Solid-State Energy Conversion Overview

John W. Fairbanks
Department of Energy
Vehicle Technologies

Annual Merit Review
June 11, 2010

Overview

- Potential of Thermoelectric Applications in Vehicles
- Thermoelectric Materials
- Vehicular Thermoelectric Generators
- Vehicular Thermoelectric Air Conditioner/Heater
- Summary

Vehicular Thermoelectric Generators (TEG's)

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

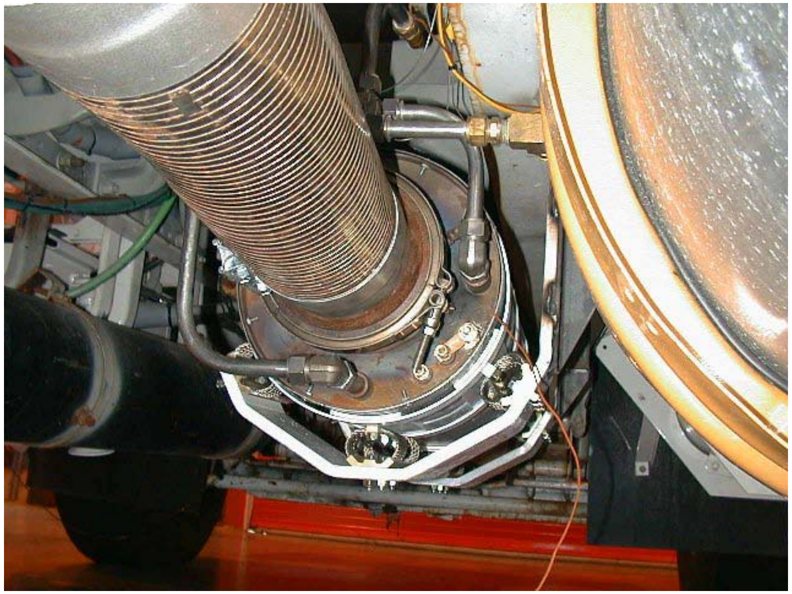
- Generate Electricity Without Introducing any Additional Carbon into the Atmosphere

Vehicular Thermoelectric Air Conditioner/Heater (TE HVAC)

- 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 of Concern

First Application of Thermoelectric Generator in Vehicle

Front View

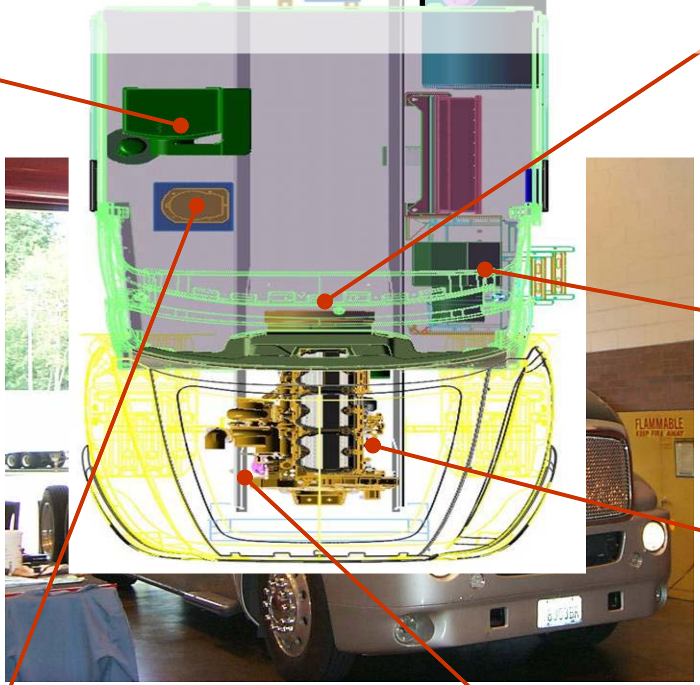


Rear View

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

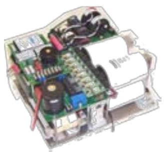


Modular HVAC

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

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

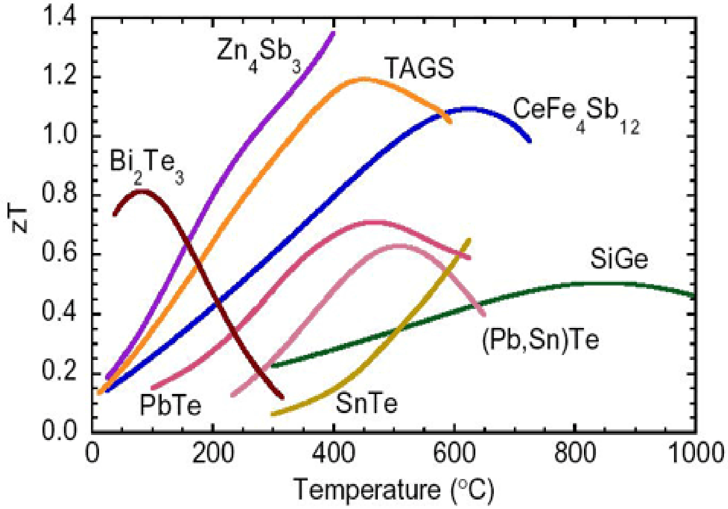
Electric Water Pump

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

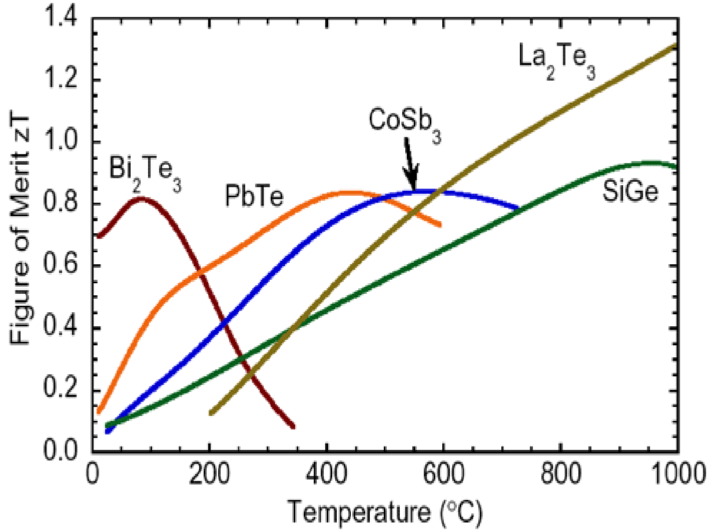
Electric Oil Pump

Variable speed
Higher efficiency

Current TE Materials



P-type TE material



N-type TE material

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

TE Materials Performance: Figure of Merit (ZT)

