Develop Thermoelectric Technology for Automotive Waste Heat Recovery

Sponsored
by
US Department of Energy
Energy Efficiency Renewable Energy (EERE)
DE-FC26-04NT42278

Jihui Yang
GM Research & Development Center

Outline

- Background
  - Objective, partnering, …
  - Motivation: fuel economy
- Technology Development
  - Subsystem modeling
  - Cost
  - Cost-effective materials
- Summary

DOE Program Objective

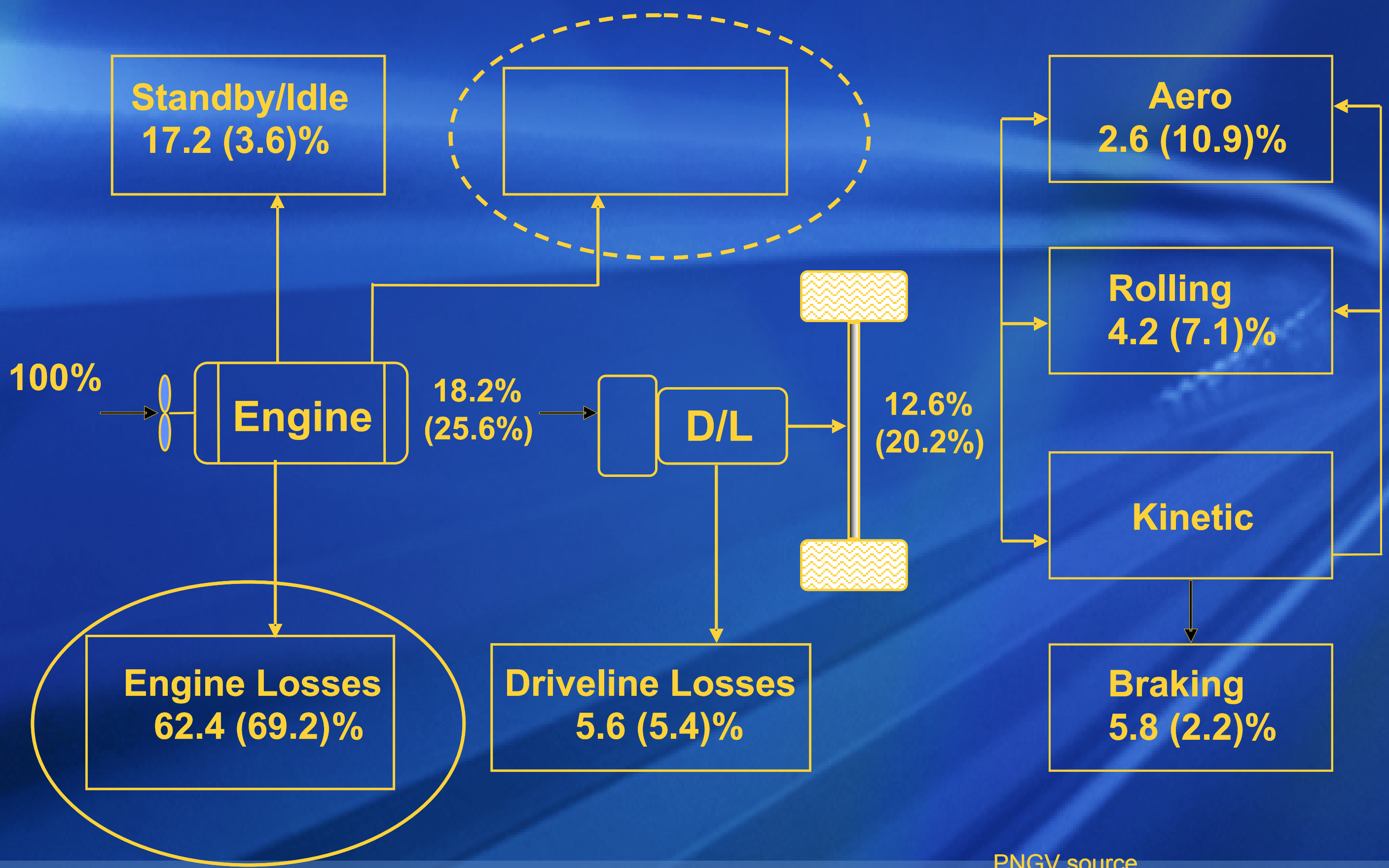
Demonstrate a 10% fuel economy improvement using thermoelectric waste heat recovery technology, without increased emissions and at a cost-effective way.

Partnering

- **GM**
  - Materials Research
  - Subsystem design, integration, modeling, and validation
- **GE**
  - TE module design and construction
  - Subsystem design and construction
- **Oak Ridge National Lab**
  - High temperature materials properties measurement
- **RTI**
  - Superlattice-base materials and modules
- **University of South Florida**
  - bulk materials development: clathrates, nano-grain PbTe, …
- **University of Michigan**
  - Bulk materials development, skutterudites, nano-composites,…

