Thermoelectric Technology for Automotive Waste Heat Recovery

Jihui Yang
GM Research & Development Center
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Outline

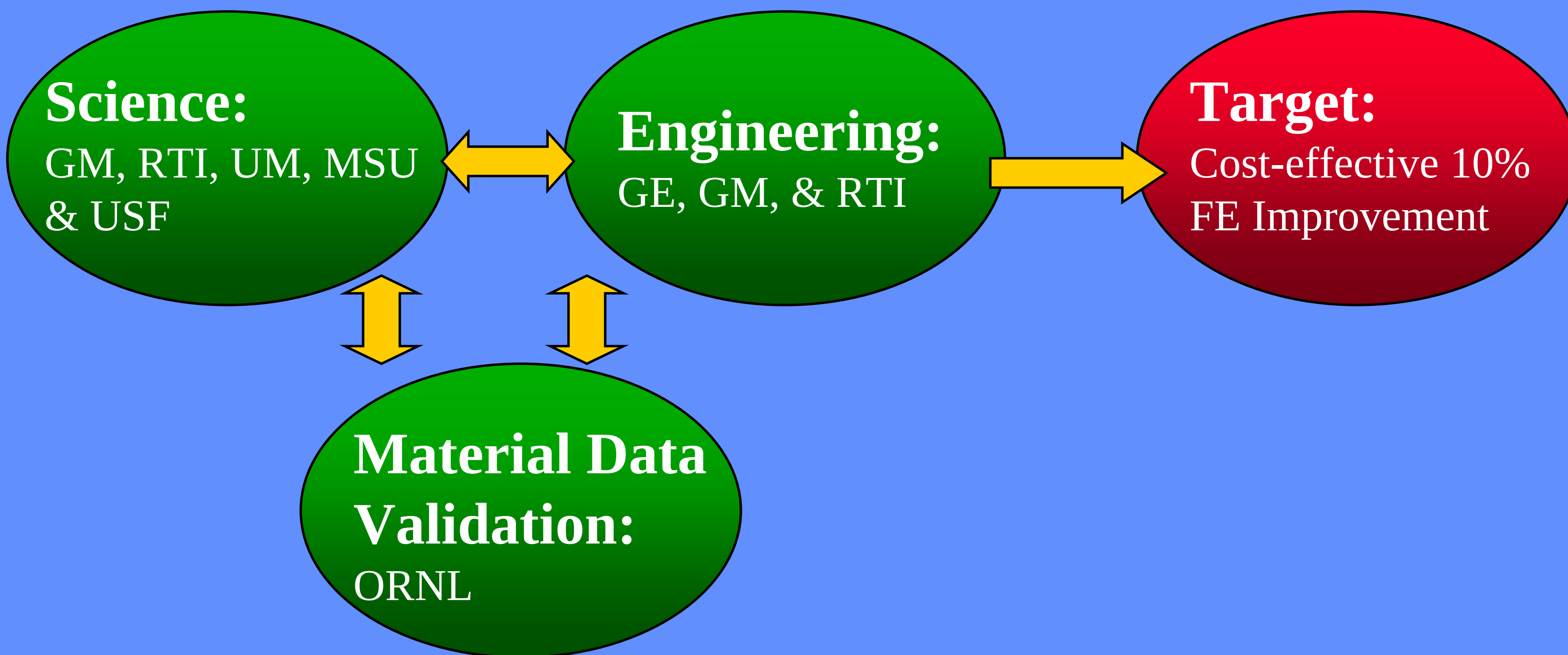
- ❑ Introduction
- ❑ Engineering Highlights
- ❑ Materials Research Highlights
- ❑ Automotive TE cooling?
  - environmental impact of R134a
- ❑ Summary

Sponsored by
US Department of Energy
Energy Efficiency Renewable Energy (EERE)
Waste Heat Recovery and Utilization Research and Development for Passenger Vehicle and Light/Heavy Duty Truck Applications
DE-FC26-04NT42278

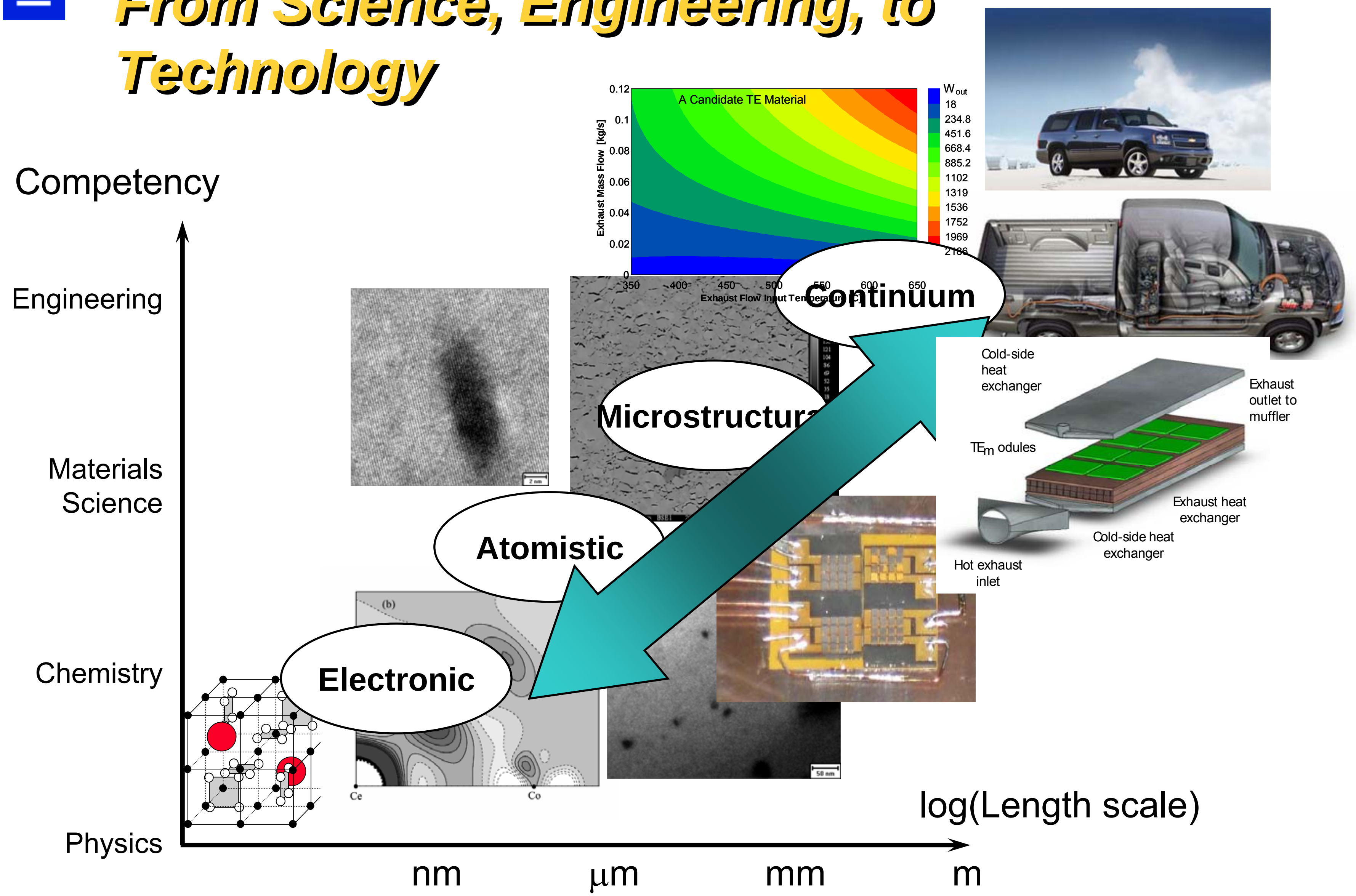
Thermoelectric Power Generation from Automotive Waste Heat Recovery

- Target : 10% fuel economy improvement without increasing emissions
- Partnering:
  - **GM** – materials research, subsystem design, integration, modeling, and validation
  - **GE** – TE module, subsystem design and manufacturing
  - **Oak Ridge National Lab** – high temperature material property measurement and validation
  - **RTI** – superlattice-based thin film materials and modules
  - **University of Michigan** – bulk materials : filled skutterudites, nano-composites,…
  - **University of South Florida** – bulk materials: clathrates, nano-grain PbTe, …
  - **Michigan State University** – bulk PbTe-based materials …