Electrical conductivity

Seebeck coefficient or thermopower (ΔV/ΔT)

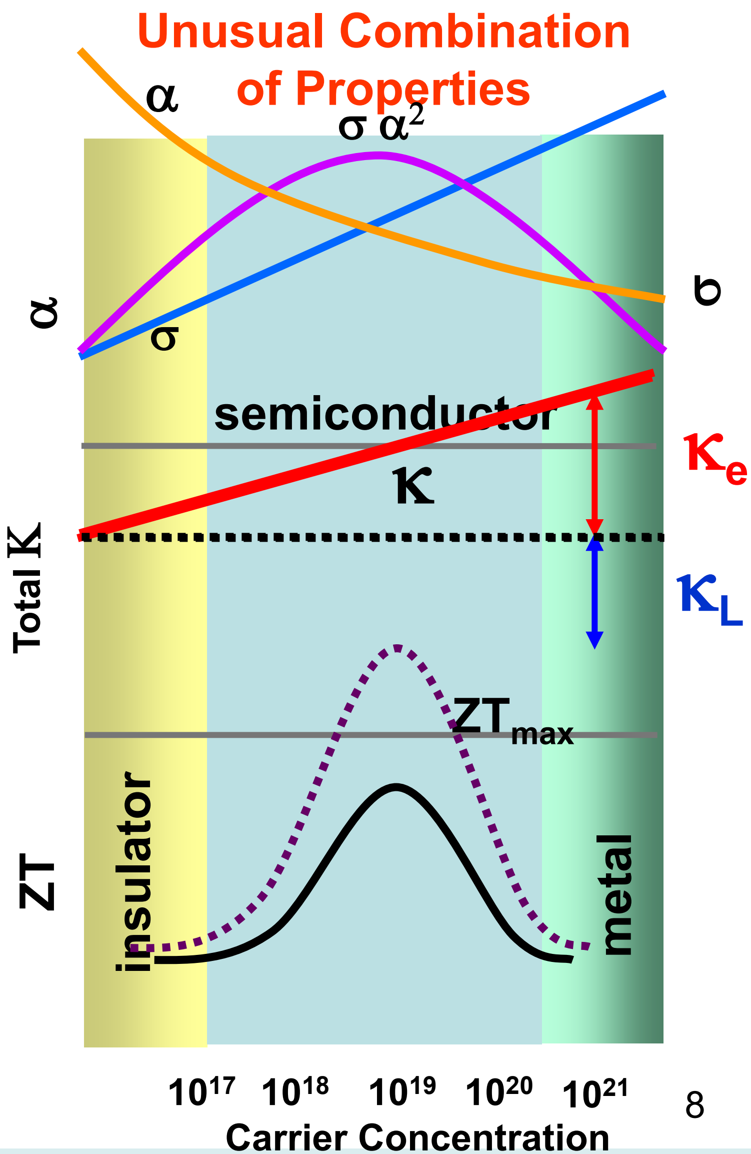
$$ZT = \frac{\sigma \alpha^2}{(\kappa_e + \kappa_L)} \cdot T$$

Total thermal conductivity

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

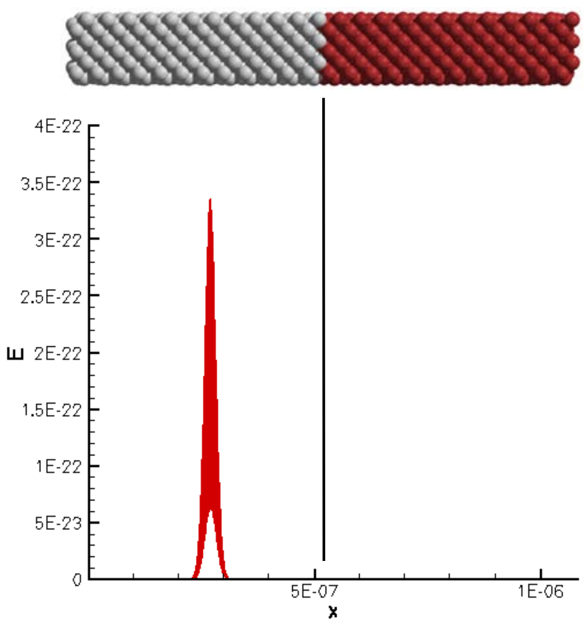
$\sigma = 1/\rho$ = **electrical conductivity**

