduced rolling resistance
- Light weight construction
- Aerodynamics

Energy Management

- Electric power steering
- Electric water pump
- Brake energy regeneration
- Auto Start-Stop function
- Gear Shift Indicator

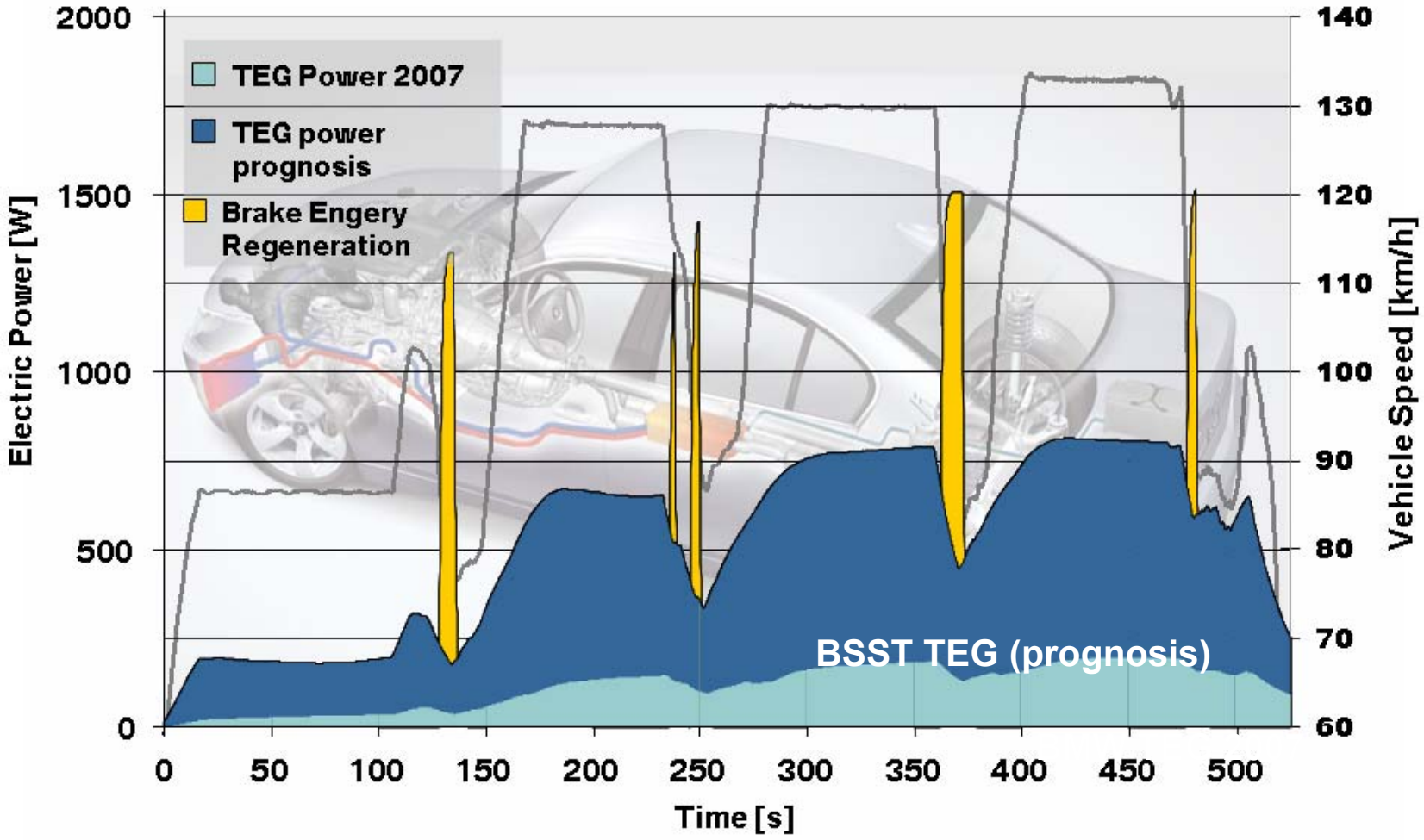
Thermal Management

- **Thermoelectrics**
- Selective cooling
- Accelerated warm up of the powertrain
- Thermal Insulation

Energy sources

- Gasoline
- Diesel
- Hydrogen

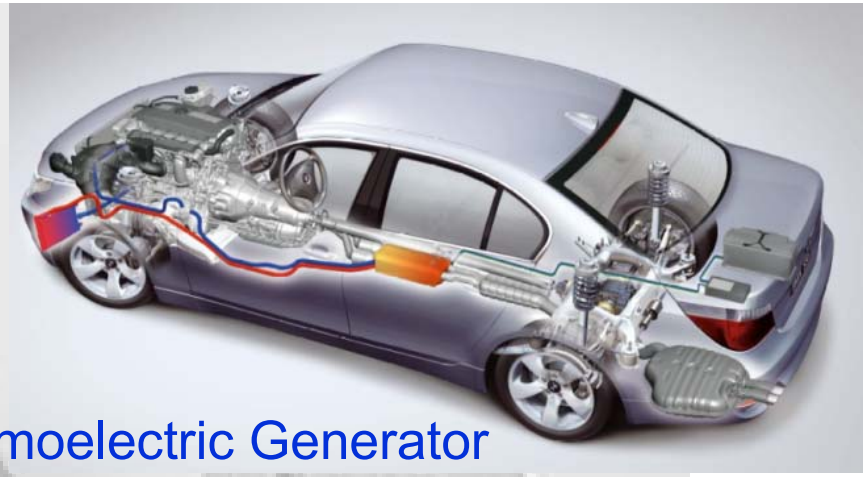
TEG is ideally compatible with Regenerative Braking



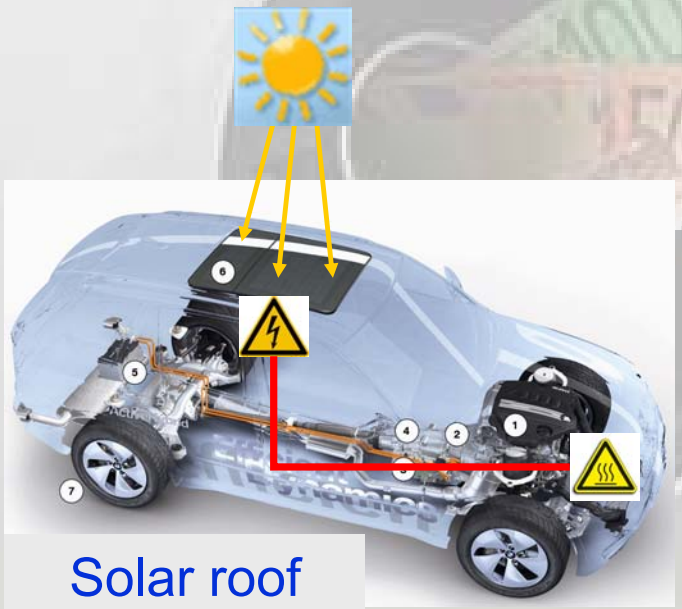
Slide courtesy of BSST

Efficient Dynamics, the Strategy of the BMW Group.