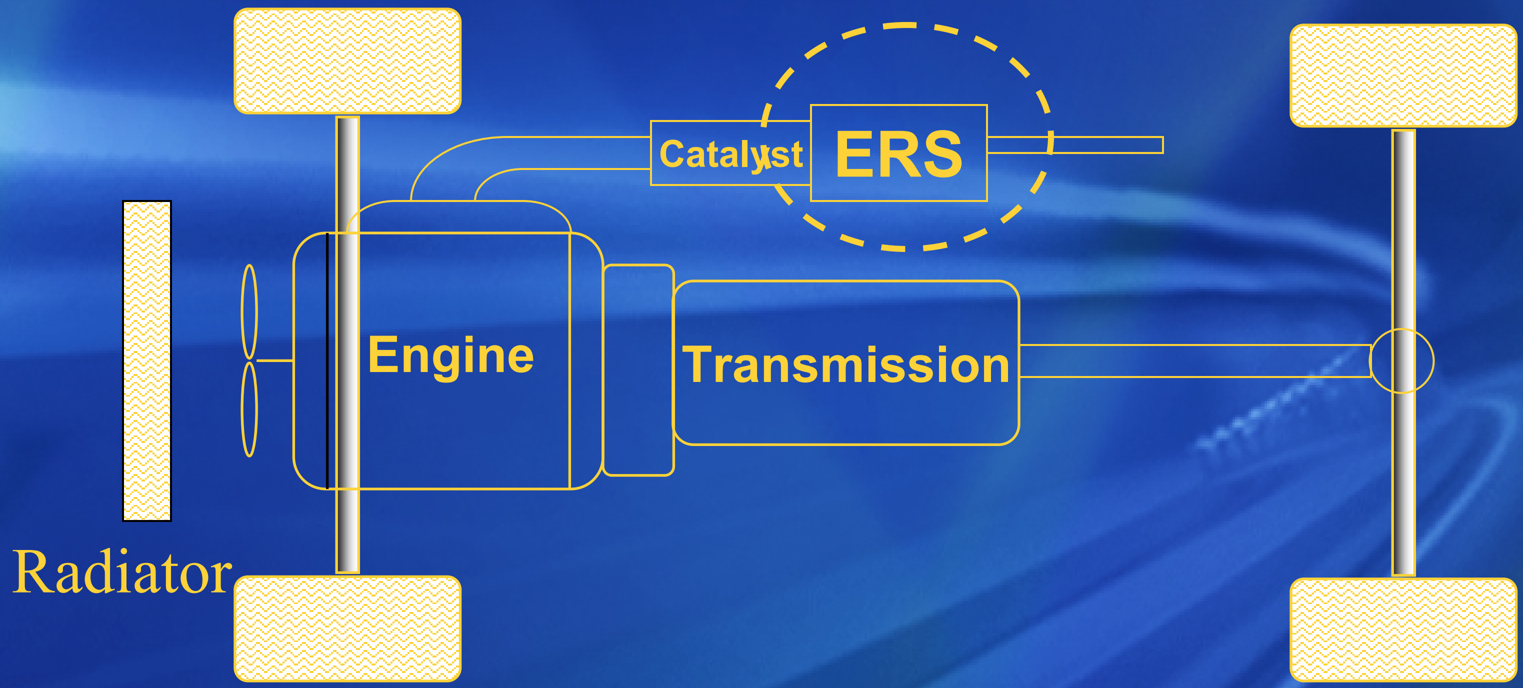
Energy Distribution –

Typical Mid-Size Vehicle on Federal Test Procedure (F
- Urban (Highway) % energy use