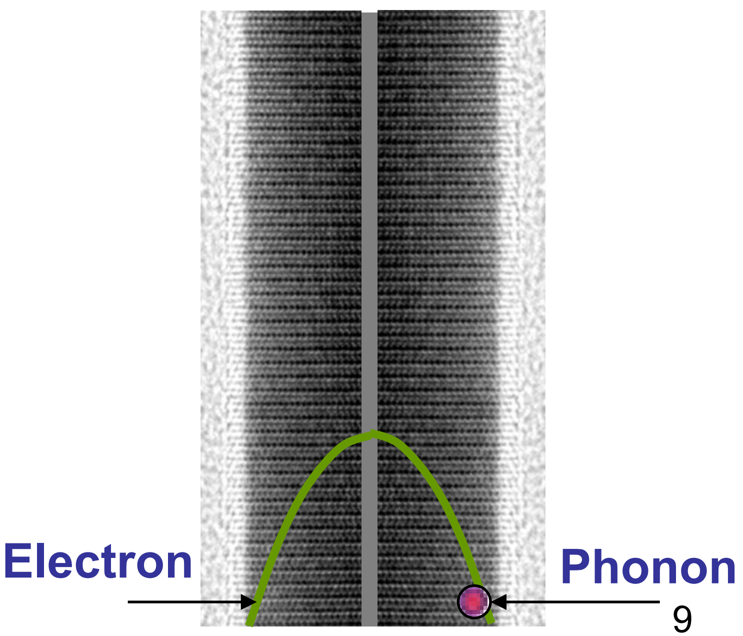
ρ = **electrical resistivity**



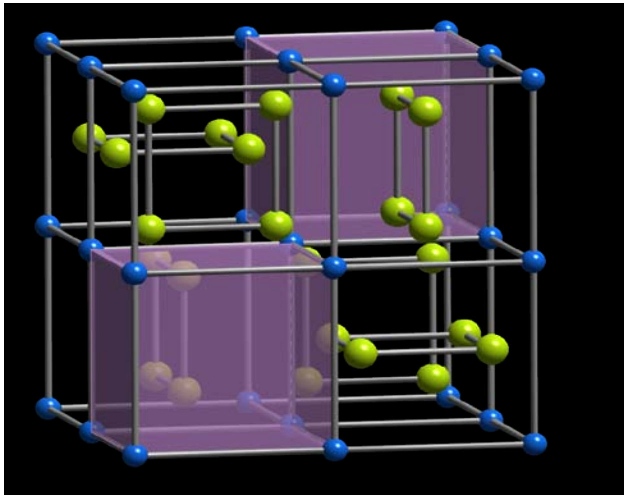
Interfaces that Scatter Phonons but not Electrons

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



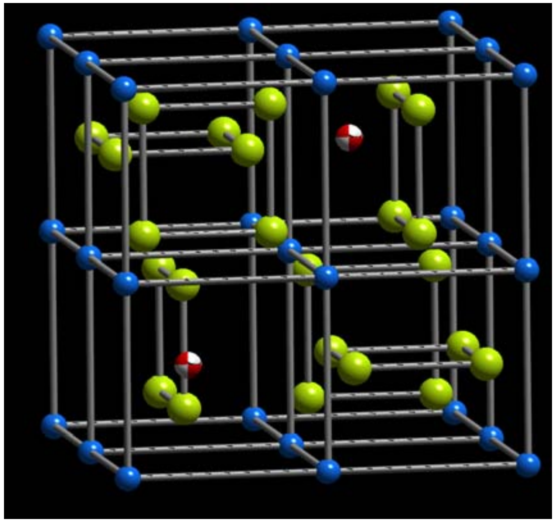


Atomic Structure of Skutterudites



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

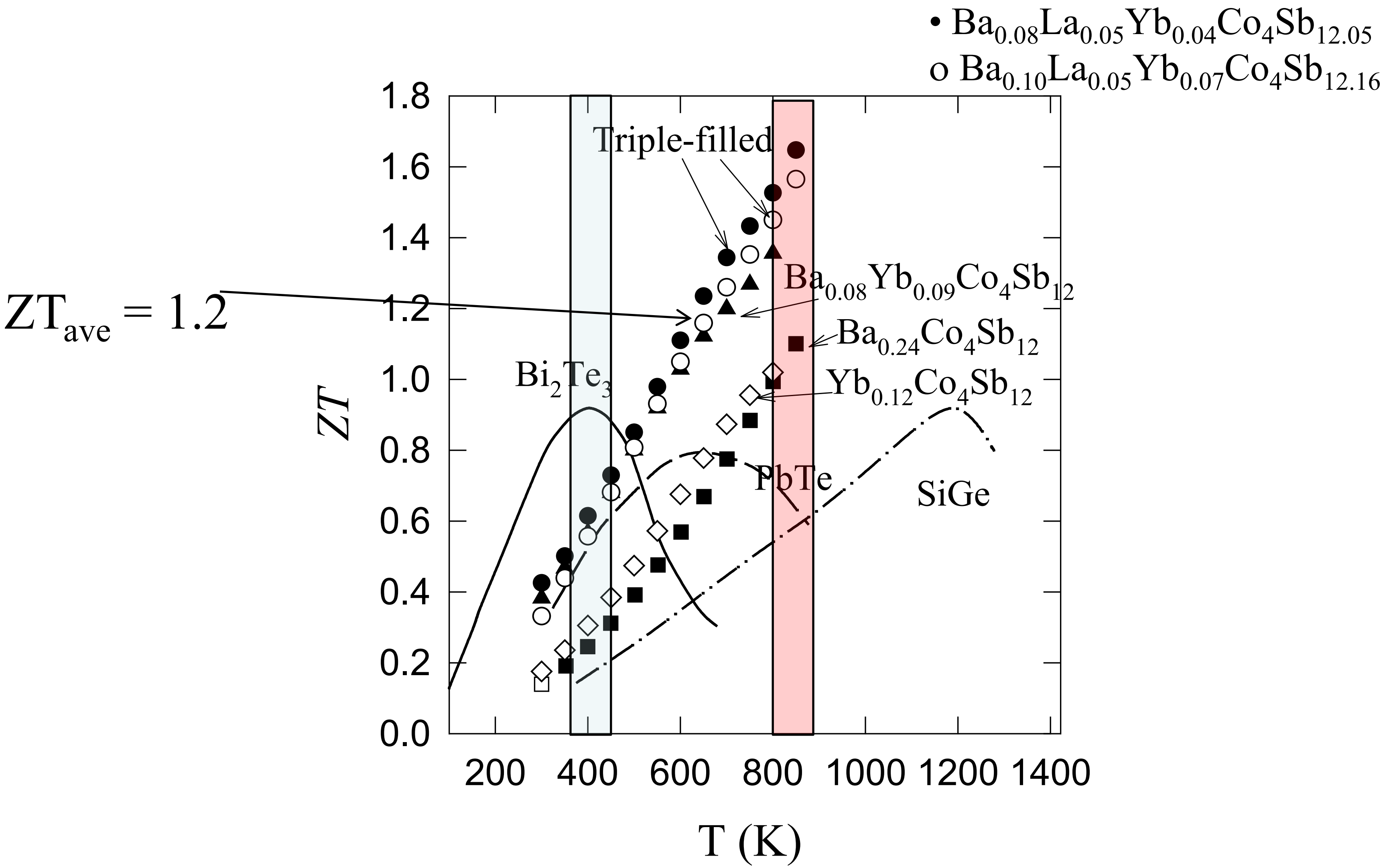
- Cobalt atoms form a *fcc* cubic lattice
- Antimony atoms are arranged as a square planar rings
- There are 8 spaces for the Sb_4 units
- 6 are filled and 2 are empty