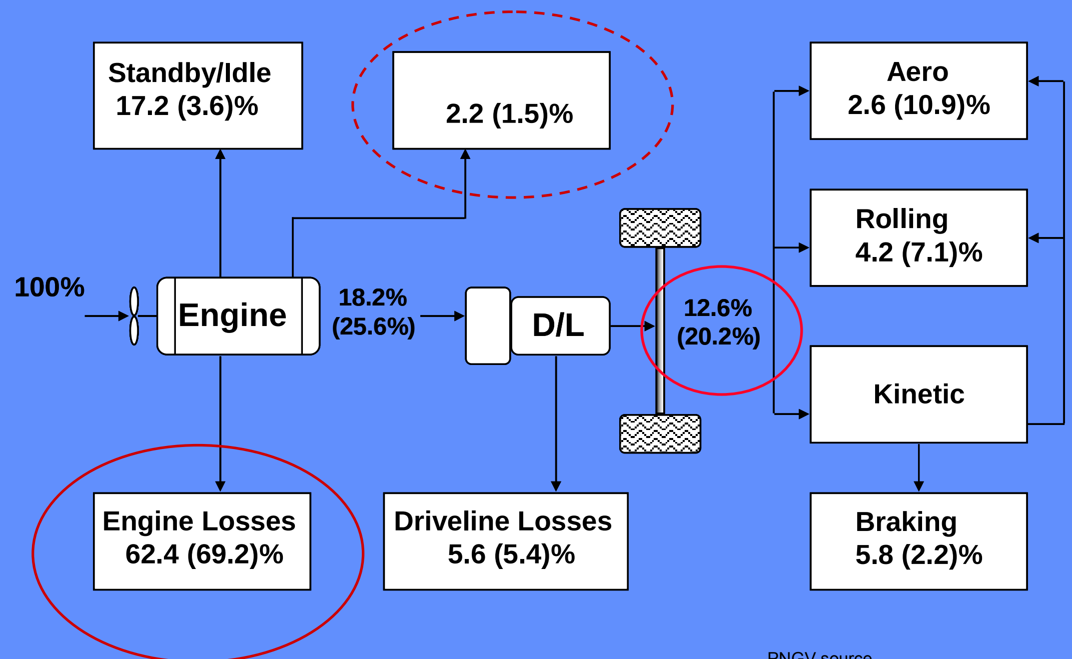
DOE Program High-Level Process



From Science, Engineering, to Technology



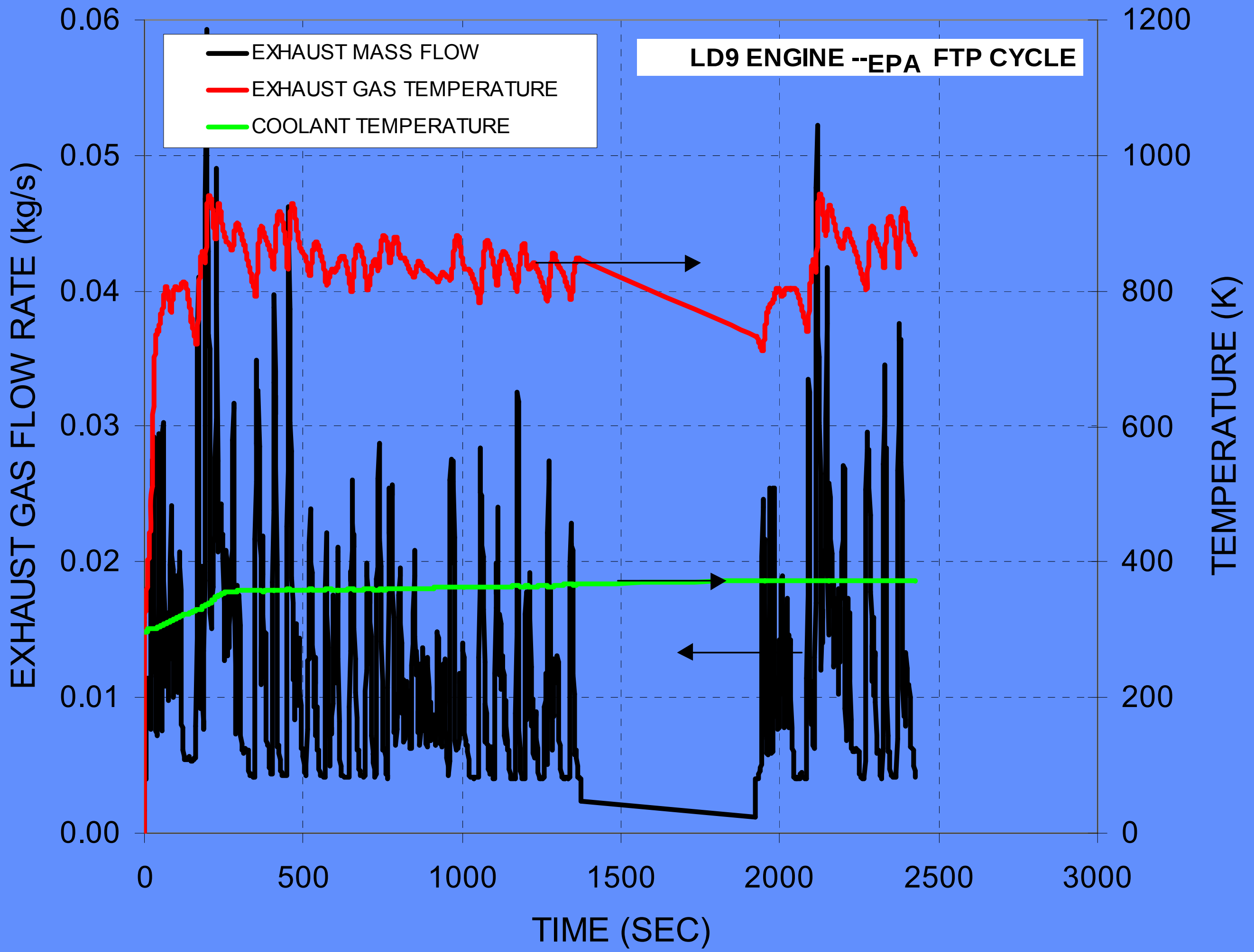
Energy Distribution - Typical Mid-Size Vehicle on the Federal Test Procedure (FTP) Schedule Urban (Highway) % energy use