Gear shift indicator



Thermoelectric Generator



Solar roof

Predictive Energy Management

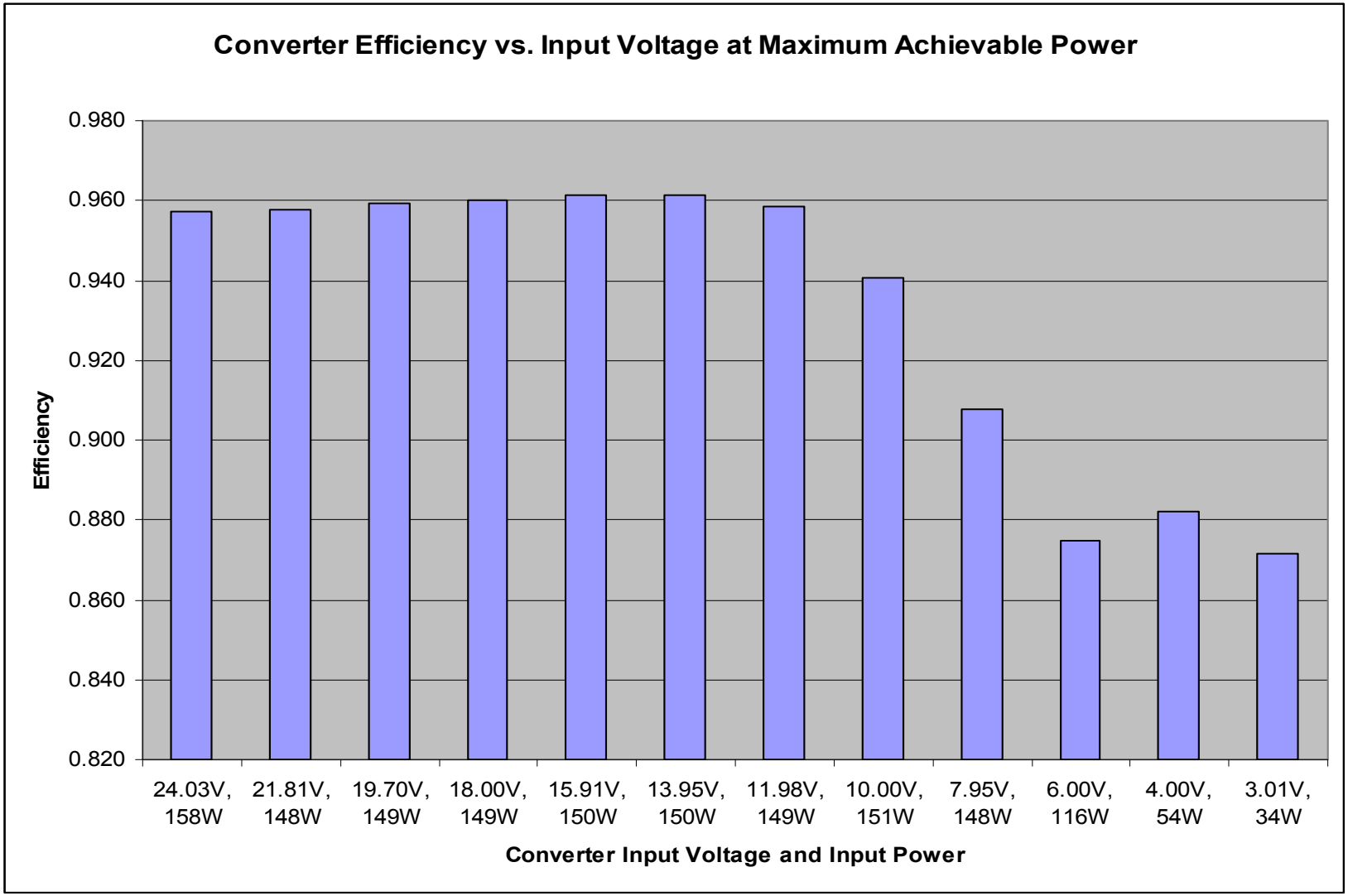
TGM Integrated Buck/Boost Converter

The PCS produces a positive output voltage that is greater than, equal to or less than the input voltage in a single stage.

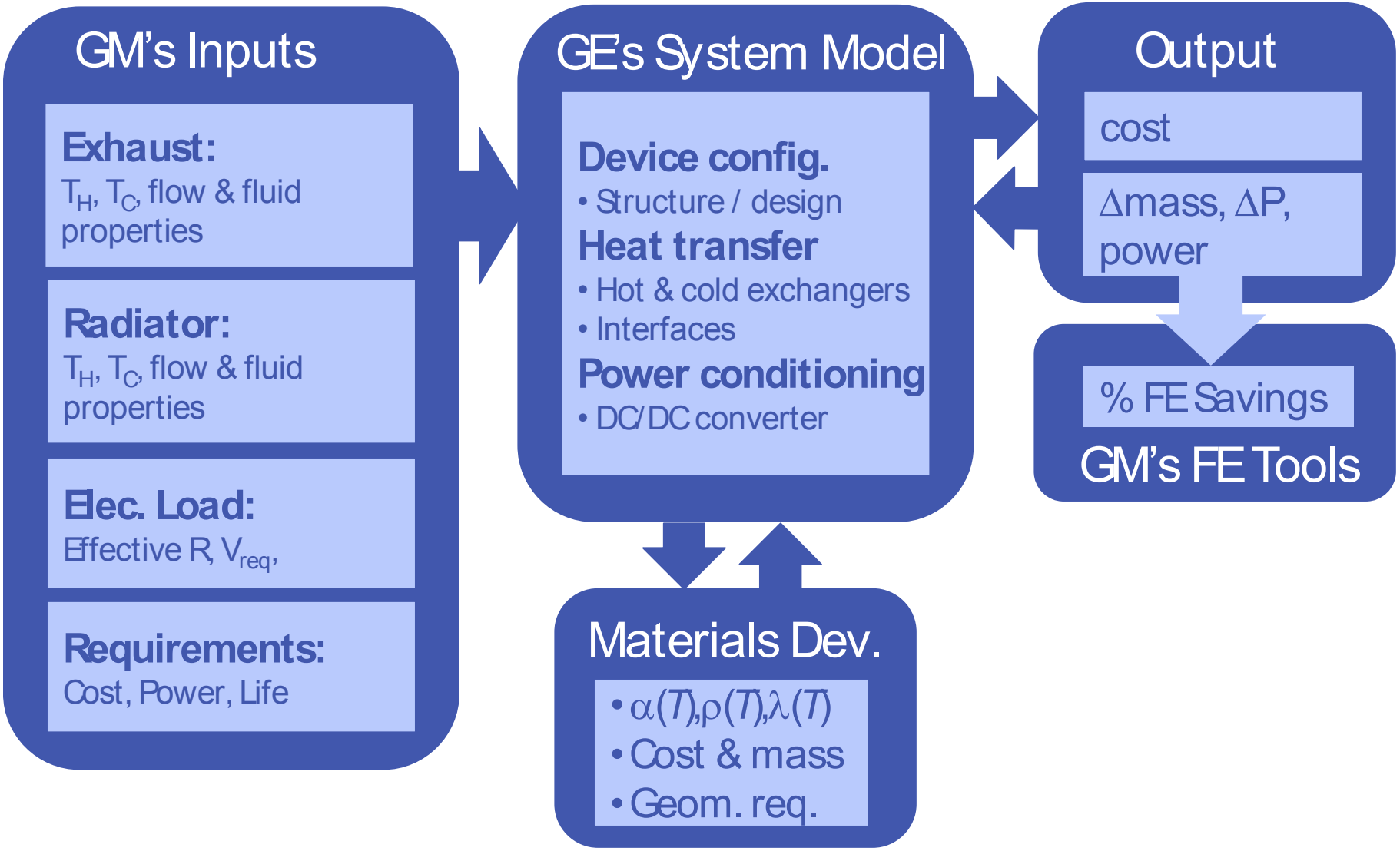
Minimizes cost, size and weight while maximizing power conversion efficiency.

Supports Maximum Power Point Tracking.