R_xCoSb_3

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

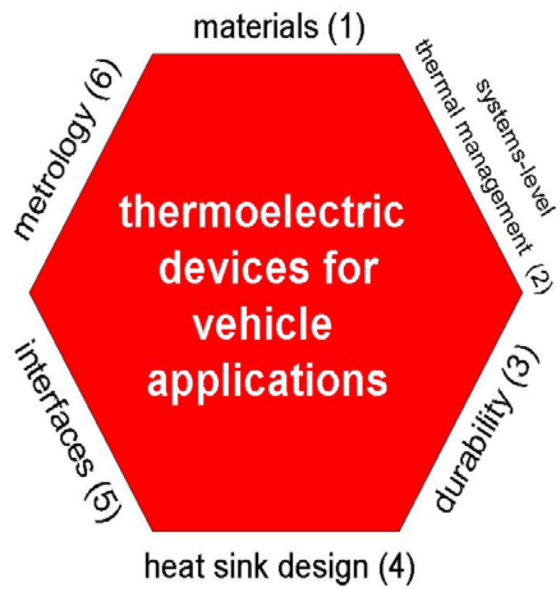
Highest ZT Achieved with Triple-filled Skutterudites



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

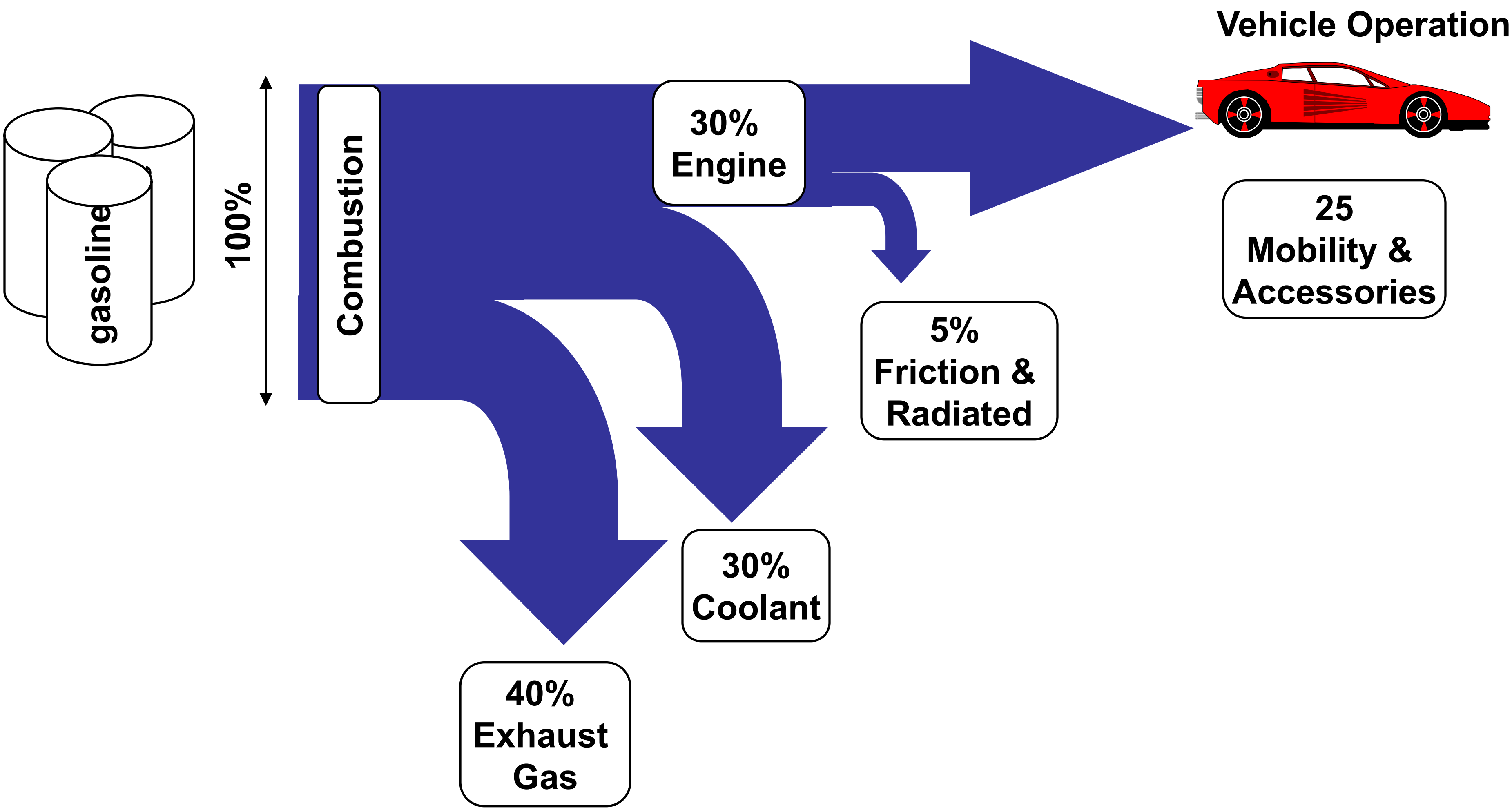
DOE/NSF Partnership in Thermoelectrics

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