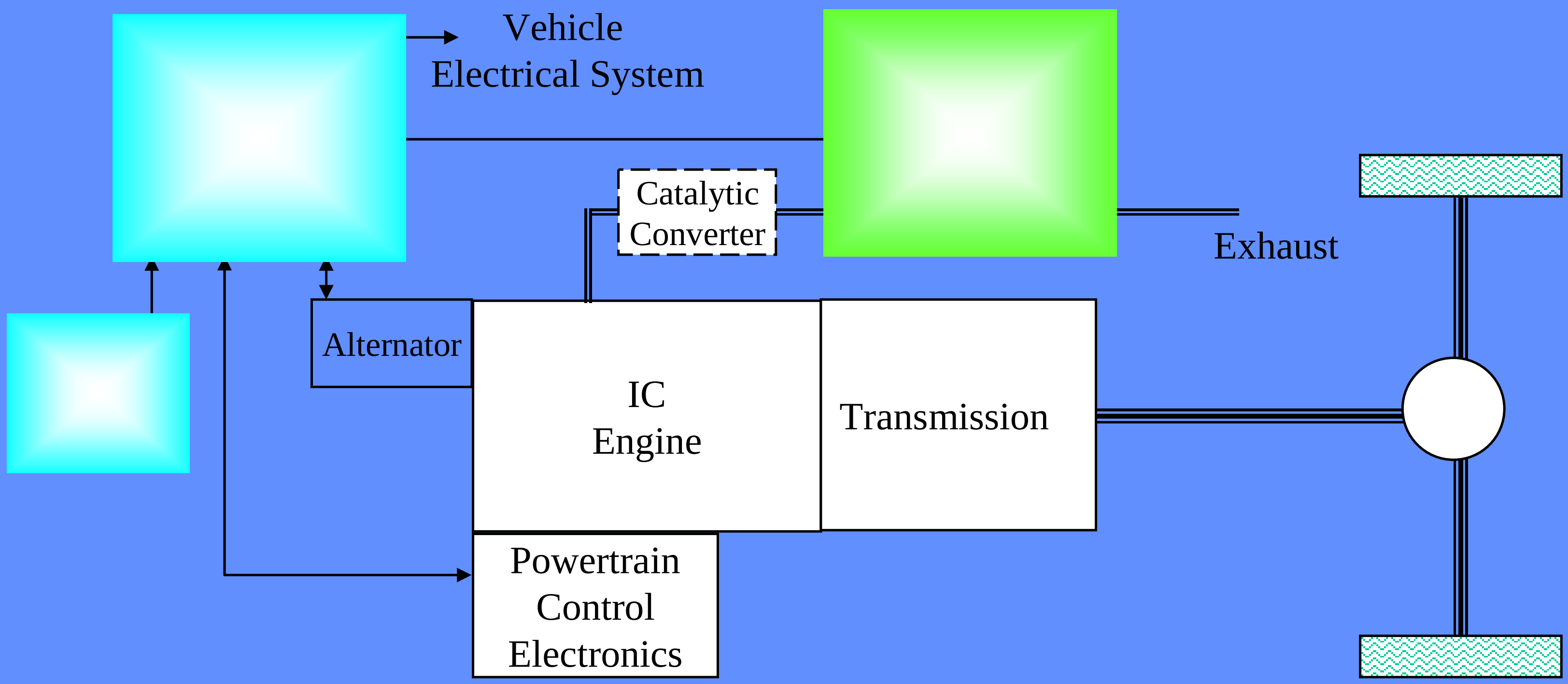
PNGV source

- Today's ICE-based vehicles: < 20% of fuel energy is used for propulsion
- > 60% of gasoline energy (waste heat) is not utilized

Exhaust Flow and Temperatures for a 4 Cylinder Engine



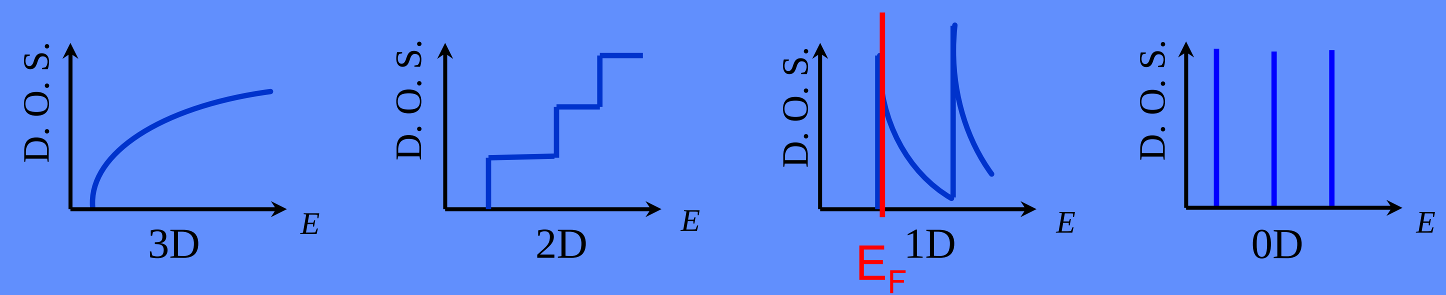
Thermoelectric Energy Recovery Augmented Electrical System



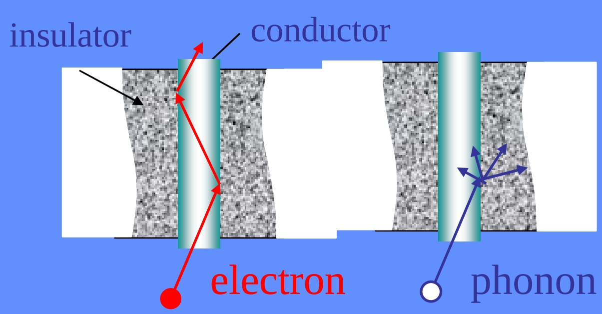
- Engine coolant is also a possible heat source, but smaller ΔT

Nano-derived materials give additional control

- Enhanced density of states due to quantum confinement effects
  - ⇒Increase *S* (sharp edge of electron D.O.S. near Fermi surface E_F)
  - ⇒without reducing σ (very high electron D.O.S. near Fermi surface E_F)
- Boundary scattering at interfaces reduces κ_L more than σ
- Possibility of materials engineering to further improve *ZT*



Bulk semiconductor | Quantum well | Quantum wire | Quantum dot

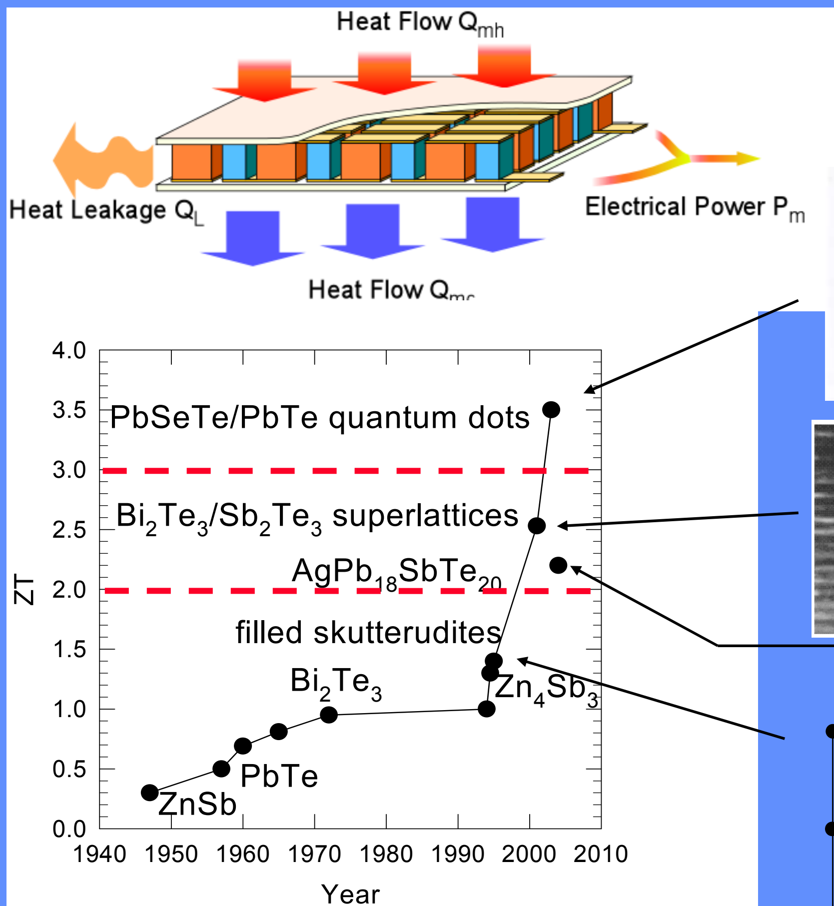


TE Figure of Merit

$$ZT = \frac{S^2 T}{\kappa_T \rho} = \frac{S^2 \sigma T}{\kappa_L + \kappa_e}$$

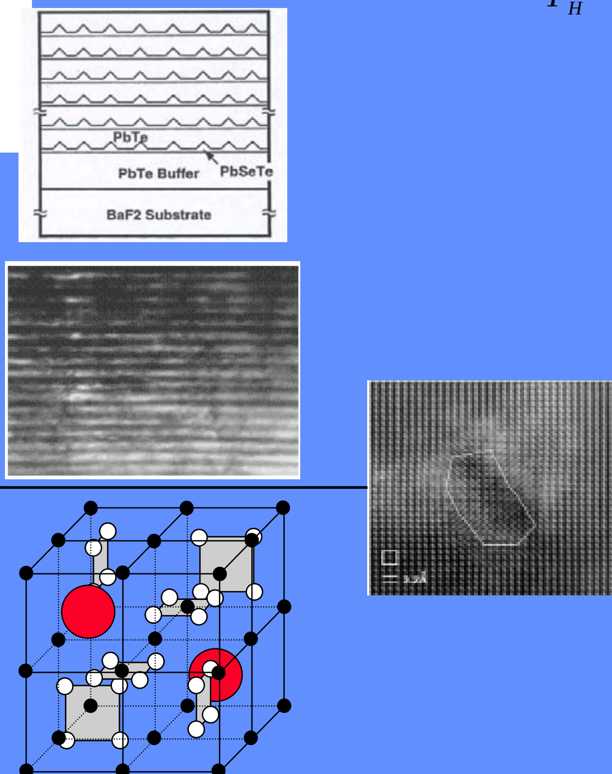
thermopower (S); temperature (T); electrical conductivity (σ); total thermal conductivity (κ_T); electrical resistivity (ρ); lattice thermal conductivity (κ_L); electronic thermal conductivity (κ_e)