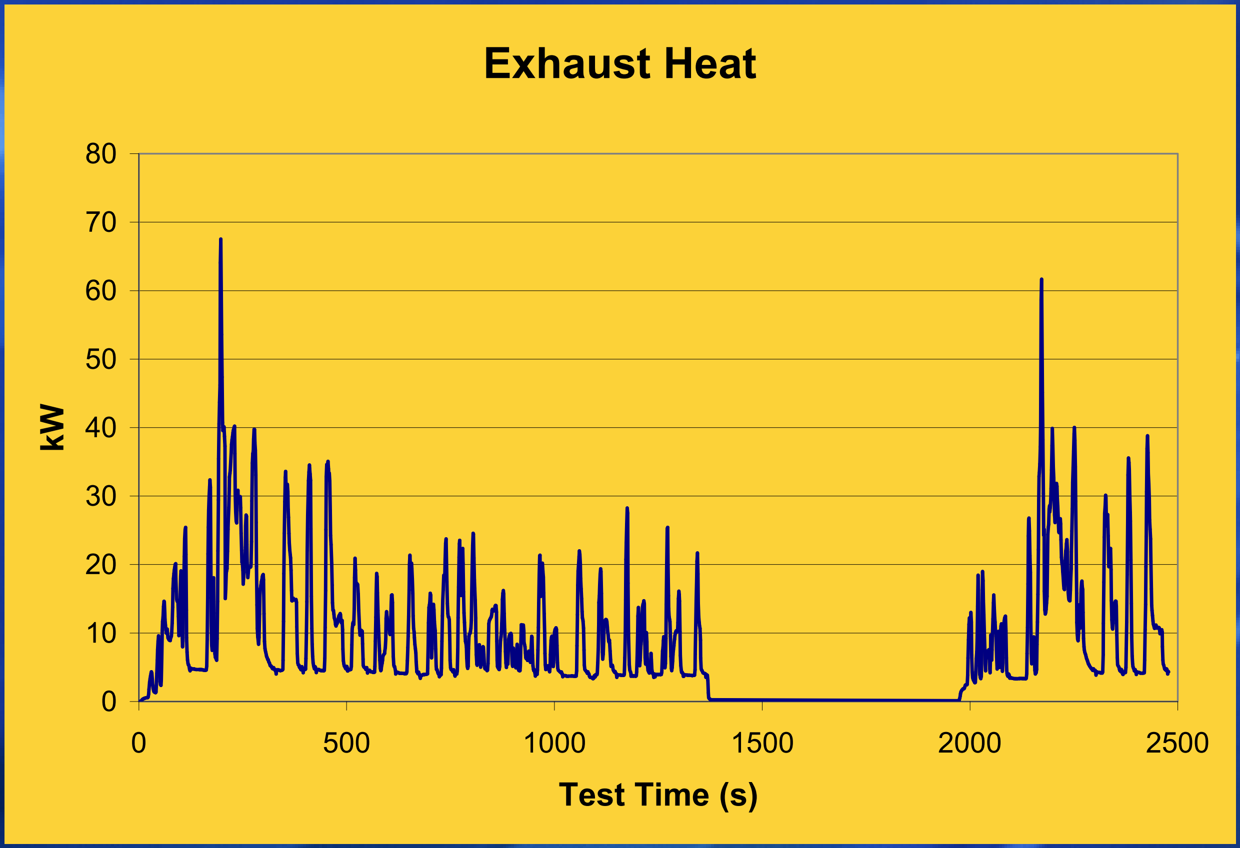
PNGV source

Example of an Energy Recovery System

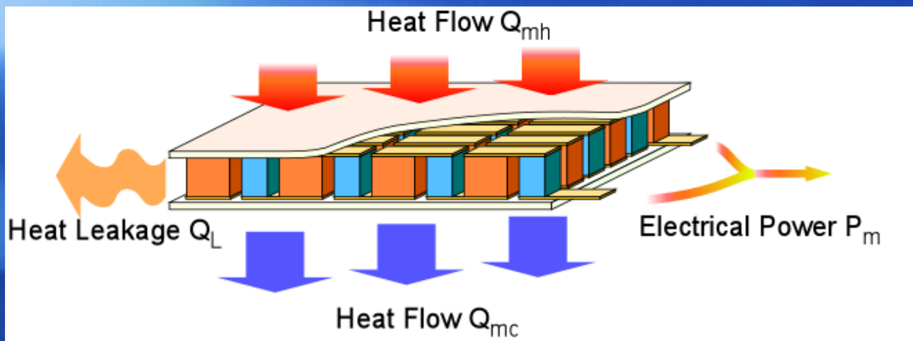


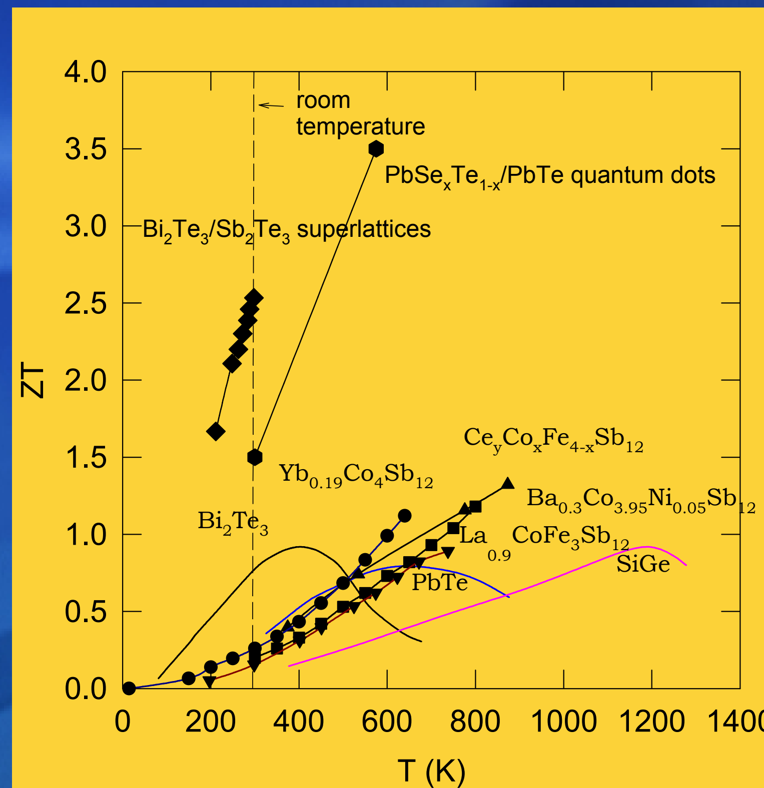
Alternate: make the radiator into an energy recovery device. (smaller ΔT)