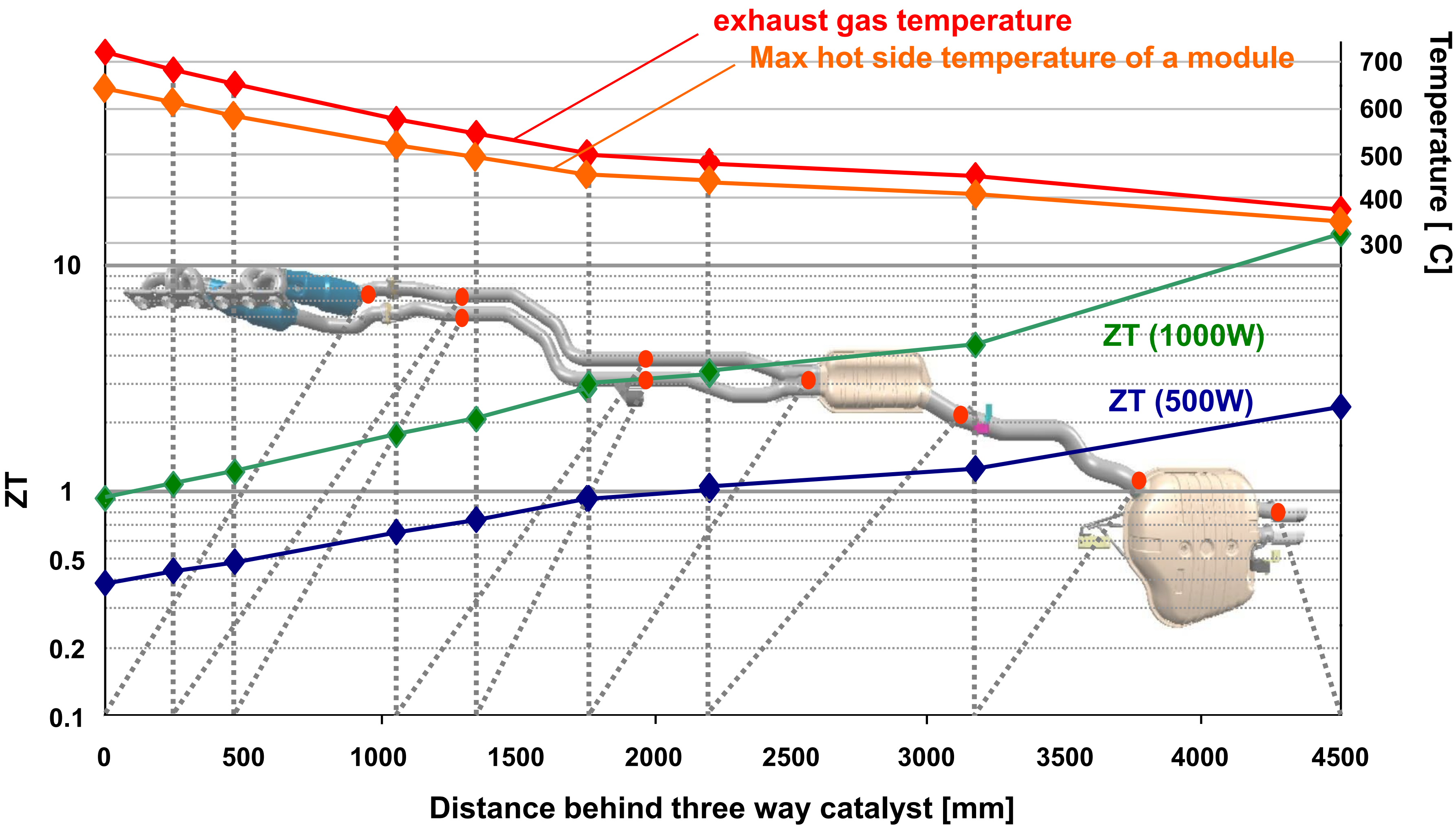


Key Element 1: Materials.
Key Element 2: Thermal management.
Key Element 3: Durability.
Key Element 4: Interfaces
Key Element 5: Heat sink design.
Key Element 6: Metrology.

Typical Waste Heat from Gasoline Engine Mid Size Sedan



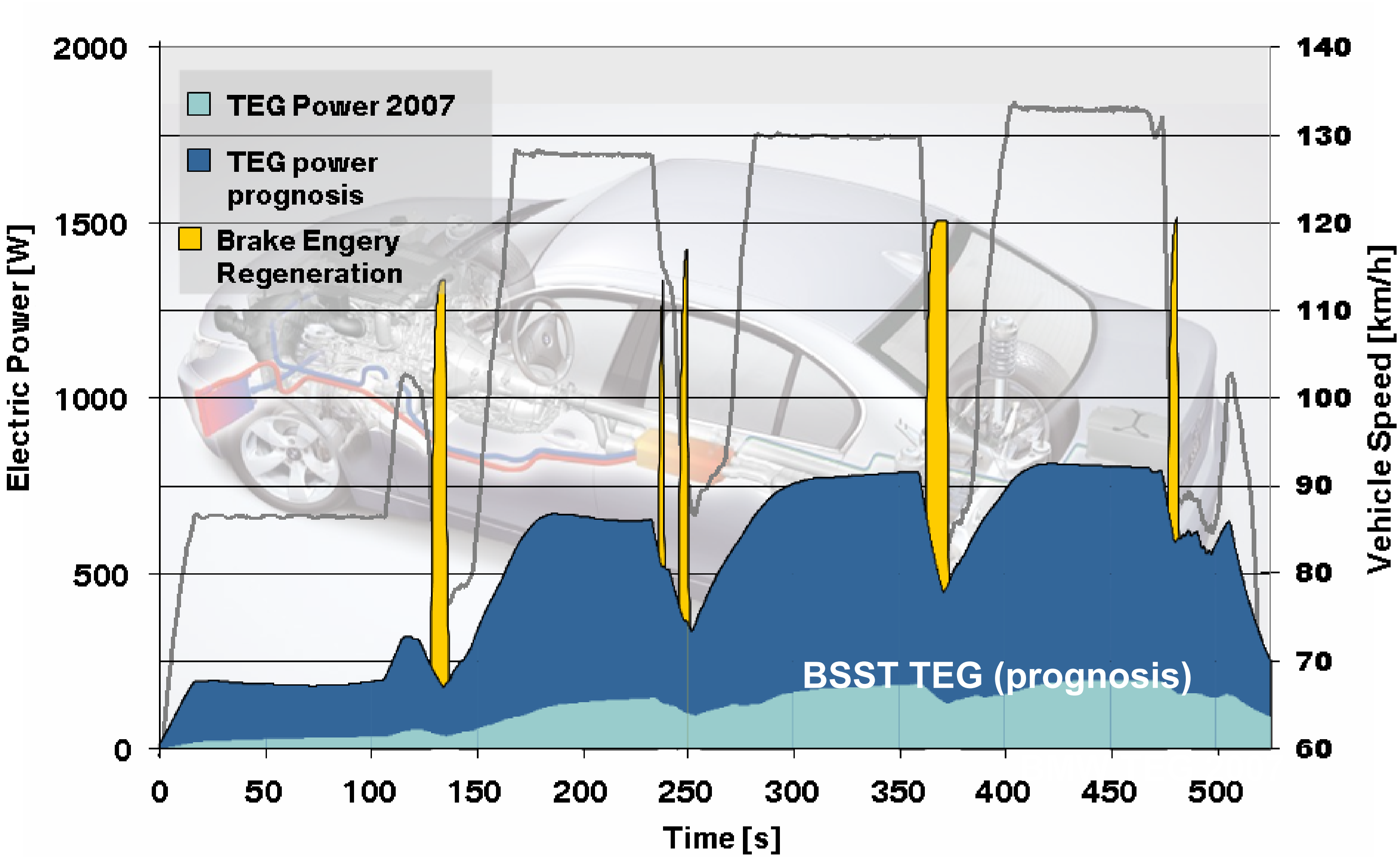
SI Engine Exhaust Temperature Profile with Potential TEG Locations