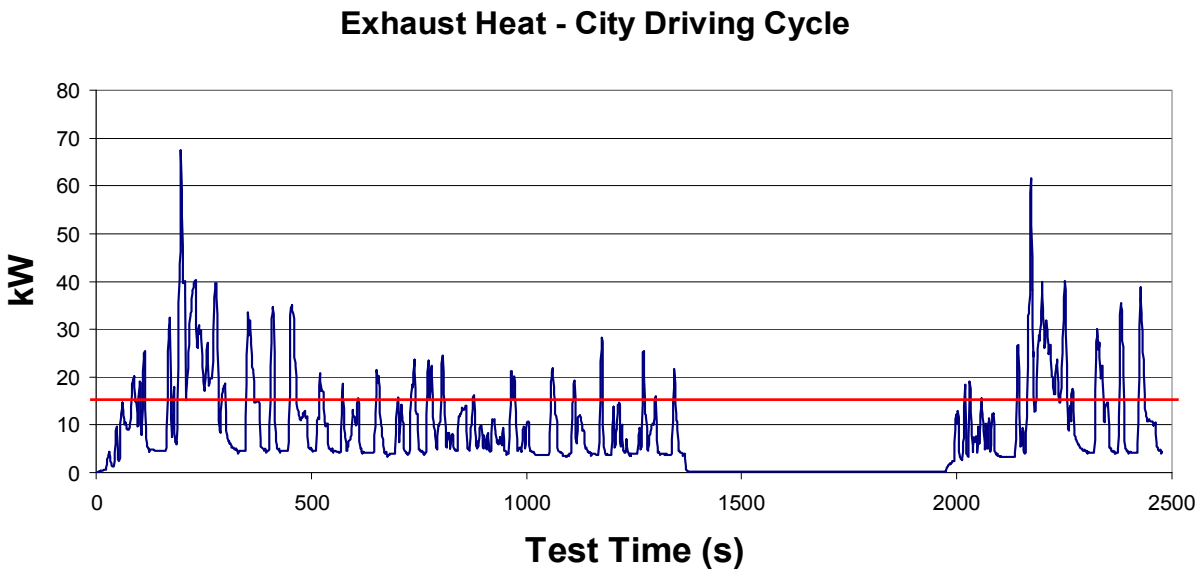
Power Converter Efficiency



Program Flow Chart



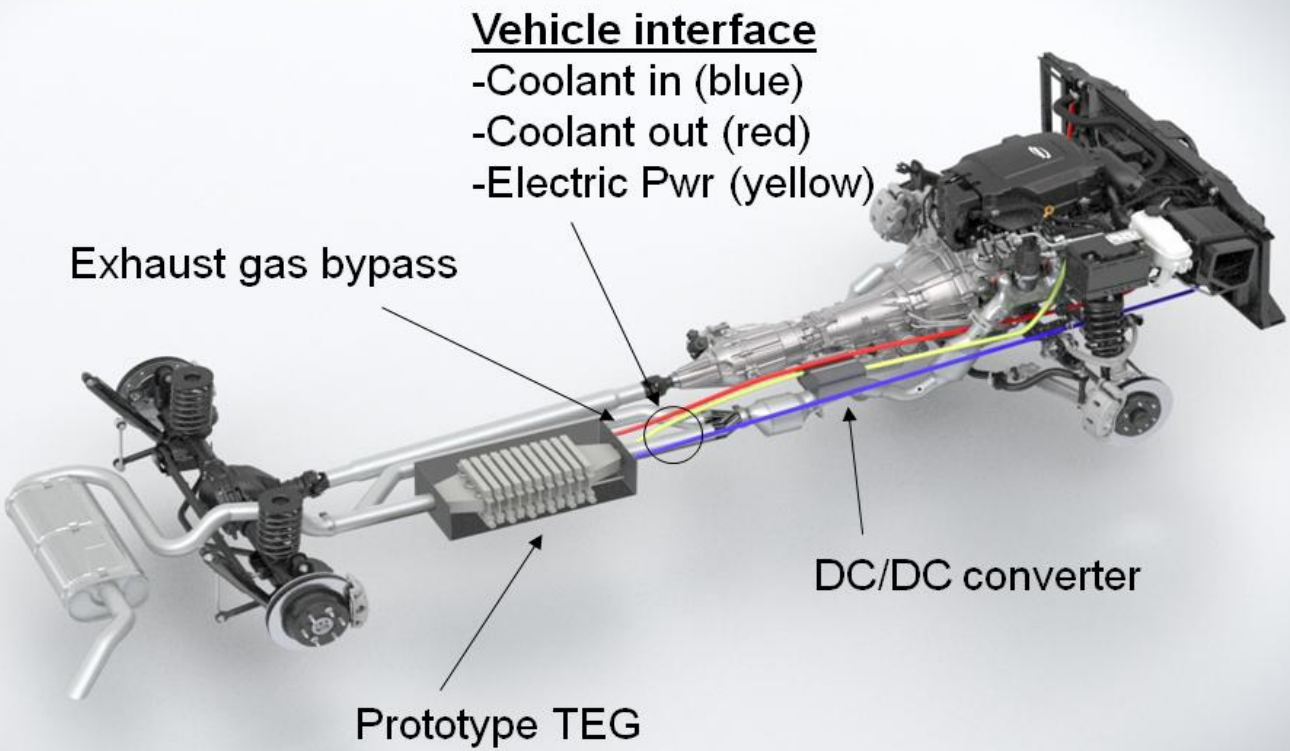
Chevy Suburban elected for GM TE Generator Application



- The Suburban selected because it simplified the modifications and installation of the prototype.
- Fuel efficiency improvement will be better in small, fuel efficient vehicles than in large vehicles because the electrical load in small vehicles is a greater percentage of the engine output.