Exhaust as Potential TE Heat Source



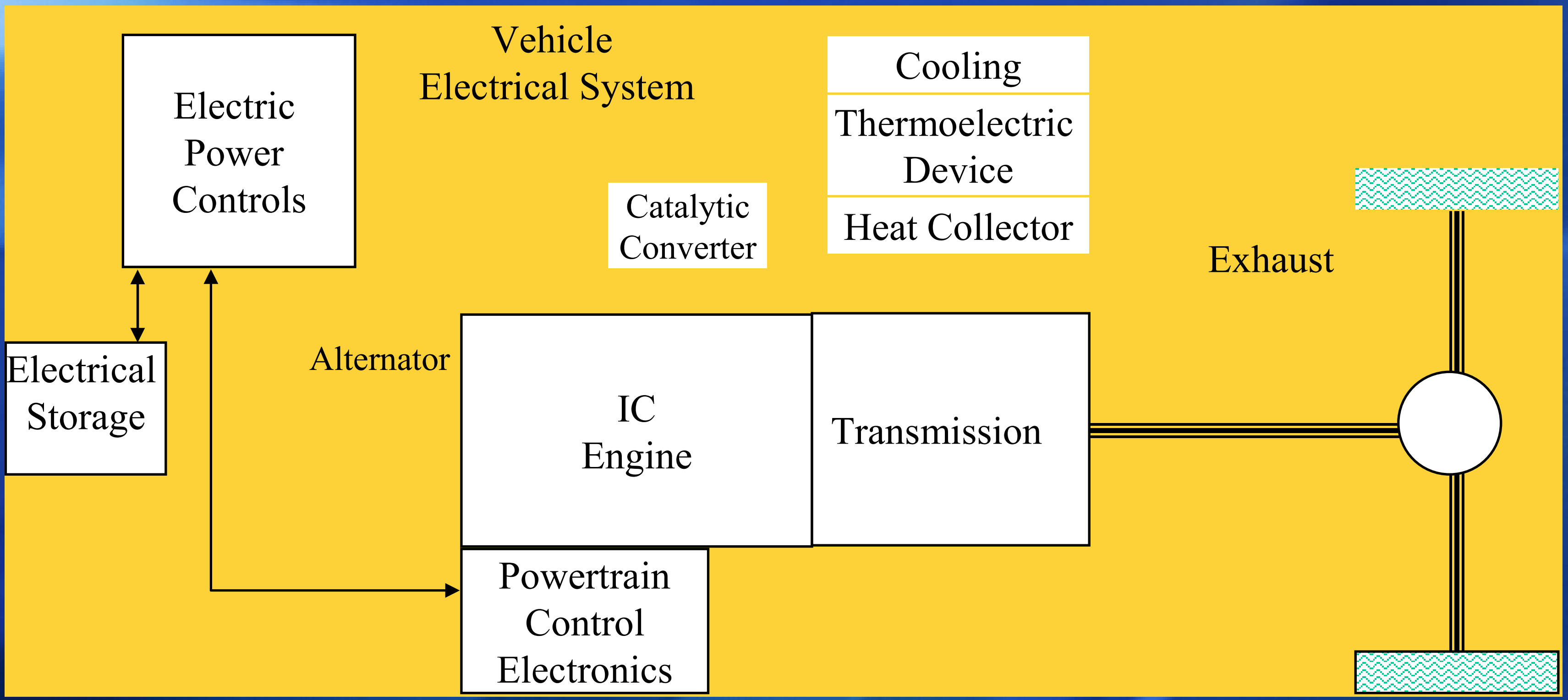
Thermoelectric Energy Conversion



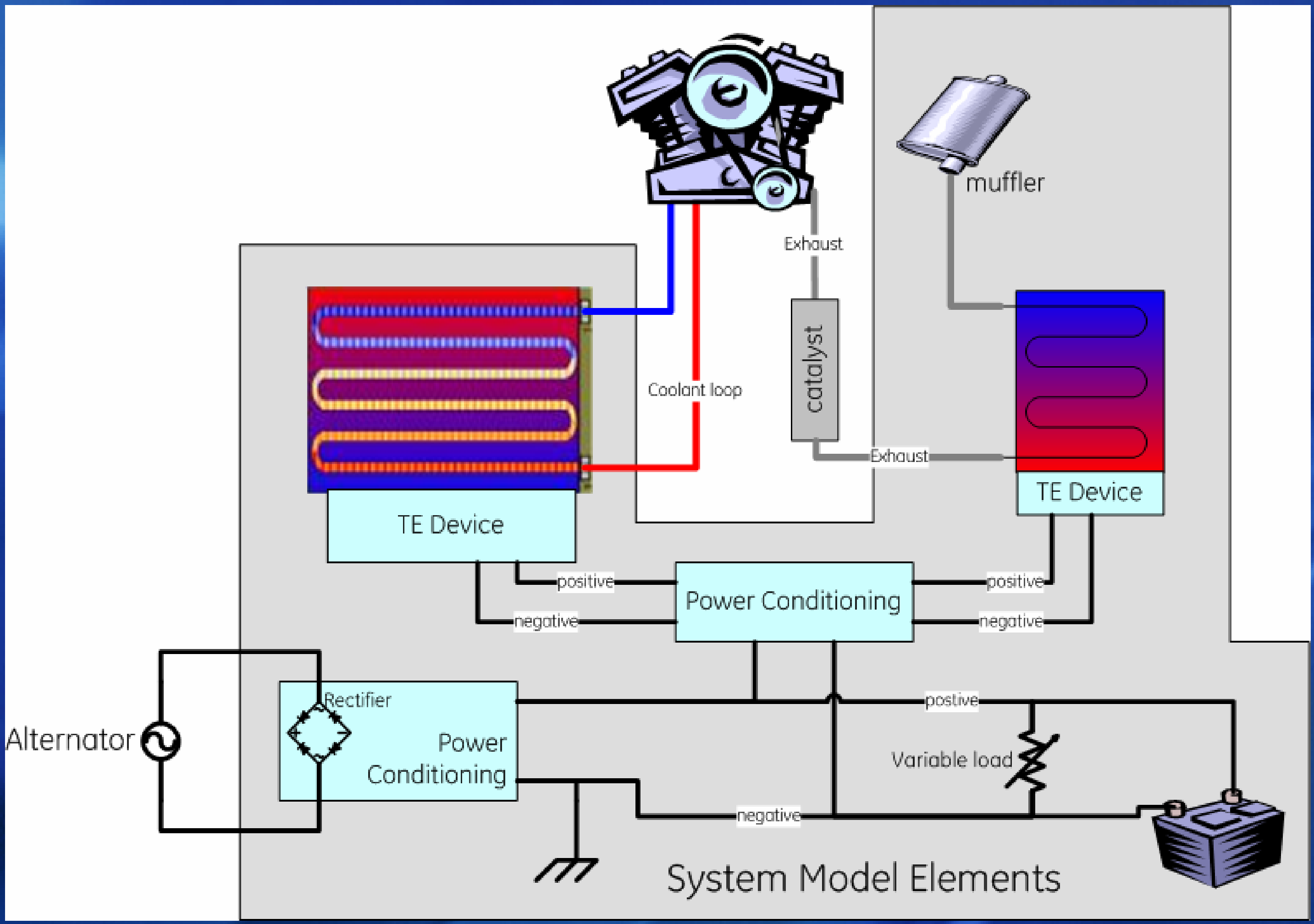


Efficiency: $\varepsilon = \dfrac{T_H - T_C}{T_H} \dfrac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \dfrac{T_C}{T_H}}$

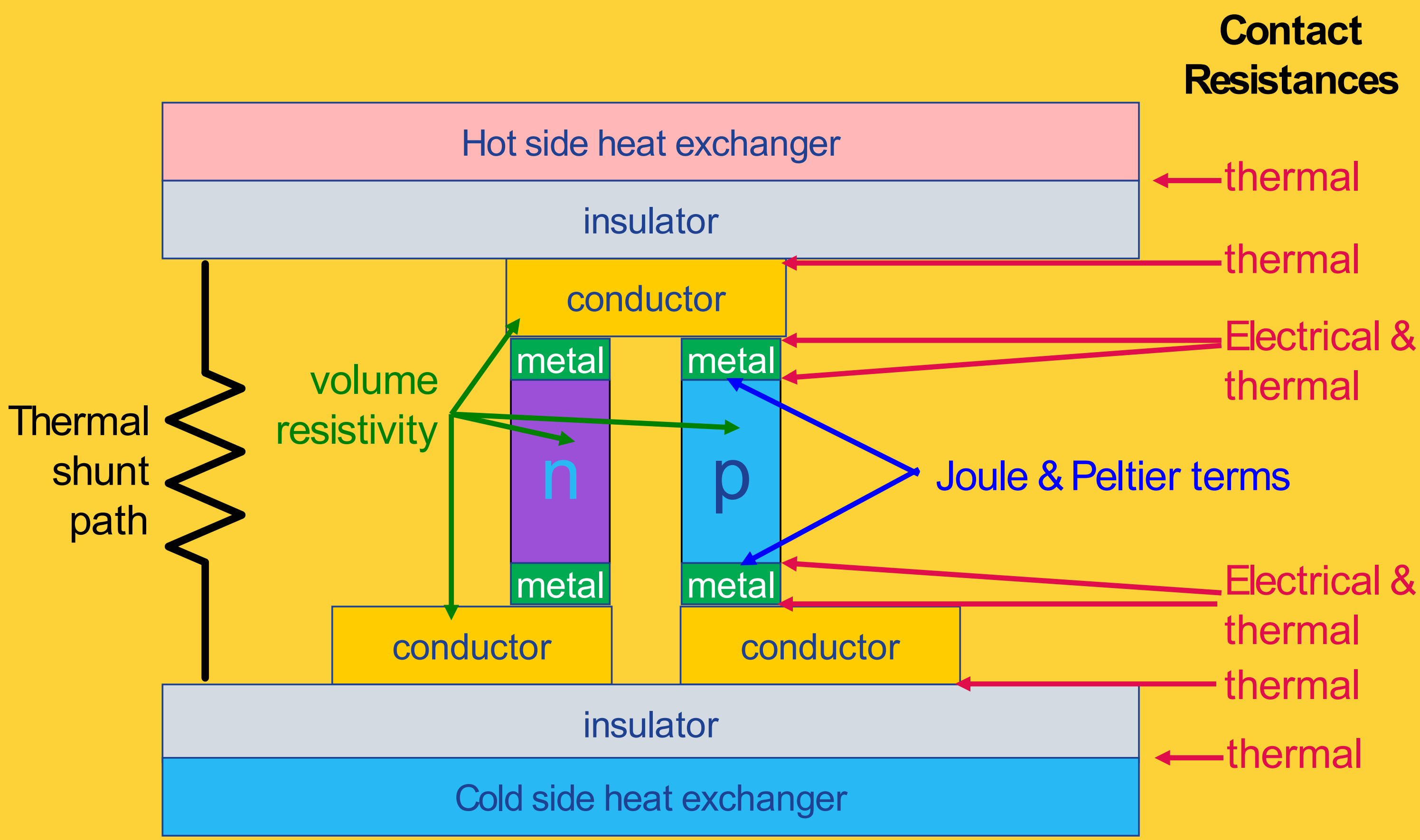
Generic Concept for a Thermoelectric Energy Recovery Augmented Electrical System