Thermoelectric Waste Heat Recovery



Efficiency:

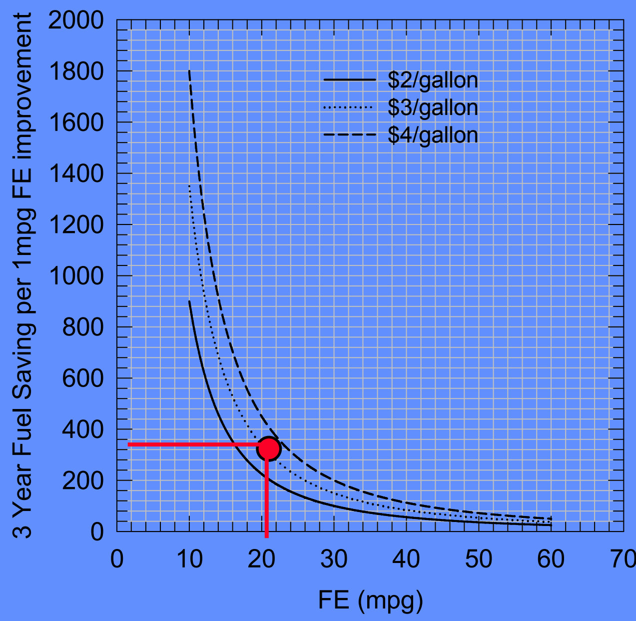
$$\varepsilon = \frac{T_H - T_C}{T_H} \frac{\sqrt{1+ZT} - 1}{\sqrt{1+ZT} + \frac{T_C}{T_H}}$$



- Many recent material advances are nano-based

$ / W – a Program Metric

- $/W (not only ZT) is used for balancing various material, module, and subsystem options
- $/W can be readily converted to $/Δmpg, and $/Δmpg < Savings/Δmpg is necessary to provide consumer value

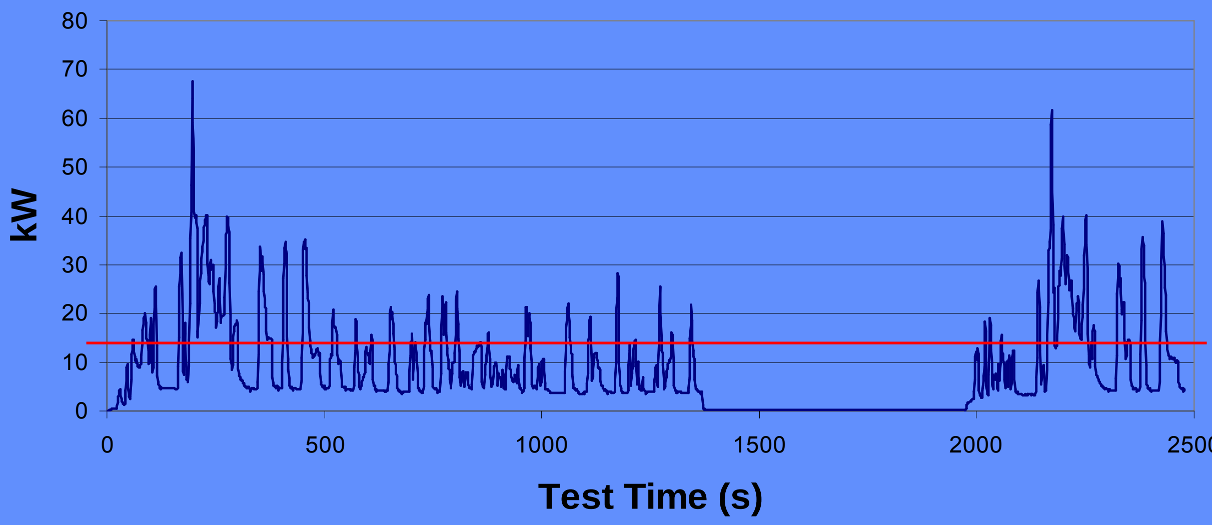


Consumer Fuel Savings/Δmpg ≈ $300-400/Δmpg (15000 mile/yr., 3yrs., 18-20 mpg)

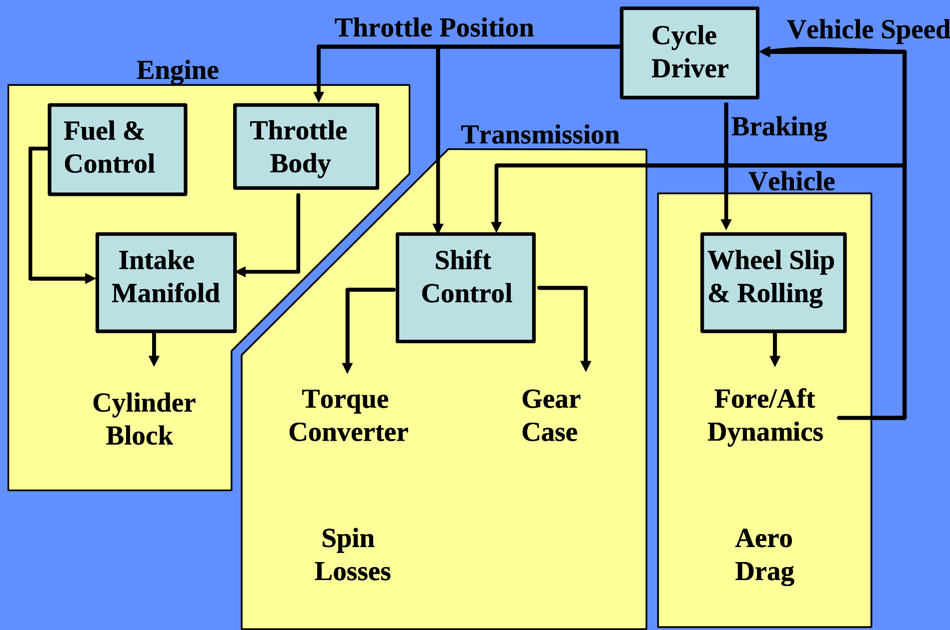
Vehicle Selection – Full Size Truck

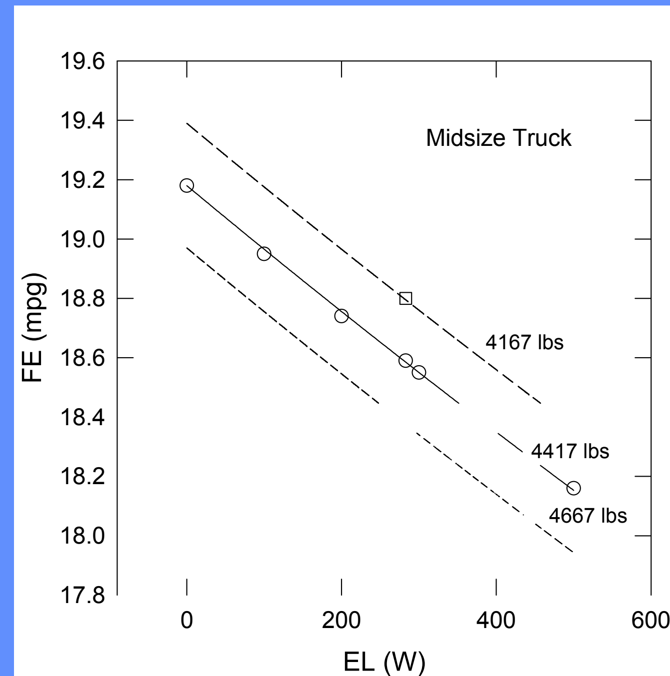
- plenty of space for accommodating TE subsystem
- a lot of waste heat: exhaust and radiator
- current muffler: 610 x 310 x235 (mm)
- available envelope: 840 x 360 x 255 (mm)