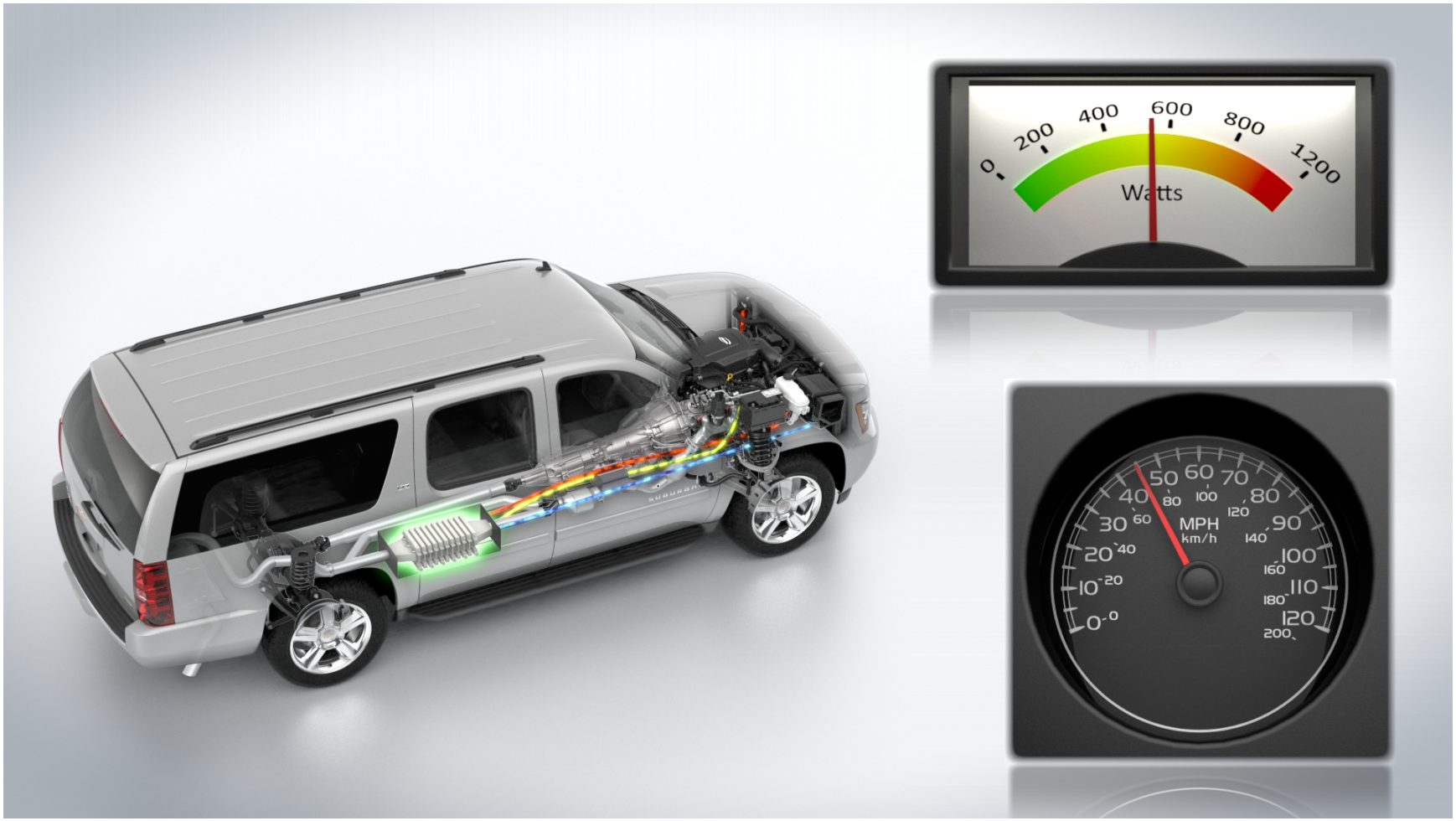
GM TE Generator on a Chevy Suburban

TEG installed in a rear drive vehicle.
GM Suburban

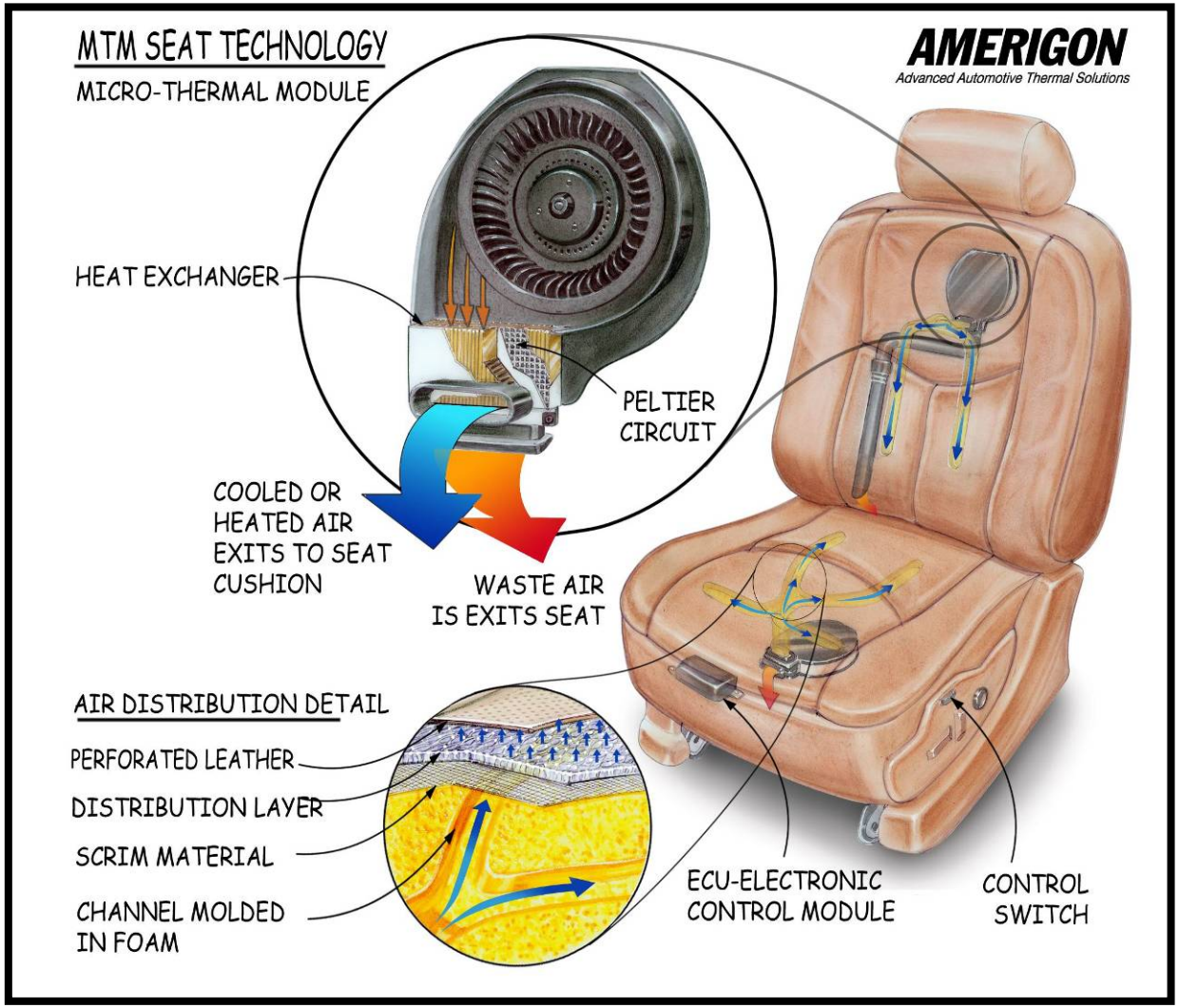


Slide courtesy of General Motors Corp.

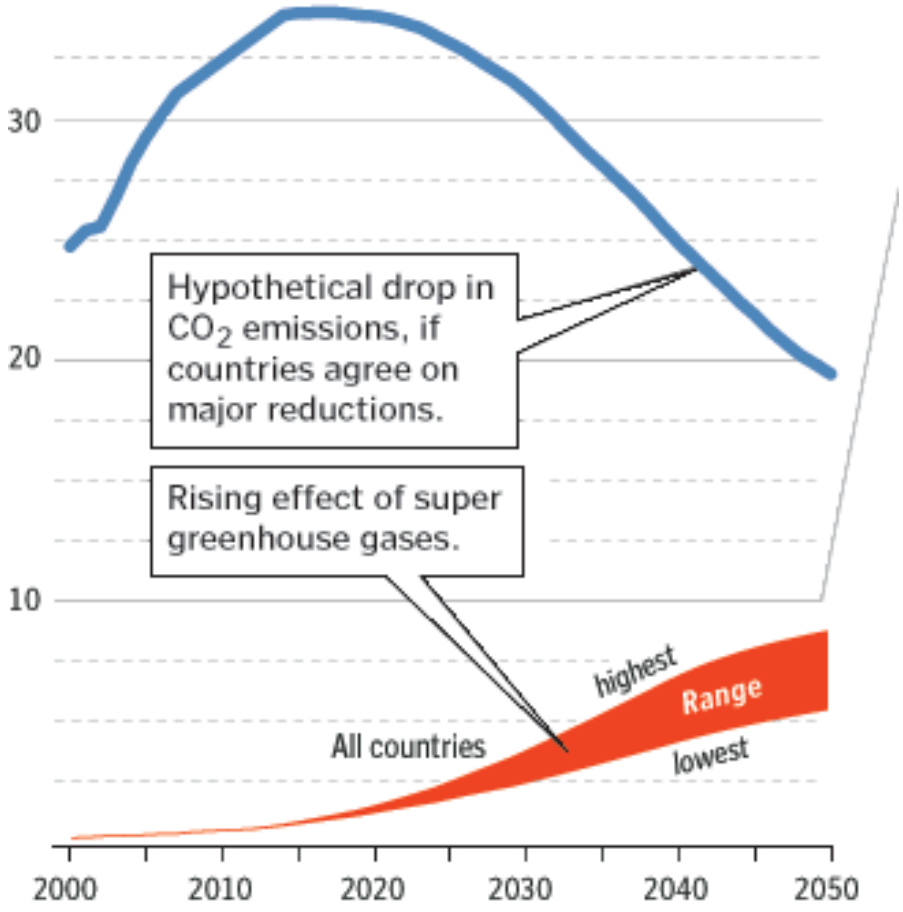
TEG installation in Chevy Suburban



Climate Control Seat™



"Super" Greenhouse Gases



Global warming effect of emissions

CO_2 PER YEAR IN METRIC TONS

SUPER GREENHOUSE GAS EMISSIONS
(Converted to the equivalent amount of CO_2)

Emissions of R 134a (with over 1,430 times the heat-trapping power that of CO_2) from automobile air conditioners would undermine any progress made in CO_2 reductions

Source: "Chemicals That Eased One Woe Worsen Another," Washington Post, Monday, July 20, 2009

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 Concept
  Maintain Occupant Comfort without Cooling Entire Cabin
  Reduce Energy used in Automotive HVAC's by 50%

Eliminate all Gases Associated with Automotive HVAC
Toxic,
Greenhouse Gases,
Flammable Gases

- 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 from personal 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 atmosphere

-- 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

630 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

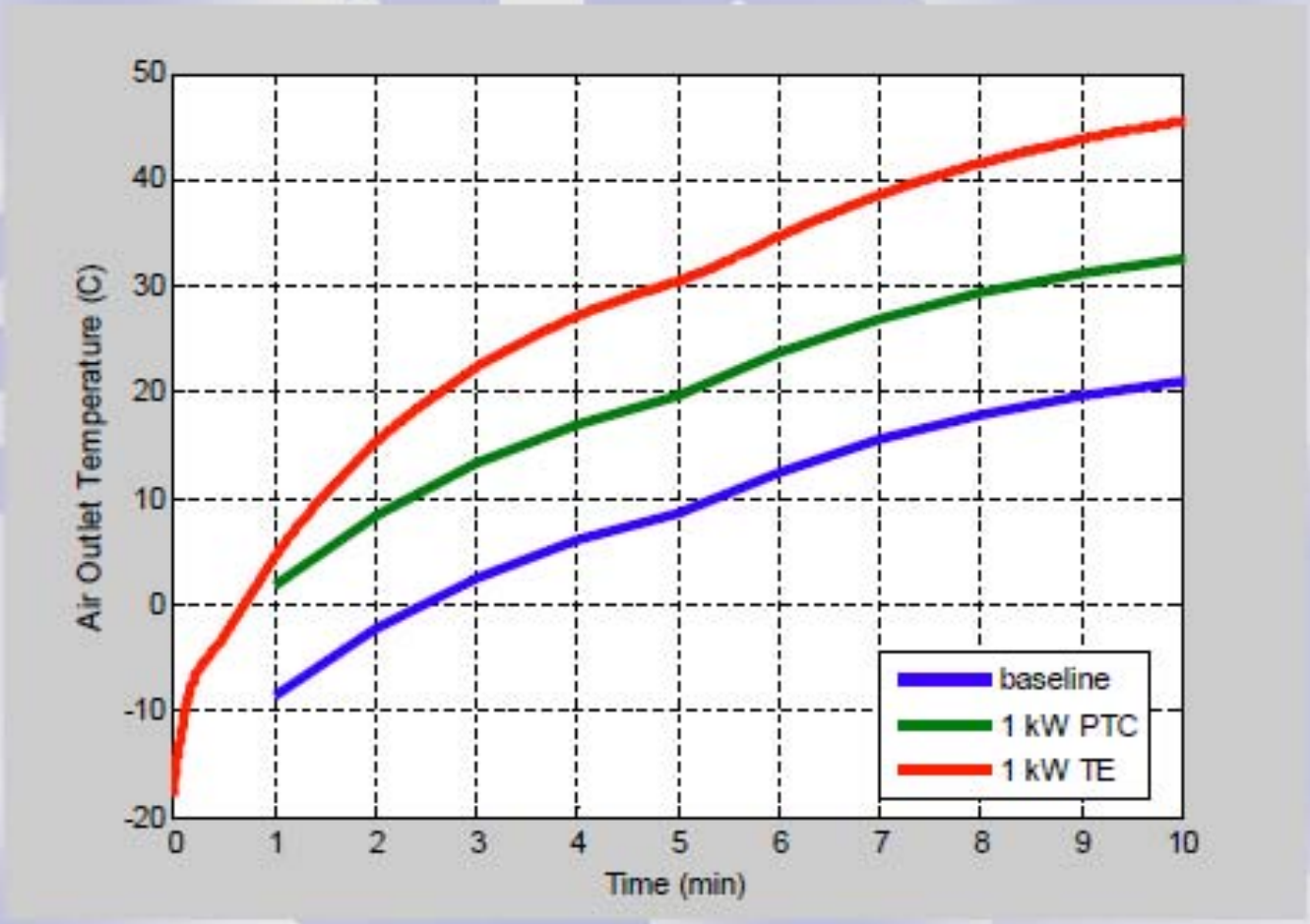
Semiconductor costs are significantly reduced with volume