Subsystem Modeling

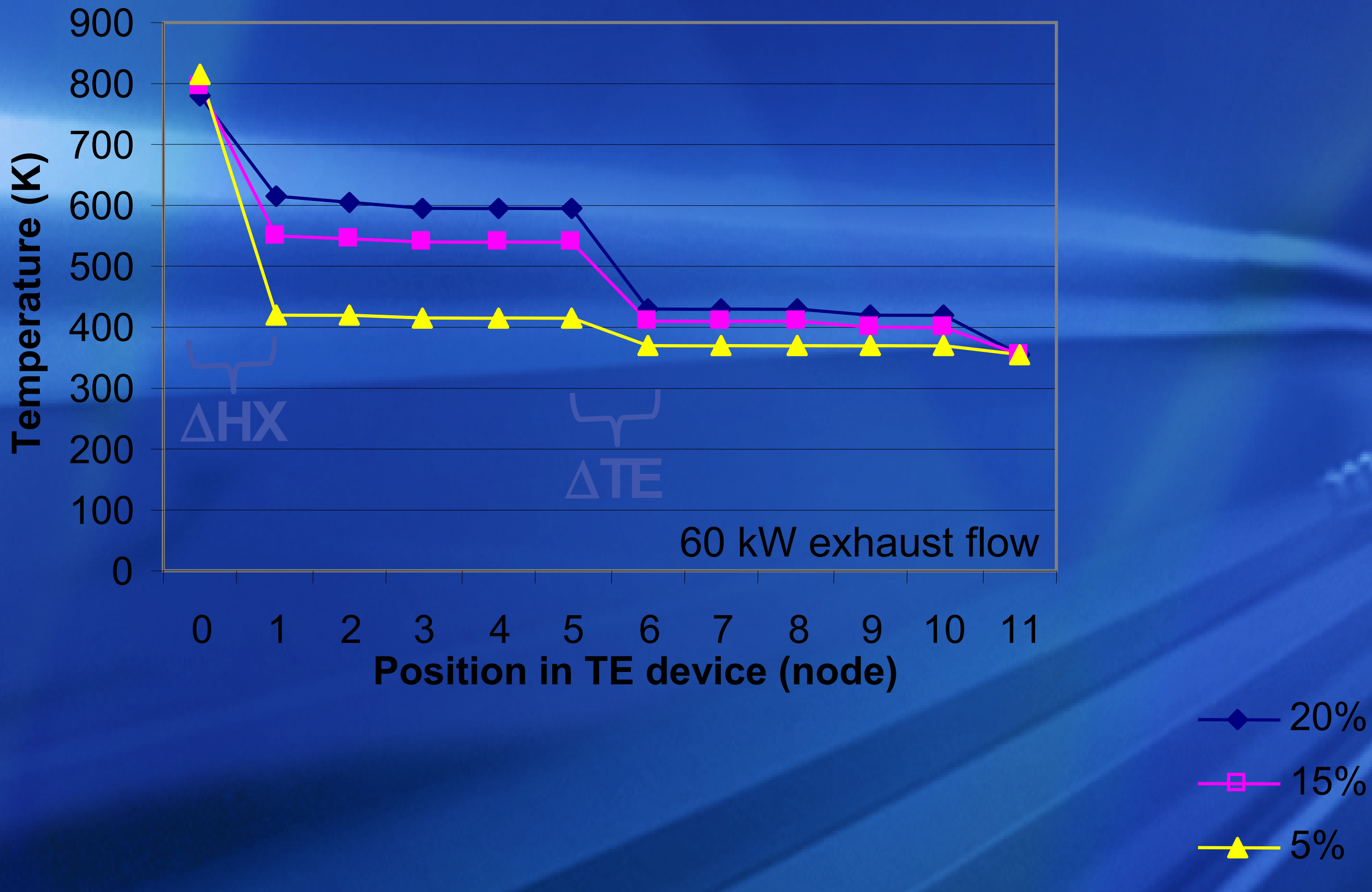


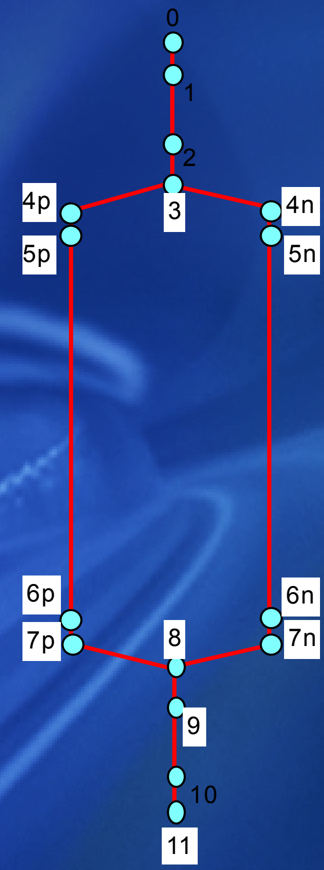
TE Module Modeling



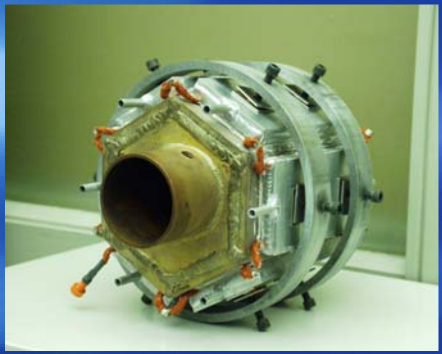
Joule heating from all electrical contacts are accounted for.