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

Slide courtesy of BMW

TEG's are Ideally Compatible with Regenerative Braking

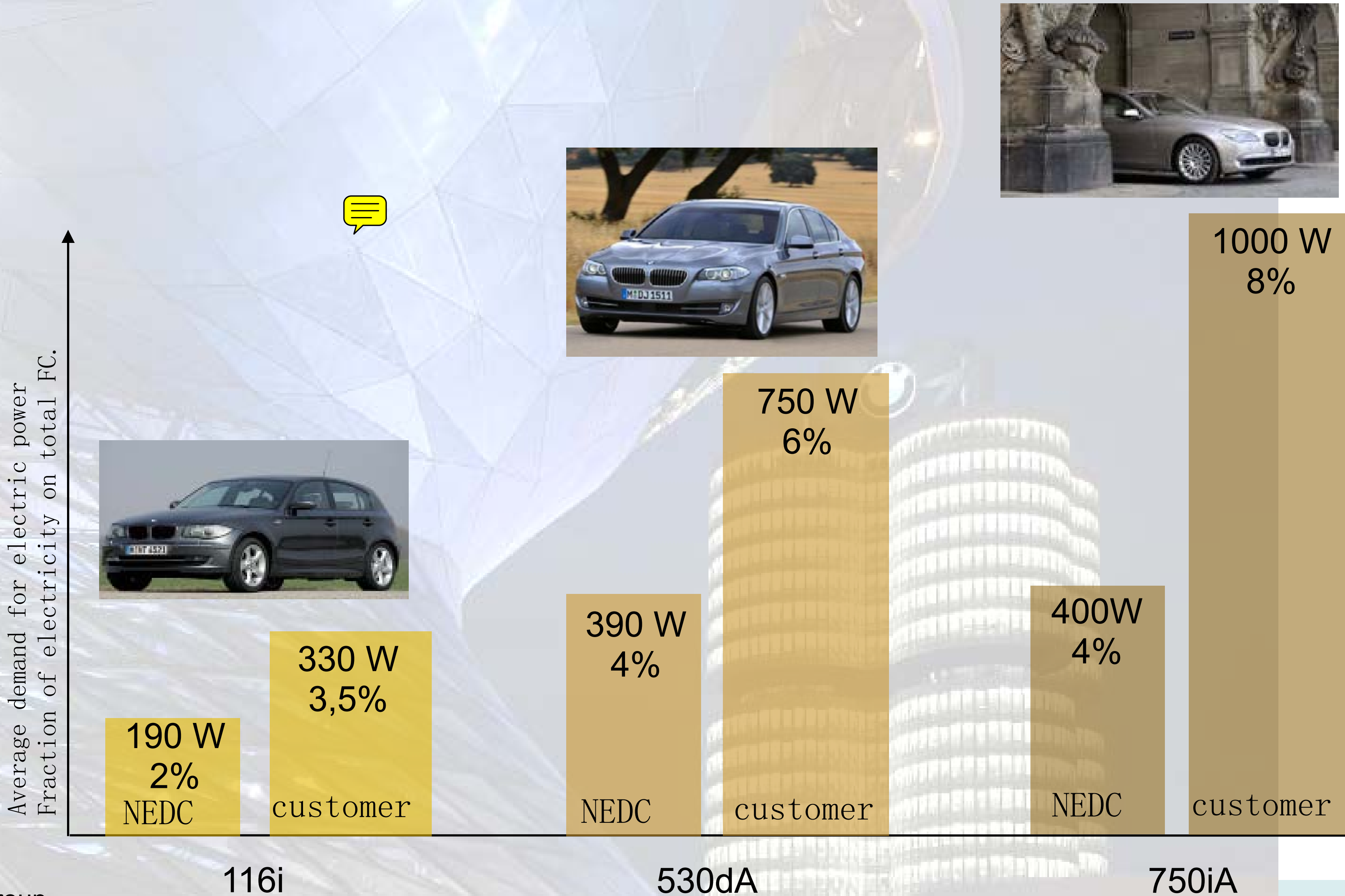


Slide courtesy of BSST

Demonstration TEGs In Ford Fusion, BMW X6 and Chevy Suburban