Typical Exhaust Heat - City Driving Cycle



Fuel Economy Analysis - Overdrive





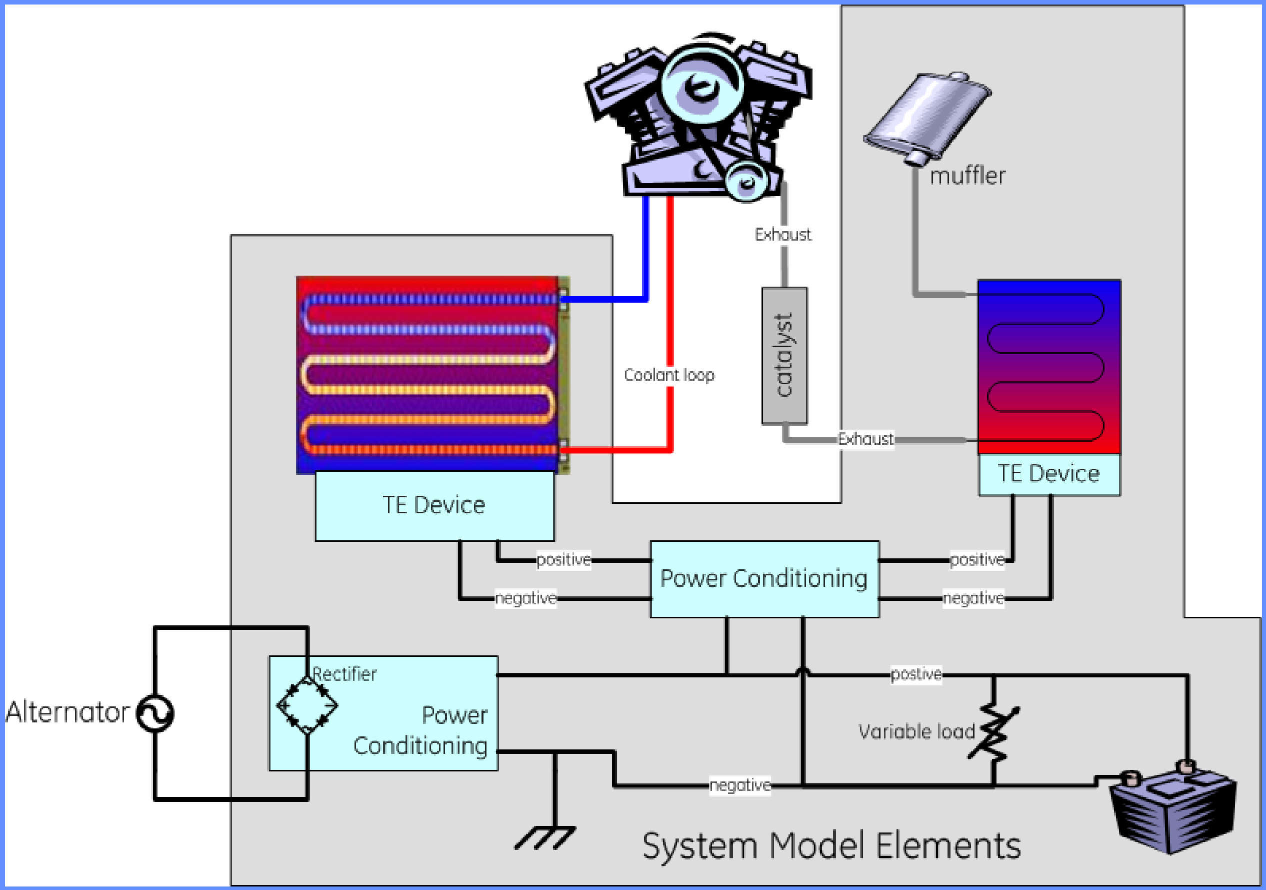
10% fuel economy improvement for a full size truck would require (for a hybrid full size truck):

- 1.65 kW – city
- 2.5 kW – Highway

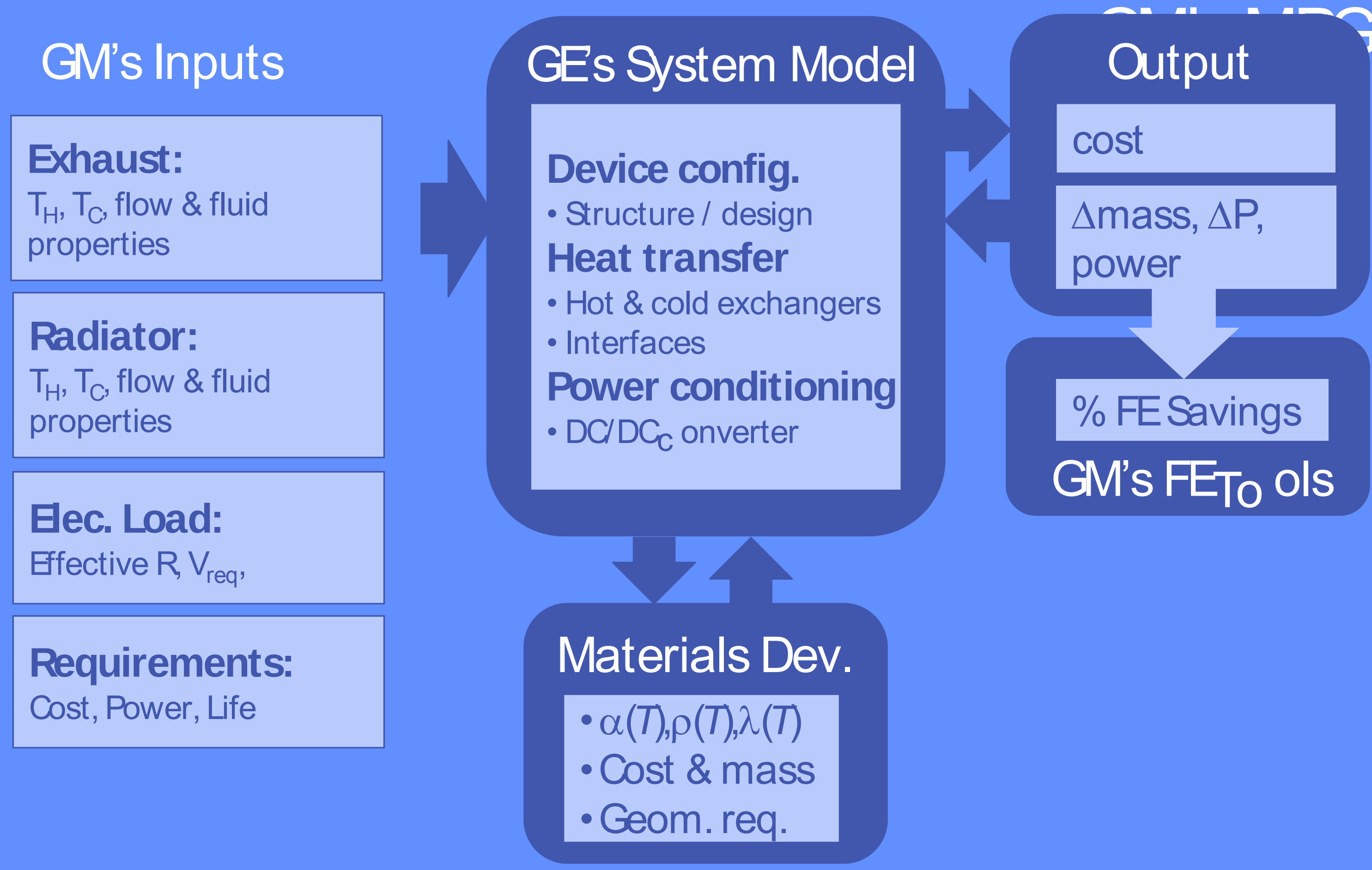
350 W is the minimum requirement

- equal to the base electrical load of today's generator on FTP, and would improve its composite Urban/Highway fuel economy by ~ 3%