Converts Air Conditioner to Heater by reversing DC polarity

Zonal HVAC System

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

Heating Duct Air Outlet Temperature



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

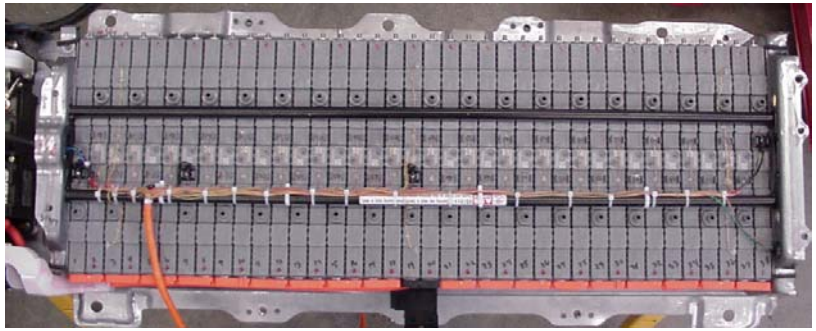
Replace Resistive Heaters

Typical COP 1.0

Battery Temperature Impacts HEV/EV

Temperature affects battery operation

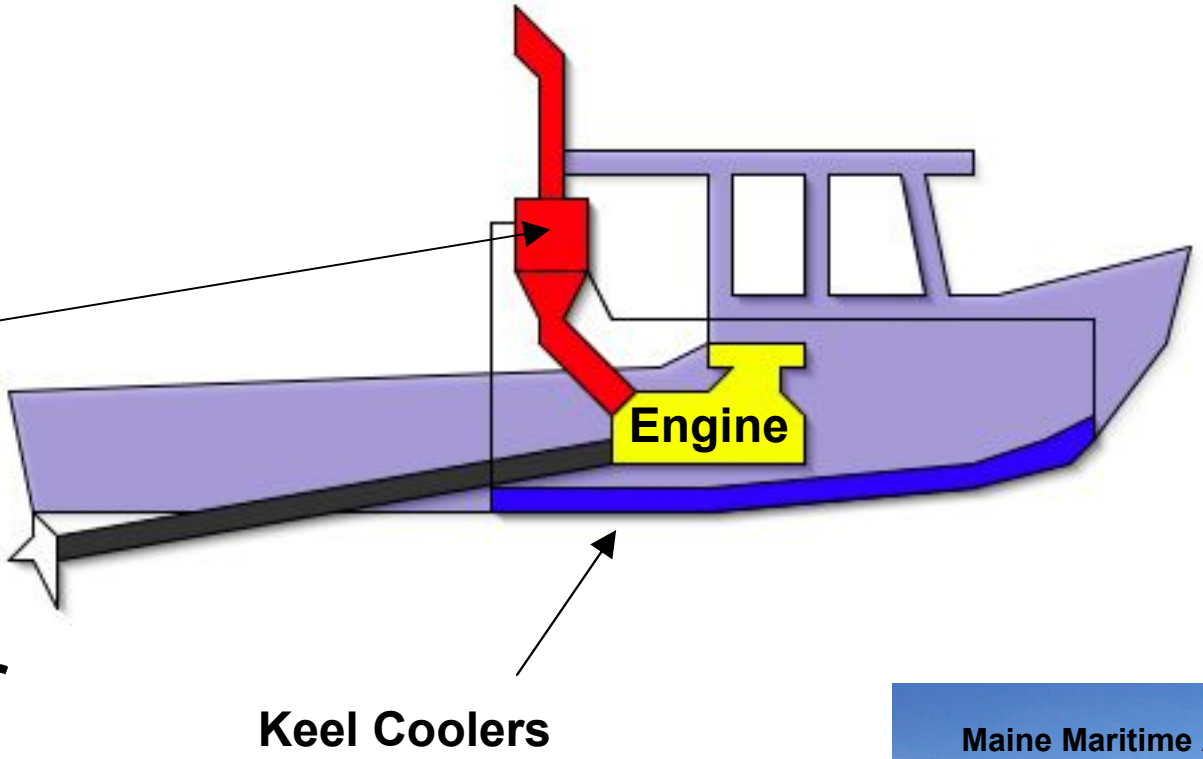
- > Round trip efficiency and charge acceptance
- > Power and energy
- > Safety and reliability
- > Life and life cycle cost



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

Thermoelectric Generator on a Fishing Vessel's Engine Exhaust

Seawater Cooled Exhaust Stack TE Generator

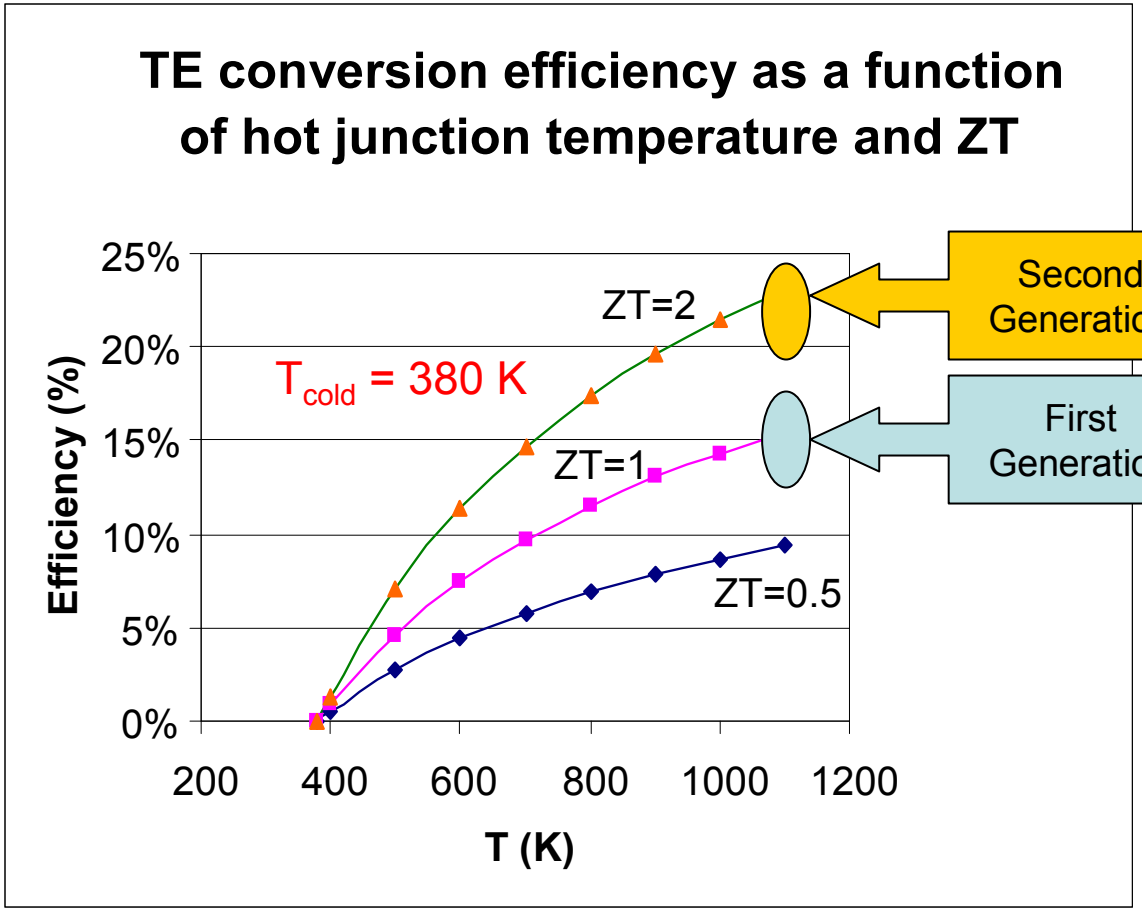


Thermoelectric Wristwatch

CITIZEN
Eco-Drive Thermo
Watch

- Converts temperature difference between body and surrounding air into electrical energy
- No battery change needed
- When not being worn, second hand moves in 10-second increments (non power generation mode)
- Number of semiconductors in thermocouple array: 1,242 pairs
- Operating time from a full charge: Approx. 6 months (approx. 16 months in power saving mode)