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

Thermoelectric Power Generation – The Next Step for CO_2 Reductions

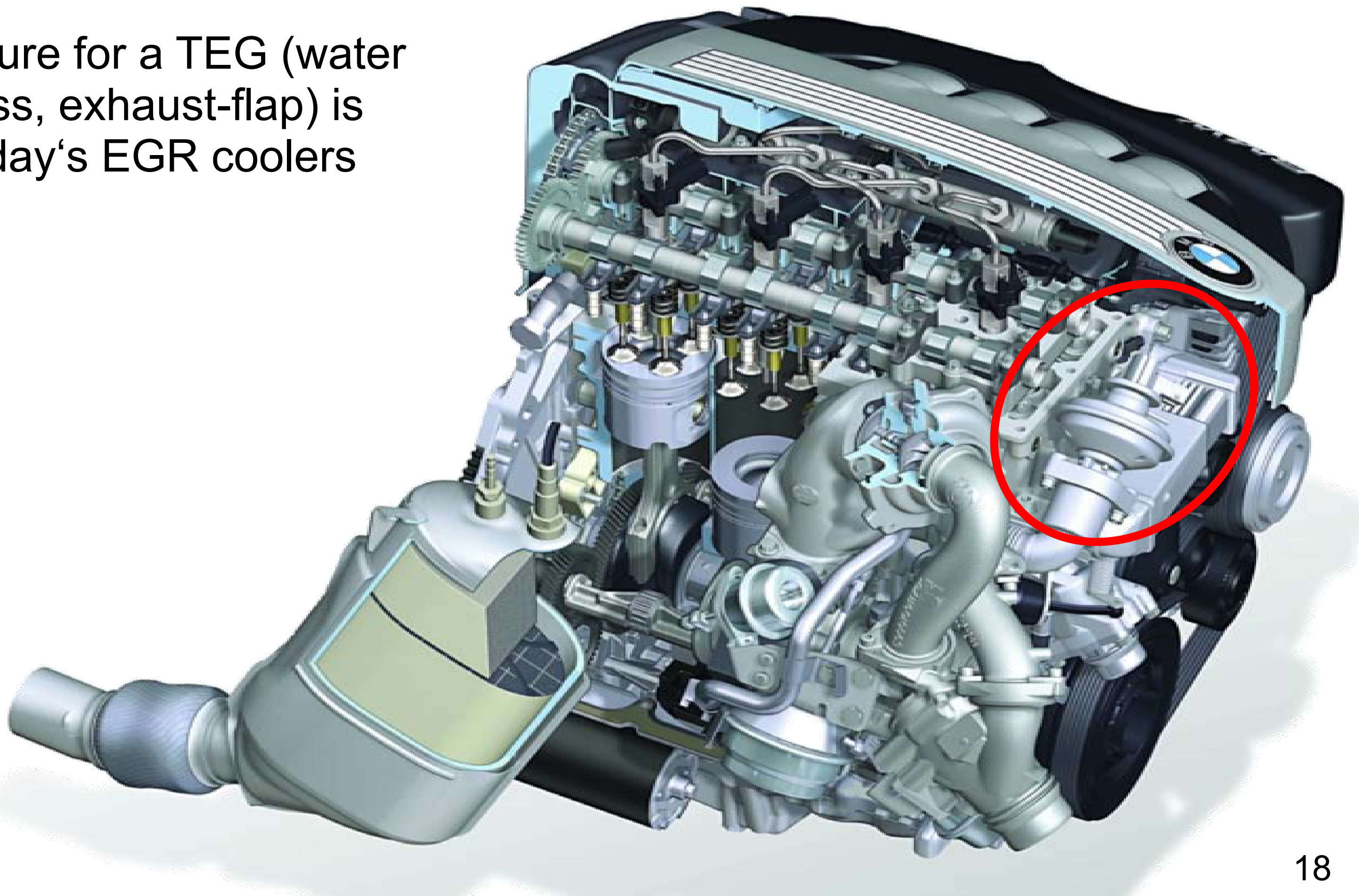


Source: BMW Group

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

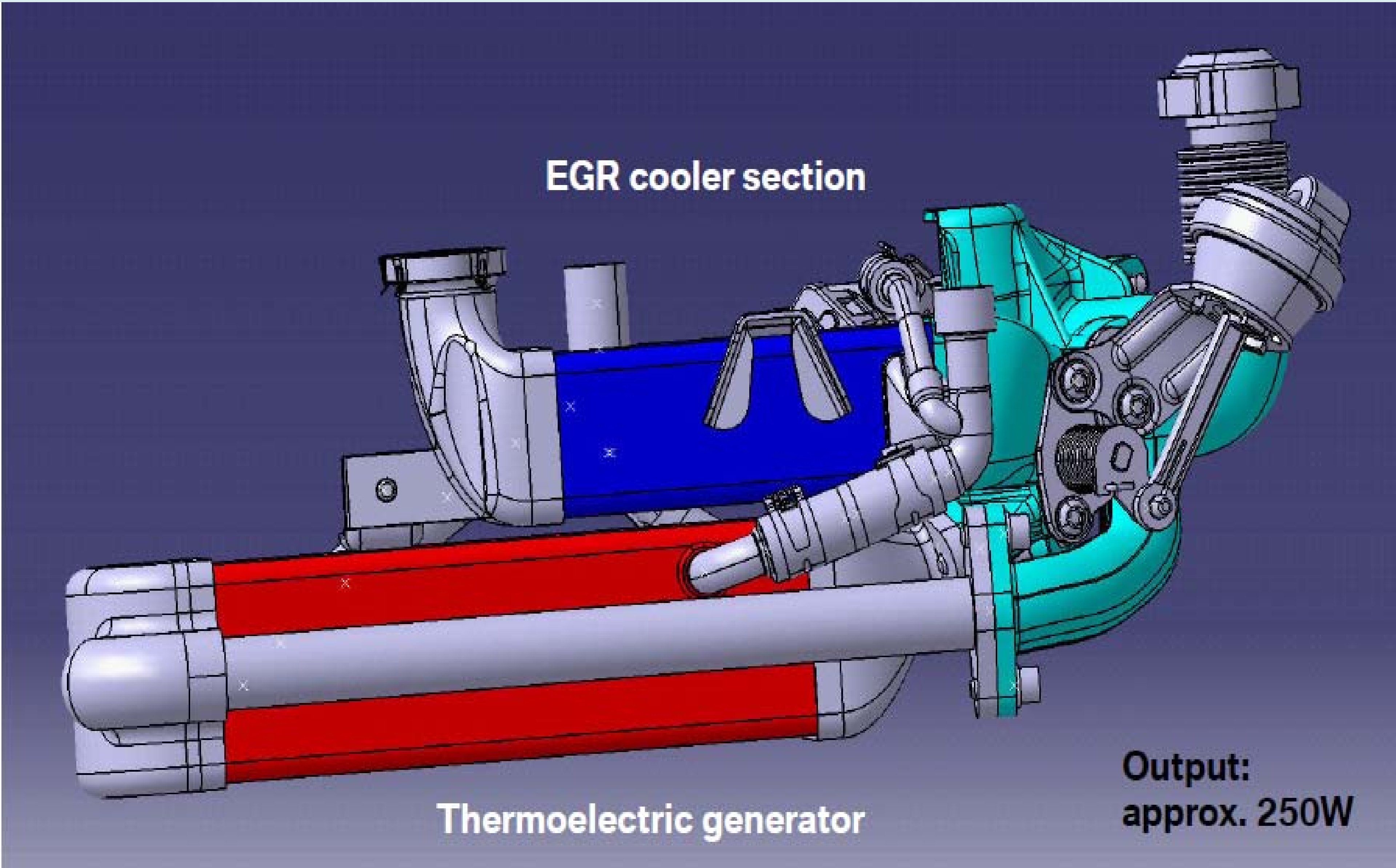
BMW Diesel Engine EGR TEG.