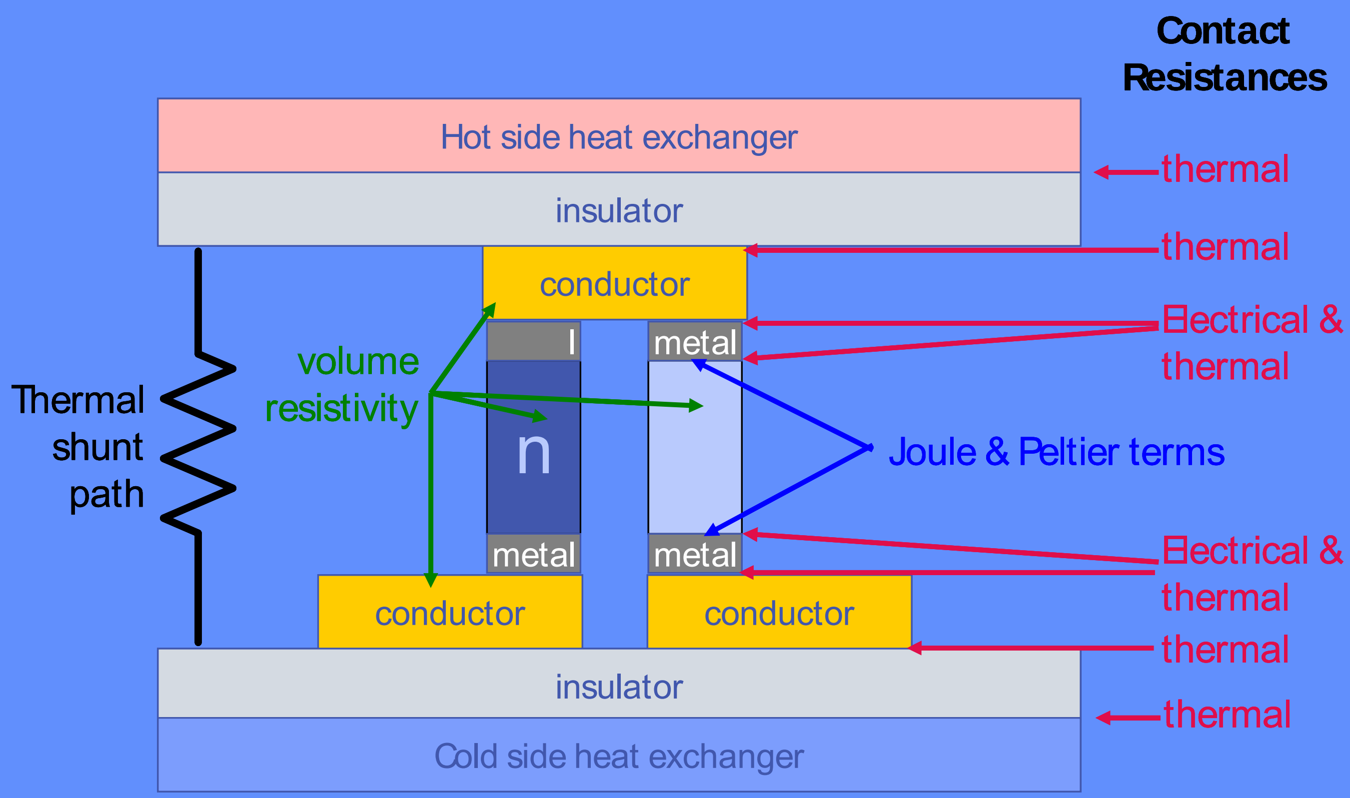
Subsystem Model Schematic



Subsystem Modeling



Subsystem Modeling – 2 D Thermoelectric Network Model



Joule heating from all electrical contacts are accounted for.

2007 Year End Module and Subsystem Goals

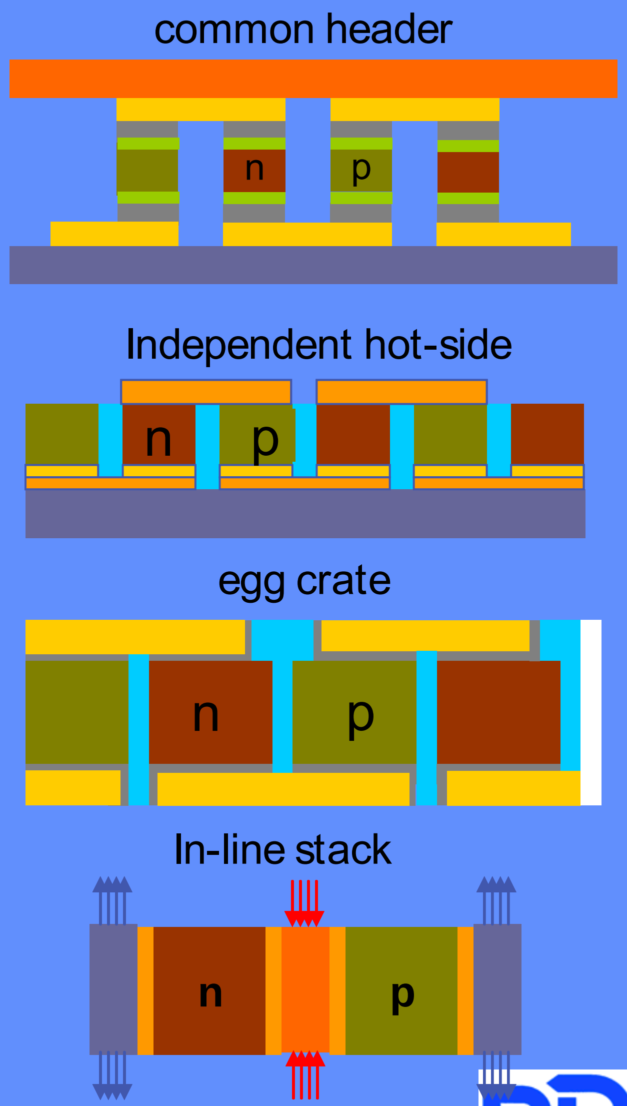
- Thermoelectric Module Design
  - TE material manufacturing
  - Thermomechanically robust materials & module design
  - Initial module characterization

- Subsystem Design and Optimization
  - Heat exchanger optimization
  - Thermal and mechanical integration strategy
  - Exhaust flow testing facility complete

TE Module Conceptual Design

Identifying and modeling candidate module designs for **cost**, **thermoelectric performance** and **thermo-mechanical durability**

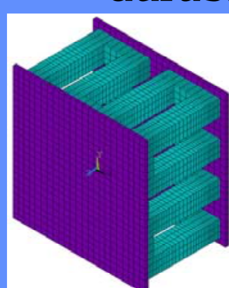
- Minimize thermal stresses
- High operating temperature
- Good ohmic contact & high thermal conductivity (diffusion barriers, solders/brazes, electrodes)
- Minimize shunt path
- No thermo-chemical degradation

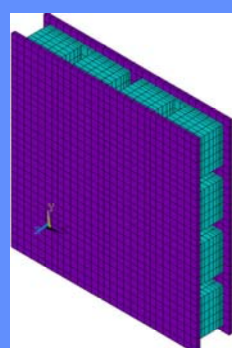


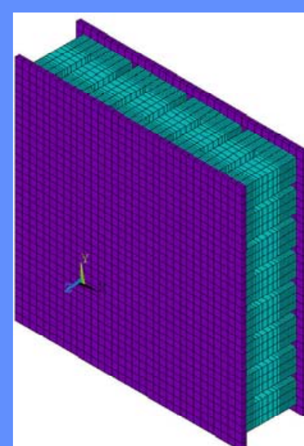
Module Design Optimization

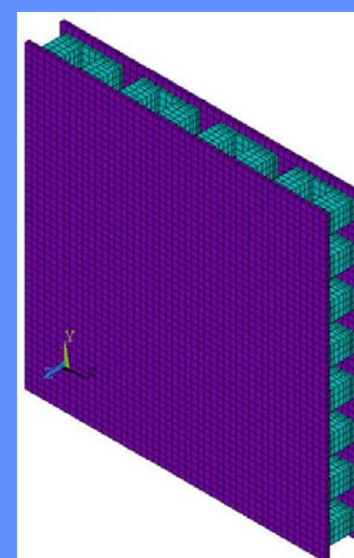
Initial Design Study:

- Identify primary module design variables
- Examine effect on primary output variables
  1. Power output
  2. Cost
  3. Thermo-mechanical durability