TE Materials Performance Objective

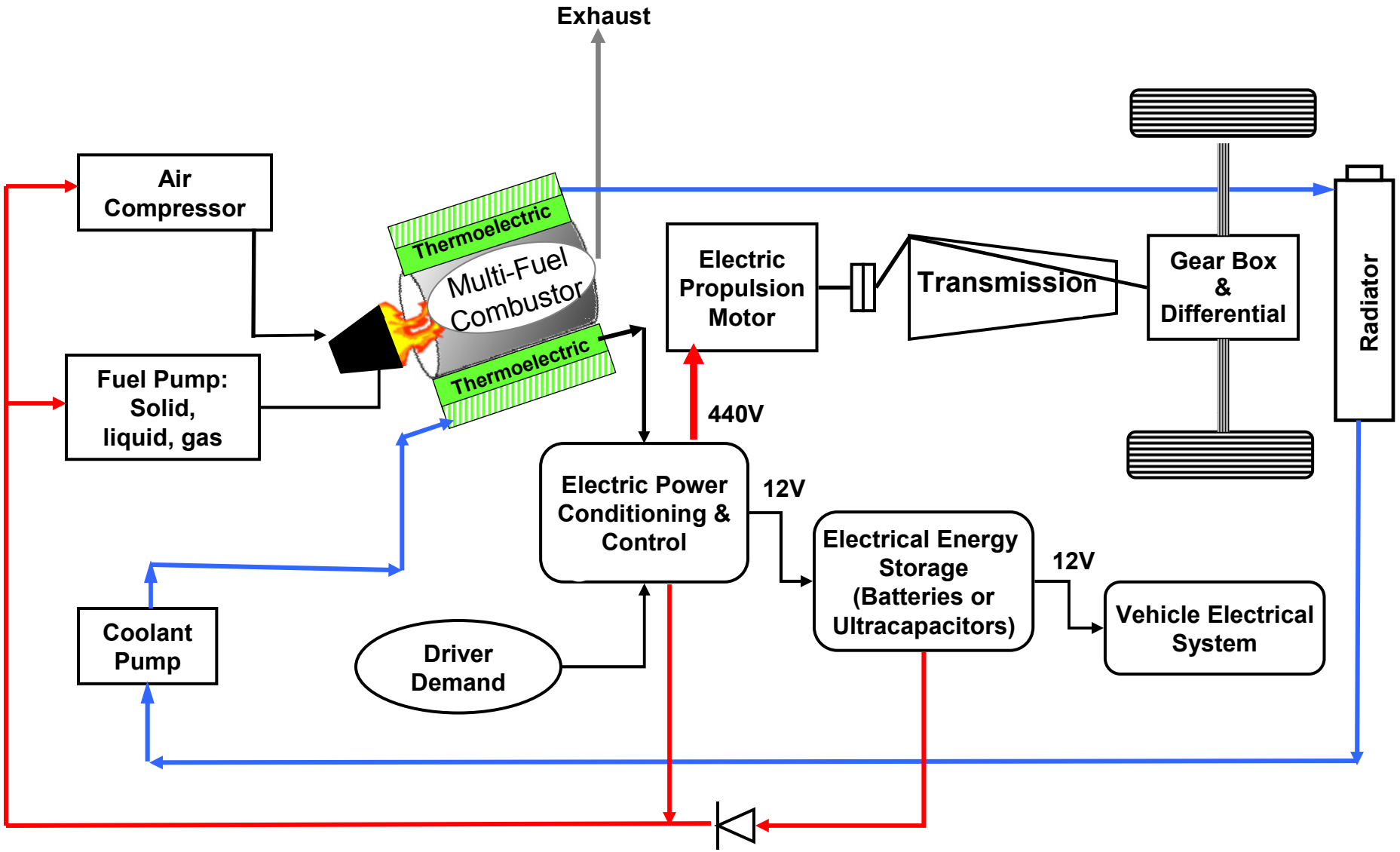


$$\eta_{\max} = \frac{T_{hot} - T_{cold}}{T_{hot}} \cdot \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_{cold}}{T_{hot}}}$$

Carnot | TE Materials

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Vehicular Thermoelectric Hybrid Electric Powertrain



TE applications: distributed energy generation

CENTRO RICERCHE FIAT

Thermoelectricity for Mobile Systems

THERMOBILE - *under evaluation*

CNRS	CNRS – France
CENTRO RICERCHE FIAT	CRF – Italy
SNCF	SNCF – France
CEA	CEA – France
EMPA	EMPA – Switzerland
DTU	DTU – Denmark
BOSCH	BOSCH – Germany
Termo-Gen AB	Termo-Gen – Sweden
BASF The Chemical Company	BASF - Germany

TE applications: heat recovery from exhausted gases

CRF CENTRO RICERCHE FIAT

Reduced Energy Consumption by Massive Thermoelectric Waste Heat Recovery in Light Duty Trucks

SEVENTH FRAMEWORK PROGRAMME

HeatReCar - EU project

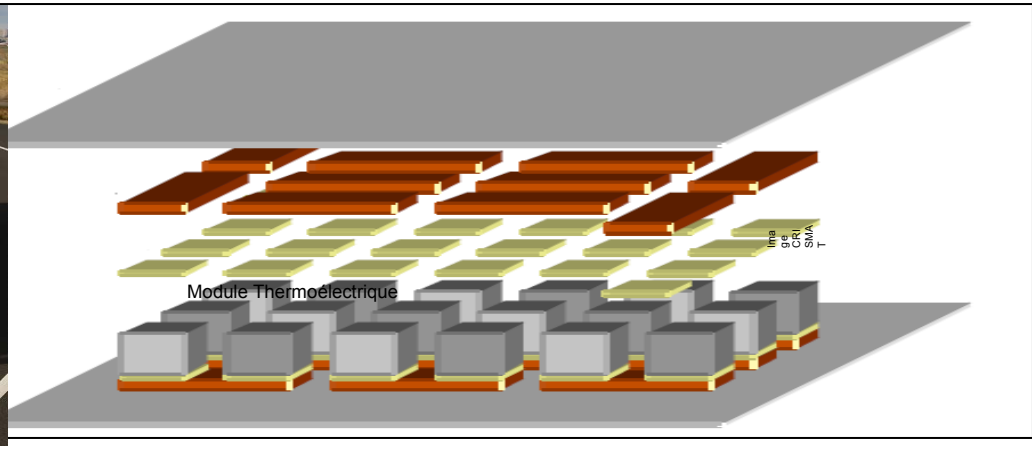
SIEMENS	Siemens - Germany
ROM INNOVATION	ROM Innovation -France
CRF CENTRO RICERCHE FIAT	CRF - Italy
BOSCH	Bosch - Germany
Termo-Gen AB	Termo-gen AB - Sweden
Fraunhofer IPM	Fraunhofer IPM - Germany
Valeo	Valeo - France

RENOTER (Projet FUI6)

« *R*écupération d'*ÉN*e*rgie* à l'échappement d'un m*O*teur par Th*ER*moélectricité »

Objectifs

- Convertir l'énergie thermique du moteur en électricité grâce à **l'effet Seebeck**.
- Etudier les **matériaux thermoélectriques** les plus adaptés (performance, coût, nocivité…).
- Concevoir et tester un démonstrateur sur moteur dXi11 d'une puissance électrique de **1 à 3 kW**.



Partenaires et durée

- Constructeurs, Laboratoires, Equipementiers
- Projet de 3 ans démarré en Octobre 2008

ICG Montpellier
RENAULT TRUCKS
RISMAT
RENAULT
L. P. M.
Valeo
SHERPA ENGINEERING

Japan's Government Supported Thermoelectric R&D II

- National Institute for Materials Science ($0.18 M)
  - Complex Structured Materials ($RB_{17}CN$, $RB_{22}C_2N$)
  - Research on Spin-Seebeck Effect
- Tohoku University ($0.21 M)
  - Basic Research on Assimilation of Thermal Insulation and Spin Electronics
  - R&D of Novel Thermoelectric Modules By Inkjet Techniques
- Japan Advanced Institute of Science & Technology ($ 0.22 M)
  - High Efficiency & Low Cost Thermoelectric Modules Based on Nanoball technology

Japan's Government Supported Thermoelectric R&D I

- Nagoya University & 3 Subcontrators ($1.90 M)
  - Layered Oxides
  - Si Base Clathrates
  - Nanostructured Materials
  - Cage –structured (Skutterudites)

- Denso Co.& 4 Subcontractors ($2.25 M)
  - Goal 12 % Efficiency w/ Delta T of 300K
  - Skutterudites

- Nagoya University ($0.33 M)
  - Basic Research Layered Oxides combined with Low Dimensional Materials

China's National Basic Research on Thermoelectrics (973 Program)

- 973 Program Organization ($10 M)