Preliminary Temperature Profile



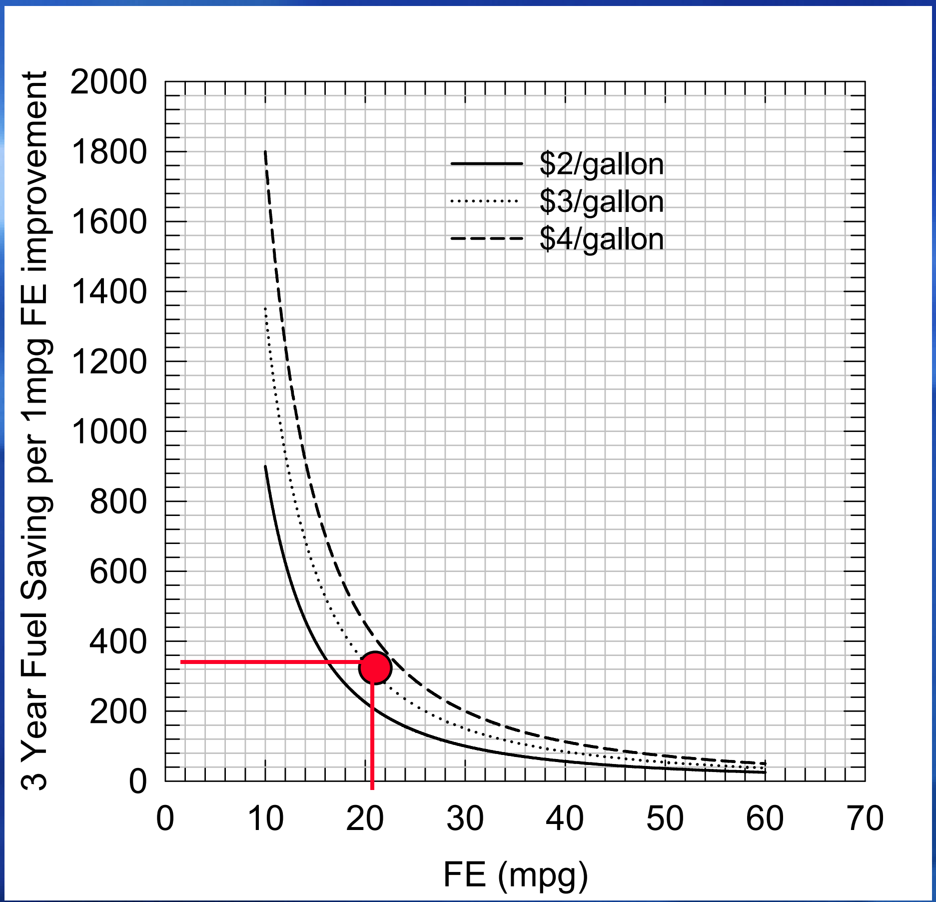


Validation of GE's subsystem Model with GEN I TE Generator



	Experiment	Model
Output Power	109W	121W
V_{load}	16.5V	17.4V
Current, I	6.6A	7.0A
Hot side temperature	183C	189C
Cold side temperature	35C	35C

On the Cost of Fuel Economy

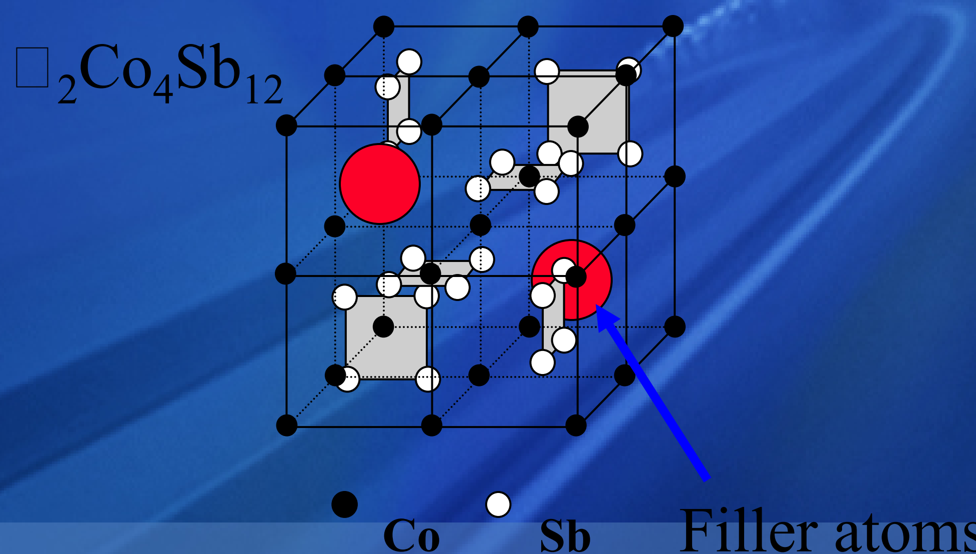


- Cost of fuel economy - \$/Δmpg
  - This kind of calculation can be used to balance technology options
- \$/Δmpg ≤ Savings/Δmpg is necessary to provide consumer value

Consumer Fuel Savings/Δmpg ≈ \$300-400/Δmpg (15000 mile/yr., 3yrs., 18-20 mpg)