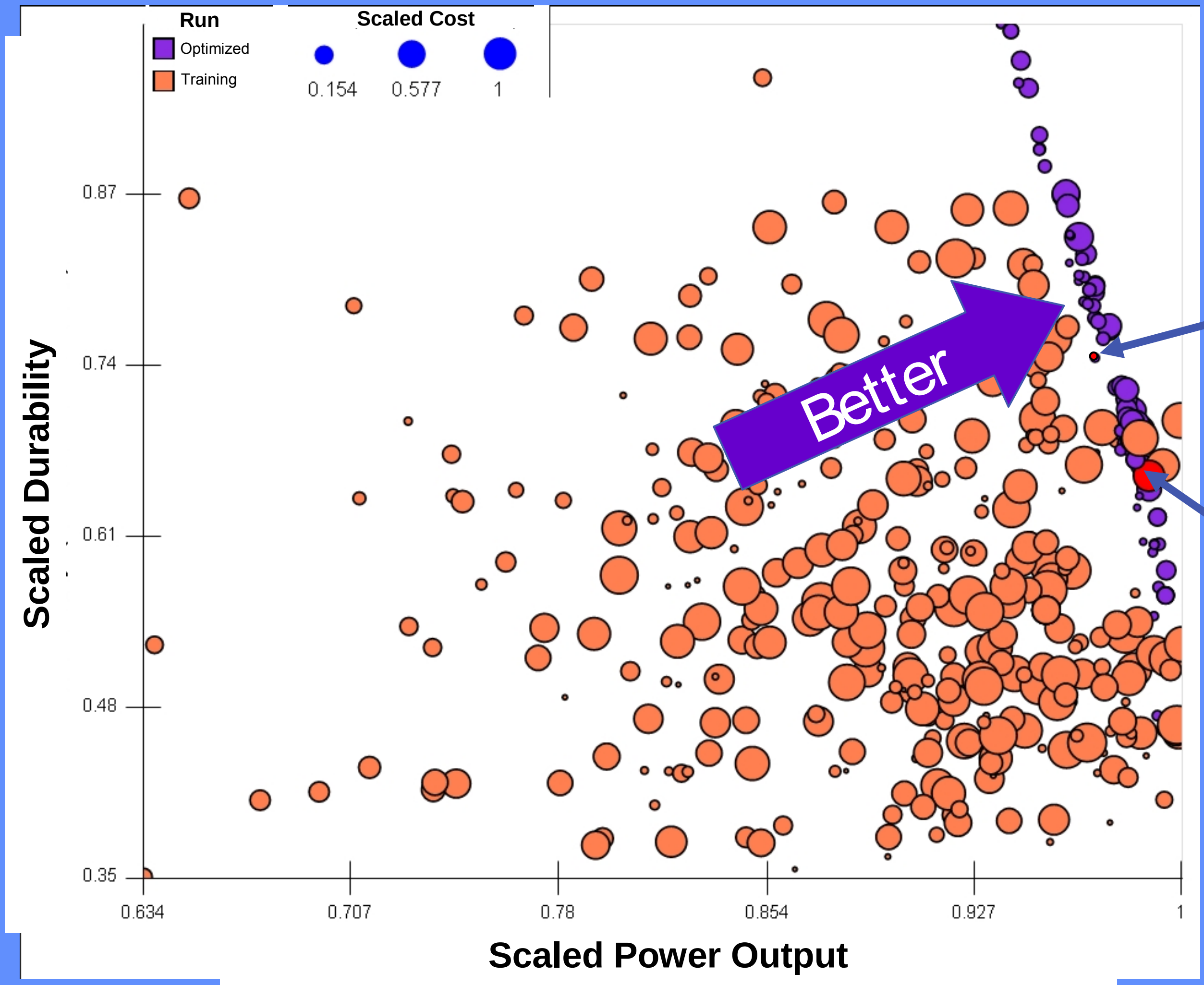


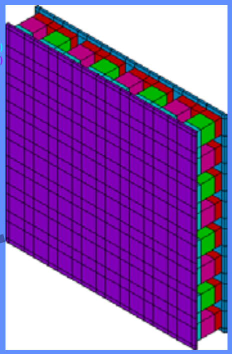


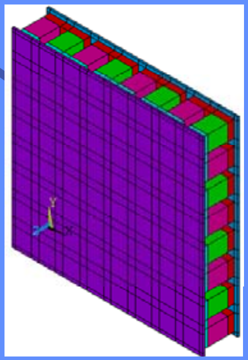




Design Space Optimization

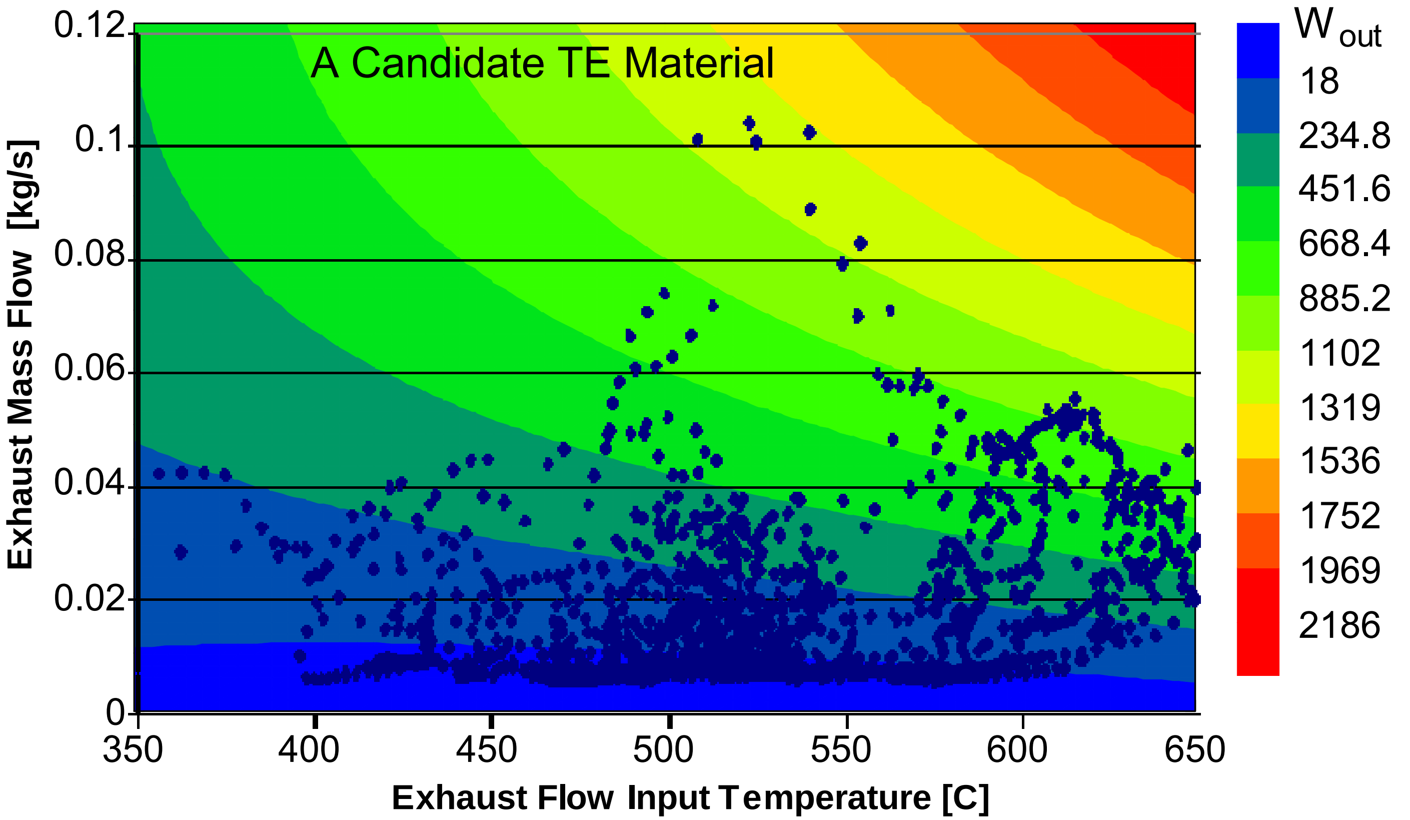






Evaluate sensitivities of designs on Pareto frontier

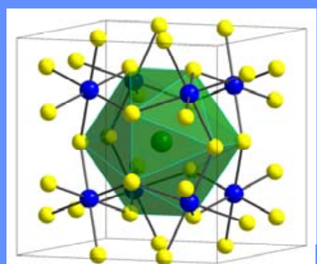
Overlay of TE System Efficiency and Expected Exhaust Conditions