  Wuhan University of Technology
  Shanghai Institute of Technology
  Chinese Academy of Sciences
  Zhejiang University
  Strangdong University
  Lanzhou University

Technical Directions

Fundamental Aspects of Low Dimesional TE
Design principles of advanced TE couples
Design and Fabrication of High Efficiency devices
Application of vehicular TE Generators
Application of thermoelectric–photovoltaic Hybrid system

Vehicular Thermoelectric Application Possibilities

Near Term (3-6 yrs)

- Thermoelectric Generator providing nominal 10% fuel economy gain augmenting smaller alternator
- "Beltless" or more electric engines
- Thermoelectric HVAC augmenting smaller A/C

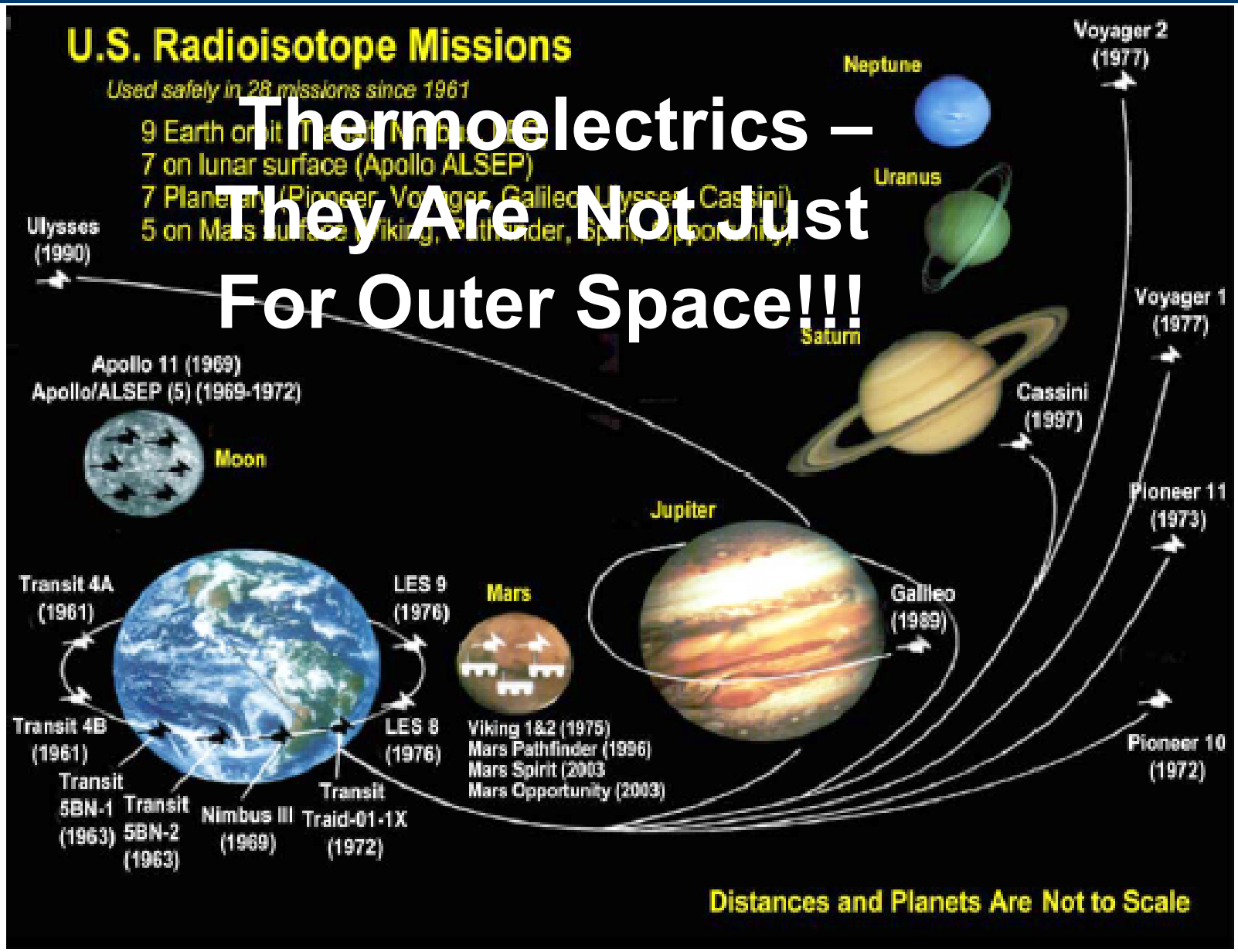
Mid Term (7-15 yrs)

- 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 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

DOE's Thermoelectric Program



THERMOELECTRIC APPLICATIONS WORKSHOP

- Where: Del Coronado Hotel, San Diego, CA
- When: September 29 –October 2, 2009
- Registration Fee: None for those actively involved in thermoelectrics.
- Plenary Speakers:

  Millie Dresselhauss, MIT, Low Dimensional Thermoelectrics

  Mike Rowe, Cardiff, University , EU Automotive TE Applications

  Harald Böttner, Franhoffer Institute, Germany

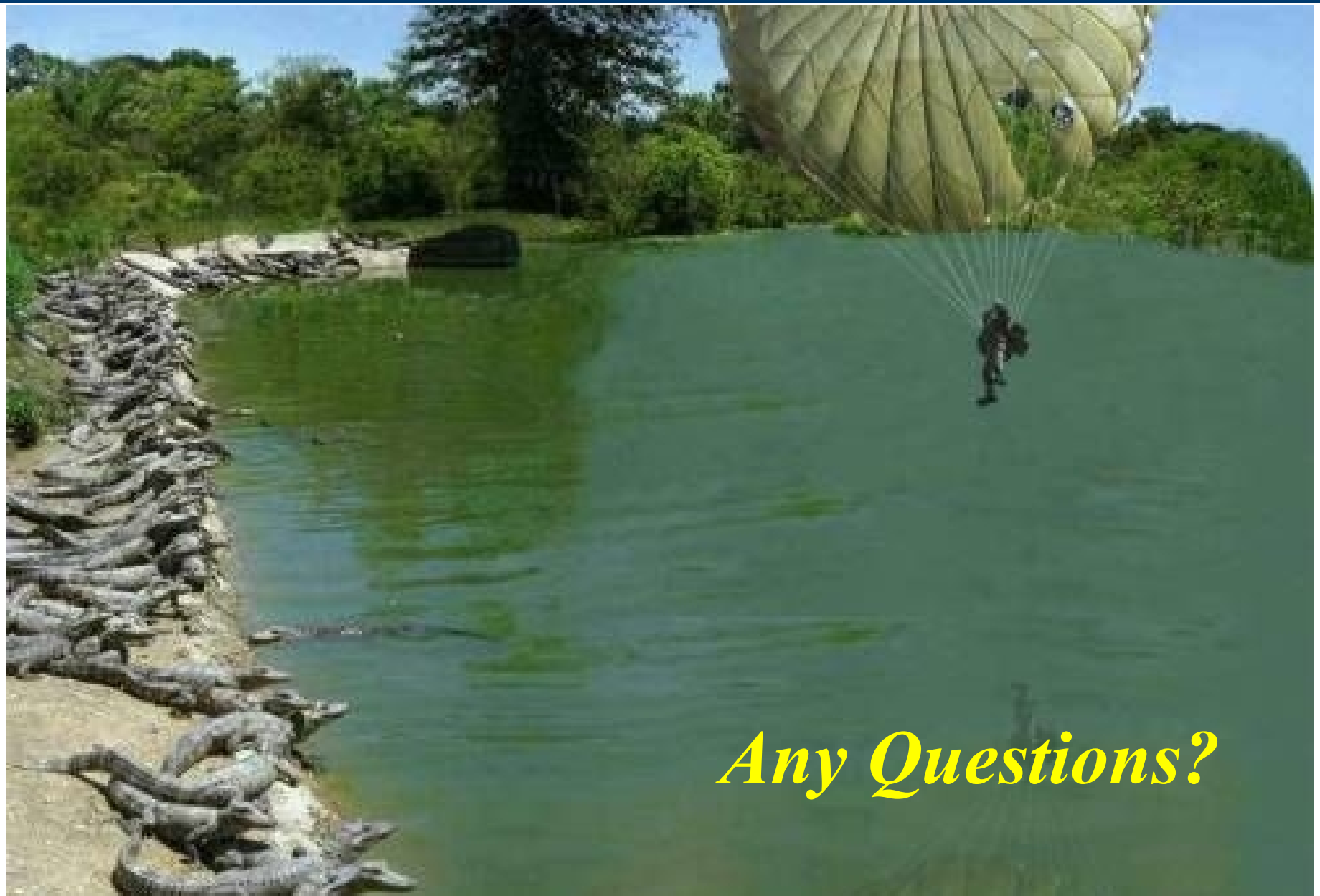
  Takenobu Kajikawa, Shonan IT, Japanese National TE Program

  Wenquing Zhang, China's 793 TE Program

  Lon Bell, BSST, US Perspective of Thermoelectrics

Organizations of Some of the Presenters;

GM, Ford, Michigan State University, BMW-Munich, NASA-JPL, Oak Ridge National Lab, Argonne National Lab, Pacific Northwest National Lab, Northwestern University , Clemson, MIT/Boston College, Maine Maritime Academy, Office of Naval Research, US Army Research Lab, Marlow Industries, Hi-Z Technologies, Cal Tech, University of South Florida, RTI, Nextreme, Tellurex, ARPA-E, NSF, NASA-JPL,BSST


Any Questions?