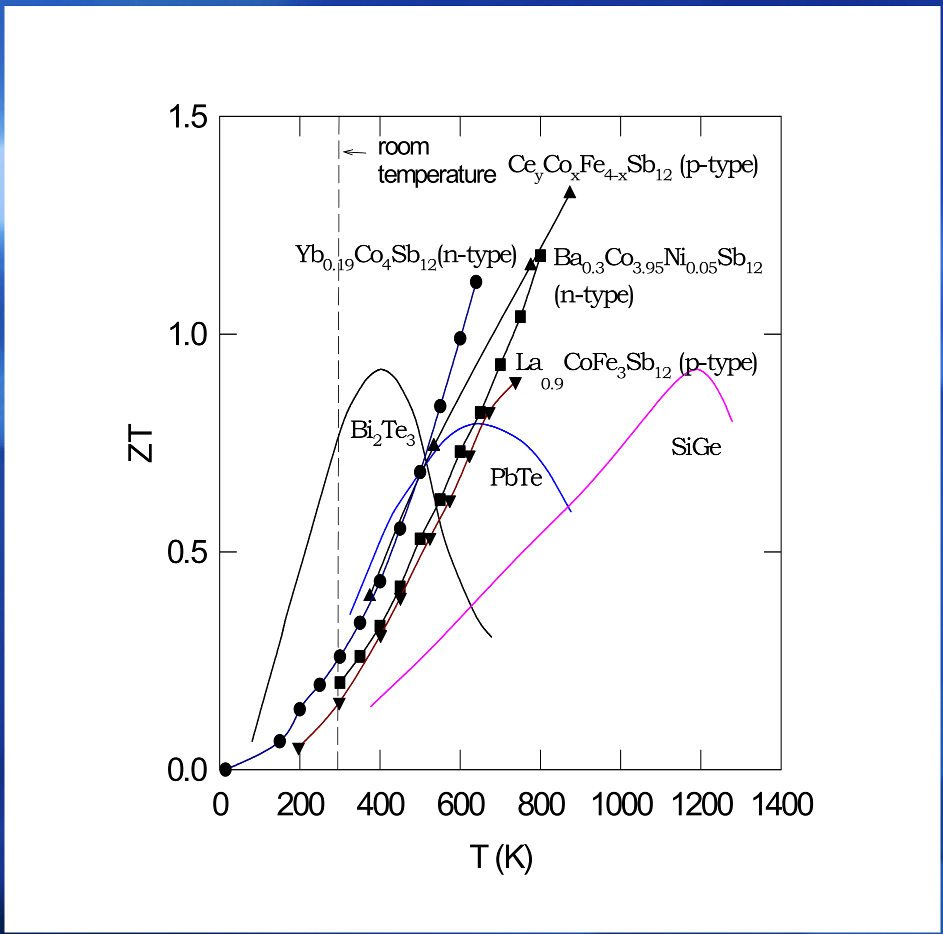
Skutterudites Nano-101

- CoAs$_3$ -based minerals found in region of Skutterud, Norway
- Compounds with the same crystal structure are known as “skutterudites”
- Filled skutterudites are electron-crystal-phonon-glass materials



$$Z = \frac{S^2}{\kappa_T \rho} = \frac{S^2}{(\kappa_L + \kappa_e)\rho}$$

Filled skutterudites as Candidate Materials for Exhaust Heat Recovery



- High ZT values near the exhaust temperature
- Both high performance n- and p-type exist – suitable for TE module

Mischmetal

- Mischmetal: from German - “mixed metals”; a naturally occurring alloy of rare earth elements
- Composition (wt%):

  Ce : 50-55 La : 30-35 Nd : 5-10 Pr : 5-10
- Cost Comparison*:

Mischmetal (99.0%):	$0.19/g
Cerium rod (99.9%):	$8.37/g
Lanthanum rod (99.9%):	$6.40/g

* source: Alfa Aesar

Mischmetal Starting Material

electron probe microanalysis

Element	Wt.%
Ce	52.4
La	23.5
Nd	17.1
Pr	5.9
Si	0.6
Fe	0.3
Al	0.1
Sum	99.9

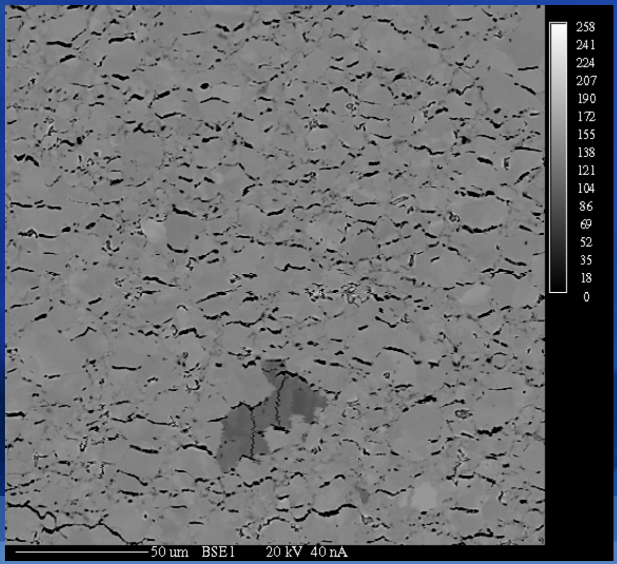
%

wet chemistry

Element	Ce	La	Nd	Pr
Sample	53	23	18	5

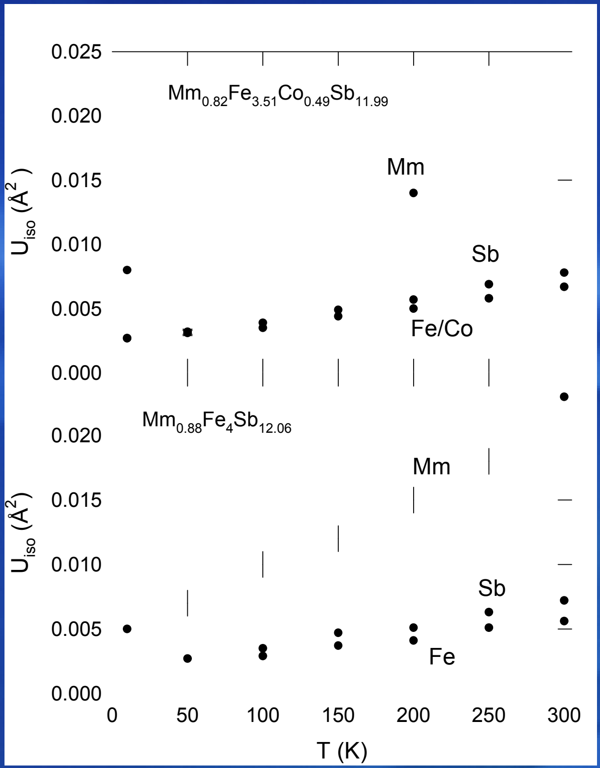
Electron Probe Microanalysis of Mischmetal-filled Skutterudites