Source: BMW Group

BMW EGR-TEG.

Source: BMW Group

BMW EGR-TEG.



Source: BMW Group

TE HVAC Approach

- Develop test protocols and metrics for real-world automotive TE HVAC system usage
- Use CAE, thermal comfort models, and subject testing to optimize heating/cooling node locations
- Develop high-efficiency advanced thermoelectric materials and assemblies
- Design, integrate, and validate performance of a production prototype TE HVAC in a demonstration vehicle

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 PHEV, HEV, EV or FC Vehicles

- 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

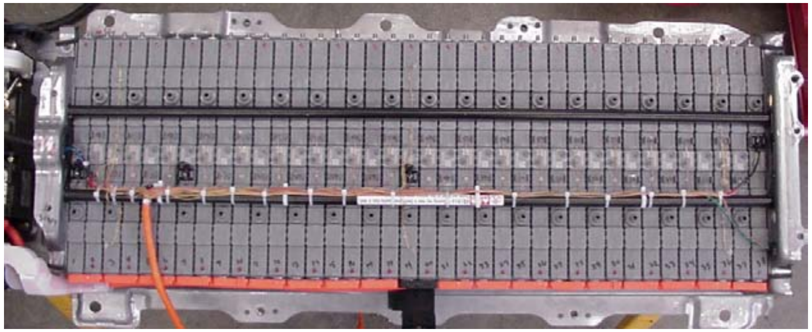
Temperature affects battery operation

> Round trip efficiency and charge acceptance

> Power and energy

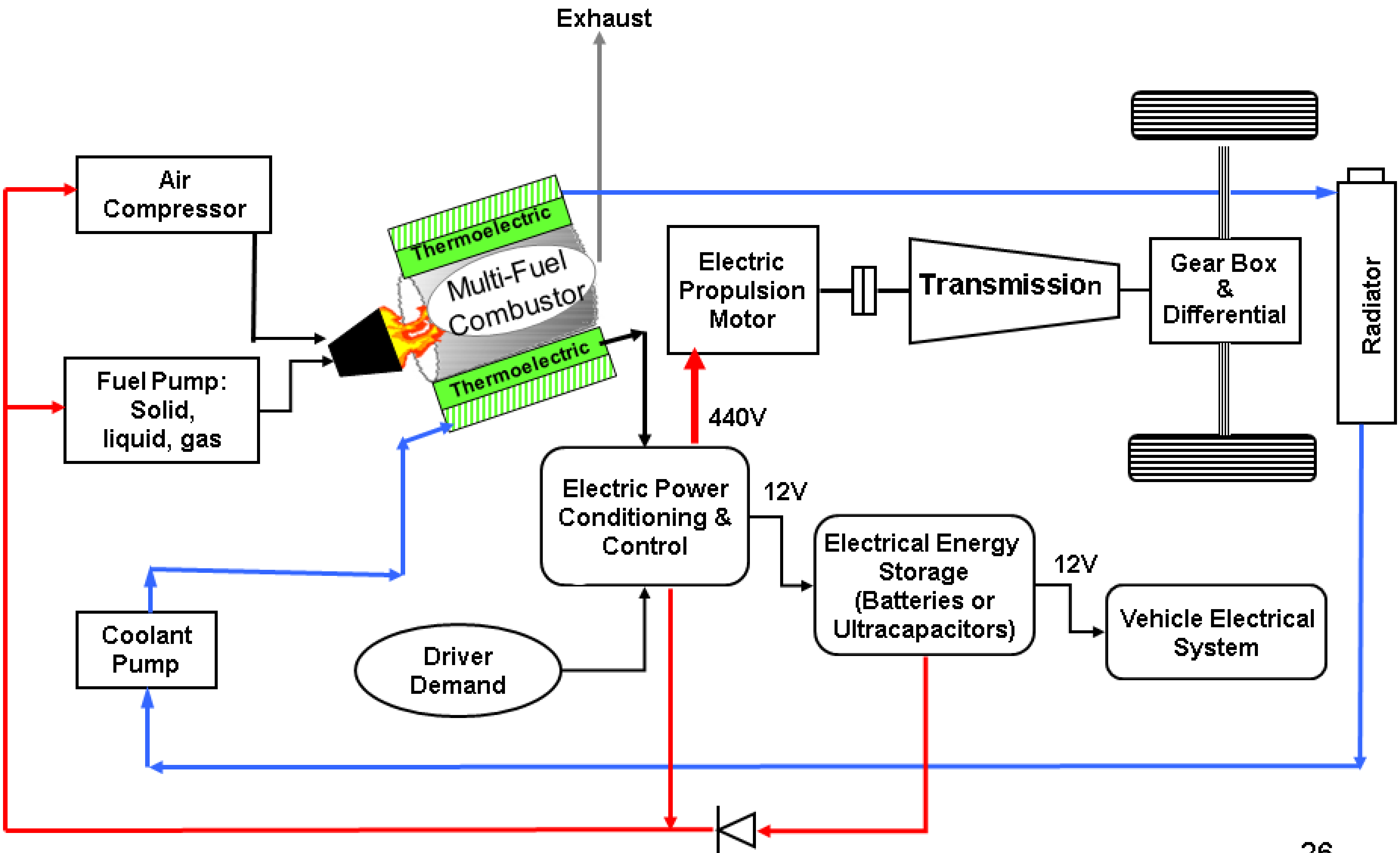
> Safety and reliability

> Life and life cycle cost



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

Vehicular Thermoelectric Hybrid Electric Powertrain



Vehicular Thermoelectric Application Possibilities

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

Near Term (3-5 yrs)

- Thermoelectric Generator providing nominal 5-6% fuel economy gain augmenting smaller alternator
- "Beltless" or more electric engines
- 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 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