Thank
You!

Transportation Entering The 19th Century

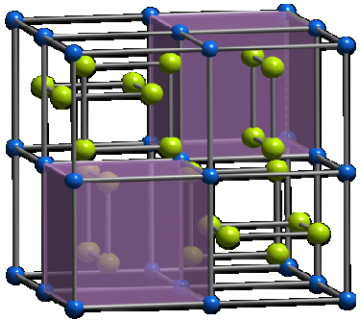
- Stage coach
  - –8 Passengers
  - –4 Horsepower (quadrupeds)
  - –Fare - One Shilling (25¢) for 4 miles

- Bio-mass derived
  - --Solid fuel
  - –Minimally processed
  - –Stable fuel cost
  - –Fueling Infrastructure already in place

- Emissions
  - –Equine methane gas
  - –Agglomeration of macro particles
    - Minimally airborne
    - Recyclable

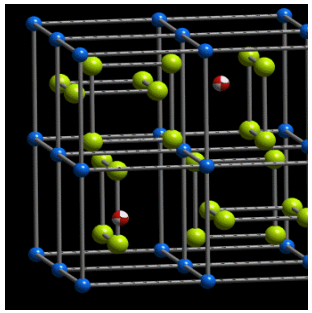
Plan "B" 3003 ?

Multiple Rattlers in Skutterudites: $R_xR_y'Co_4Sb_{12}$



Co_4Sb_{12}

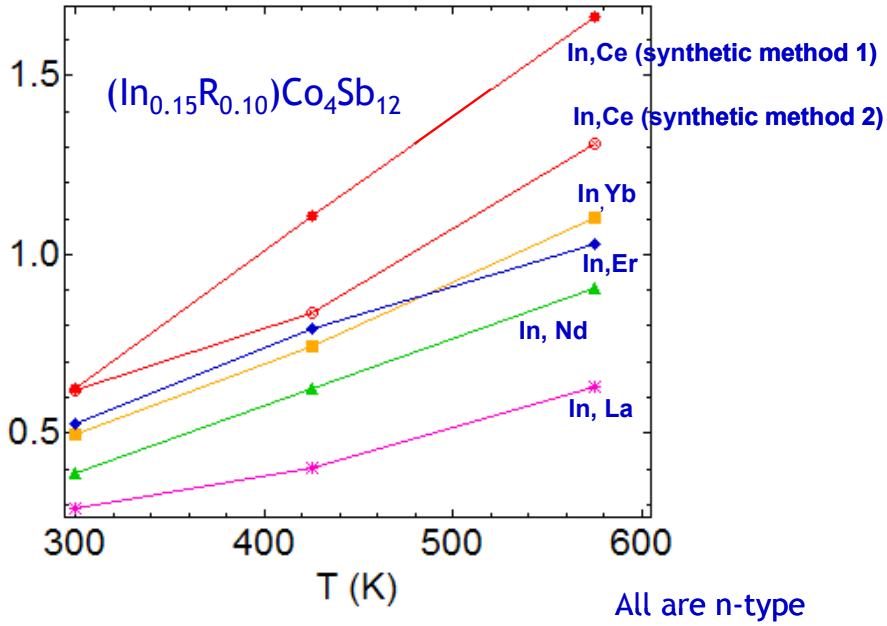
Multiple Rattlers



$R_xCo_4Sb_{12}$

R^{2+}: Ba, Ce, Sr, Ca, Ag, Pd,

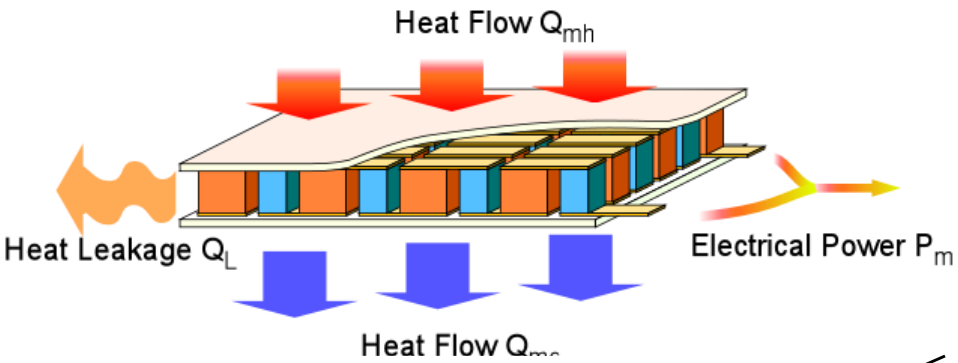
R^{3+}: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, In, Sc



All are n-type

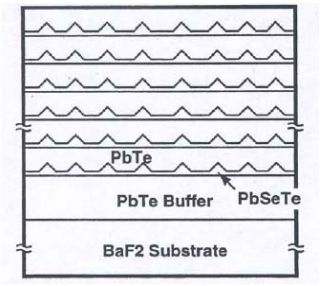
- **$In_xCo_4Sb_{12}$ Shows High ZT ~1 at 573 K**
- **$In_x La_yCo_4Sb_{12}$ Increases the ZT ~1.6 at 573K**
- **All are n-types; High Performance p-types are Needed**
- **High Performance TE Materials Expected**
  - Bulk-Type Materials for Easier Device Manufacture & Integration
  - Transition Results to Energy Recovery Projects As Appropriate & Quickly As Possible

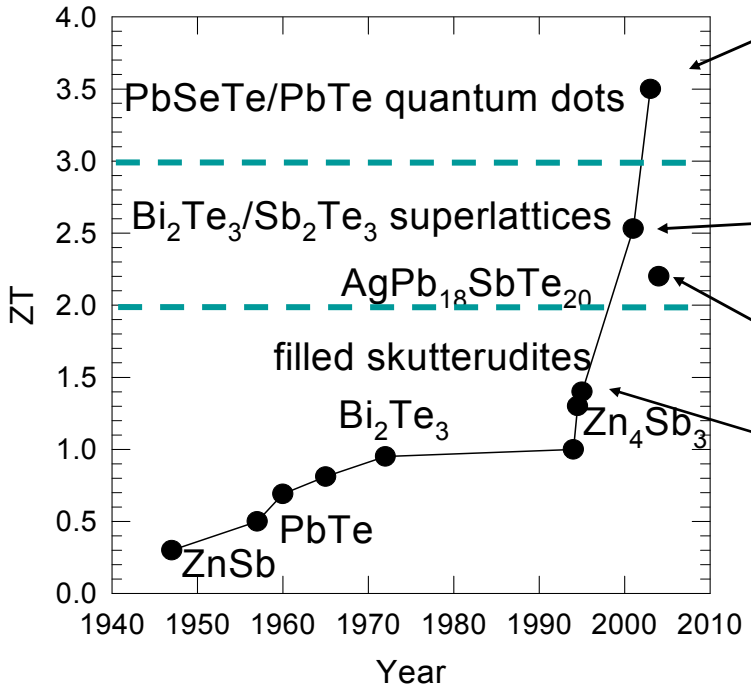
Recent Advances in Efficiency of Thermoelectric Materials

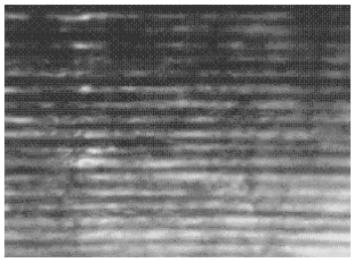


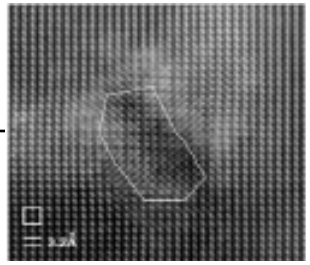
Efficiency:

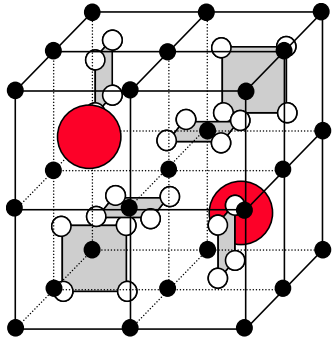
$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}}$$











» Many recent thermoelectric material advances are nano-based