Nominal composition	Actual composition	Room temperature lattice parameter (Å)
$Mm_{0.71}Fe_{2.5}Co_{1.5}Sb_{12}$	$Mm_{0.55}Fe_{2.44}Co_{1.56}Sb_{11.96}$	9.109(1)
$Mm_{0.82}Fe_{3}CoSb_{12}$	$Mm_{0.65}Fe_{2.92}Co_{1.08}Sb_{11.98}$	9.117(1)
$Mm_{0.93}Fe_{3.5}Co_{0.5}Sb_{12}$	$Mm_{0.72}Fe_{3.43}Co_{0.57}Sb_{11.97}$	9.126(1)
$MmFe_{4}Sb_{12}$	$Mm_{0.82}Fe_{4}Sb_{11.96}$	9.146(1)
$Mm_{0.93}Fe_{3.5}Co_{0.5}Sb_{12}$ *	$Mm_{0.82}Fe_{3.51}Co_{0.49}Sb_{11.99}$	9.1294(2)
$MmFe_{4}Sb_{12}$ *	$Mm_{0.88}Fe_{4}Sb_{12.06}$	9.1433(2)



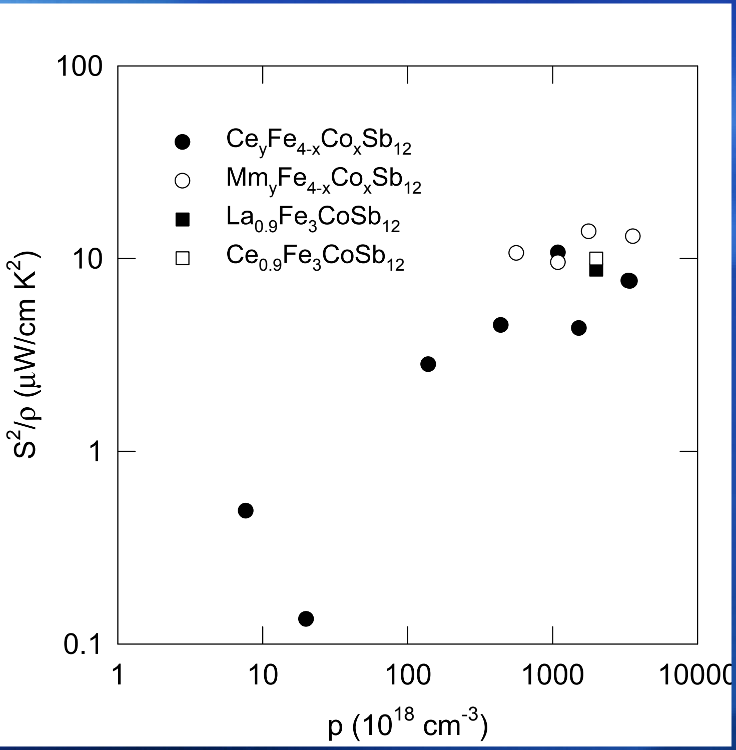
- nominal comp. chosen according to the optimal filled skutterudites $Ce_yFe_{4-x}Co_xSb_{12}$ ~ PRL 80, 3551 (1998)
- Mm actual concentration < nominal due to high Mm vapor pressure
- all samples are nearly phase pure
- typical secondary phase: $MnSb_2$ or $CoSb_2$ < 1 vol. %

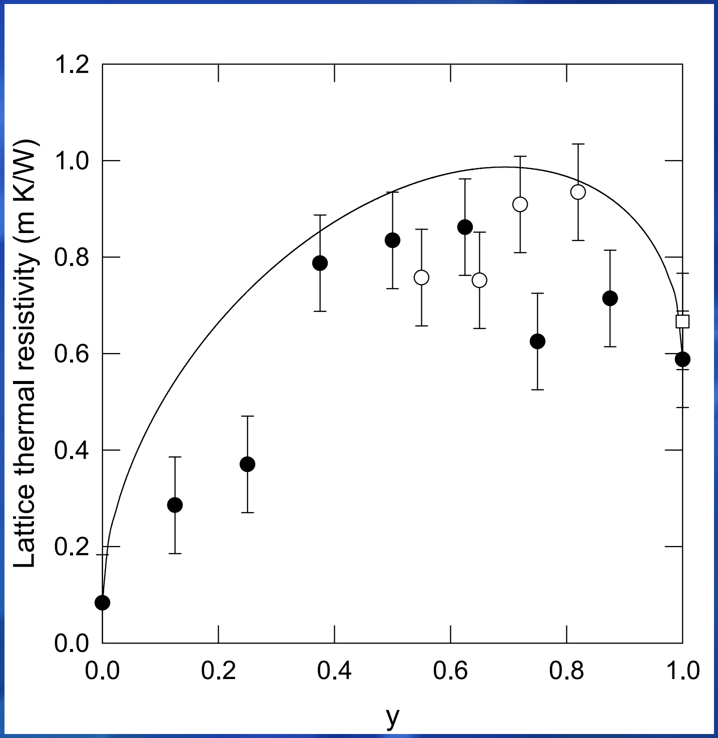
Isotropic Atomic Displacement Parameter – Evidence of Rattling



- low T intercepts of U_{iso} represent a combination of zero-point vibration and static disorder at the corresponding crystallographic sites
- zero-point vibration ∝ 1/M, expected contribution ~ Mn < Sb < Fe → static disorder at the Sb sites, more so at the Mn sites (Mn vs. □)
- θ_E ~ 71.5 K (La: 80 K, Ce: 78 K, Eu: 83 K, and Yb: 65 K)

Room Temperature Properties Comparison





Summary of Challenges for Automotive TE Waste Heat Recovery

Outline

- ❑ Background
  - – Objective, partnering, …
  - – Motivation: fuel economy
- ❑ Technology Development
  - – Subsystem modeling
  - – Cost
  - – Cost-effective materials
- ❑ Summary

Need better materials, heat exchanger, contact joining, thermal & mechanical stability, …

Consumer focus: consider $/Δmpg (also valuable for balancing tech. options)

Low cost materials is a must

Thank you ! Questions ?