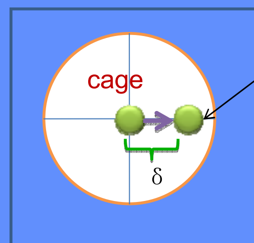


Phase I Summary

- quantified electric power requirements for 10% FE improvement
- established $/W as a program metric – automotive and consumer focus; and determined cost target for both exhaust and radiator TE waste heat recovery (materials, modules, subsystems)
- completed the initial exhaust and radiator subsystems design, performance analysis, and cost modeling
- assessed manufacturability of bulk and thin-film modules and subsystems
- validated many known materials' performance, and enhanced the design of thin-film modules
- explored routes toward higher ZT and low material cost
- exhaust recovery can meet the 350 W requirement with existing materials with high starting purities but at high cost
- radiator recovery alone will not meet the 350 W requirement and is cost prohibitive

Dual-frequency Resonant Phonon Scattering in Skutterudites



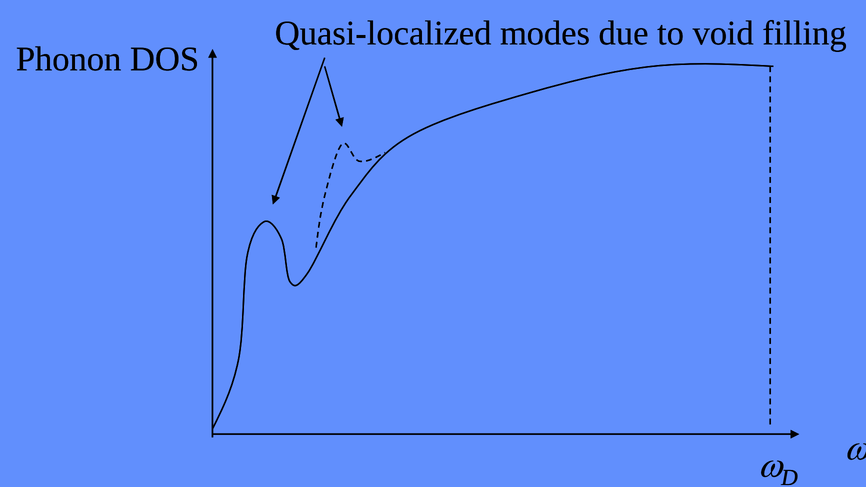


Small displacement δ of the filler from it equilibrium x will lead to an increase of the total energy of the system.

$$E(x+\delta) = E(x) + \underbrace{\frac{1}{2}\ddot{E}(x)\delta^2}_{\text{onic term}} + \underbrace{\frac{1}{6}\dddot{E}(x)\delta^3 + \cdots}_{\text{anharmonic term}}$$

In a harmonic approximation, $\ddot{E}(x)$ is the spring constant.

$$\omega_0 = \sqrt{\frac{\ddot{E}(x)}{m}}$$



APPLIED PHYSICS LETTERS **90**, 192111 (2007)

Dual-frequency resonant phonon scattering in $Ba_xR_yCo_4Sb_{12}$ (R=La, Ce, and Sr)

J. Yang[a)]
Materials and Processes Laboratory, GM R&D Center, Warren, Michigan 48090

W. Zhang,[b)] S. Q. Bai, Z. Mei, and L. D. Chen
State Key Laboratory of High Performance Ceramics and Superfine Microstructure, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 200050, China

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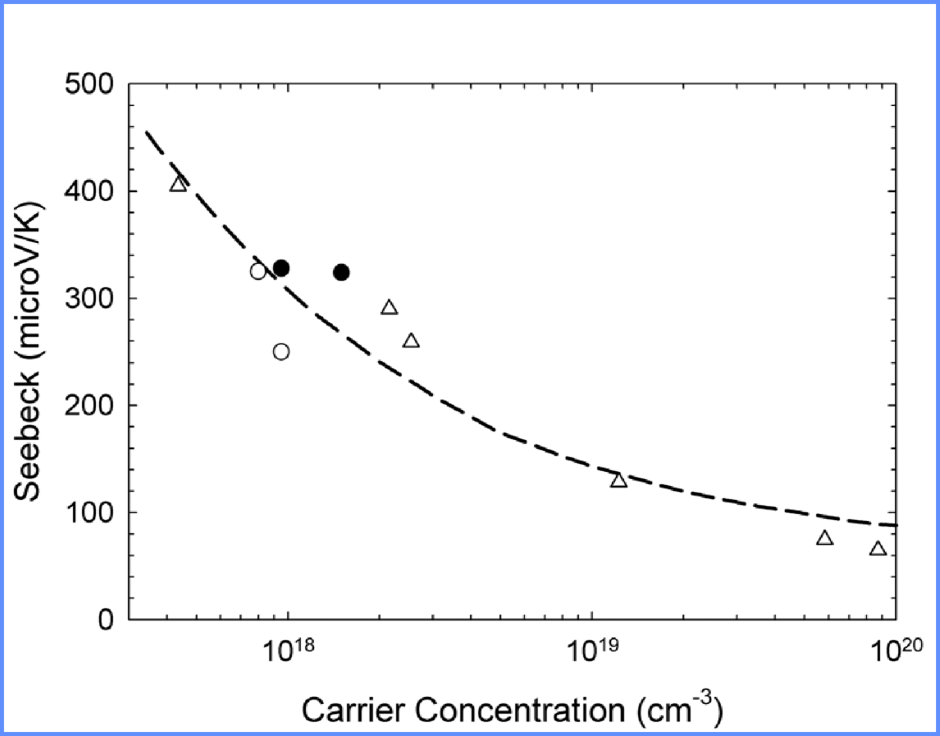
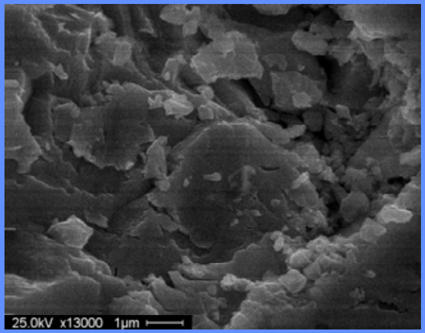
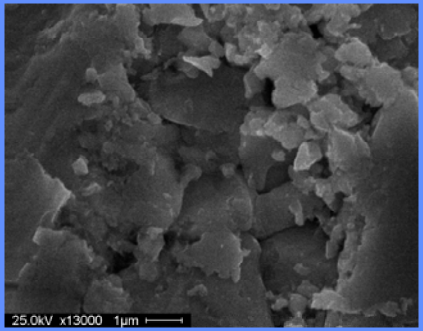
Thermoelectric Enhancement in Nanocomposites





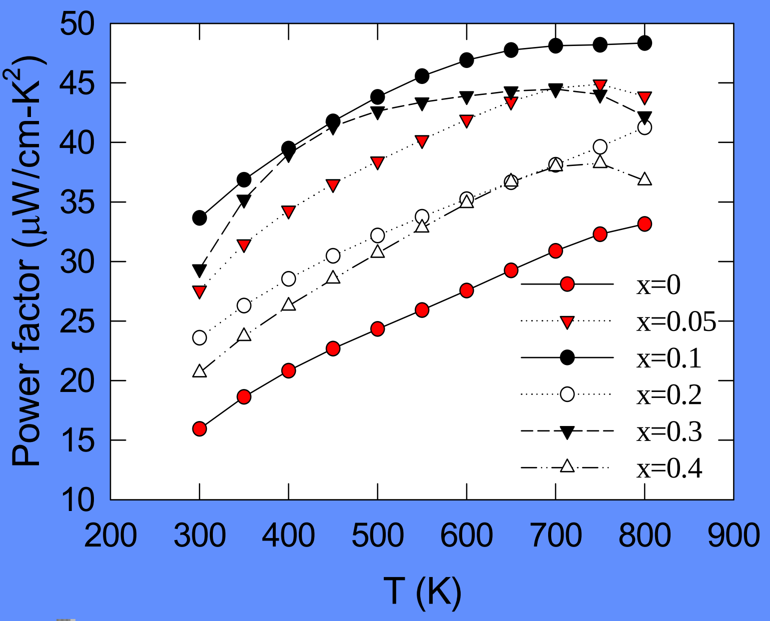


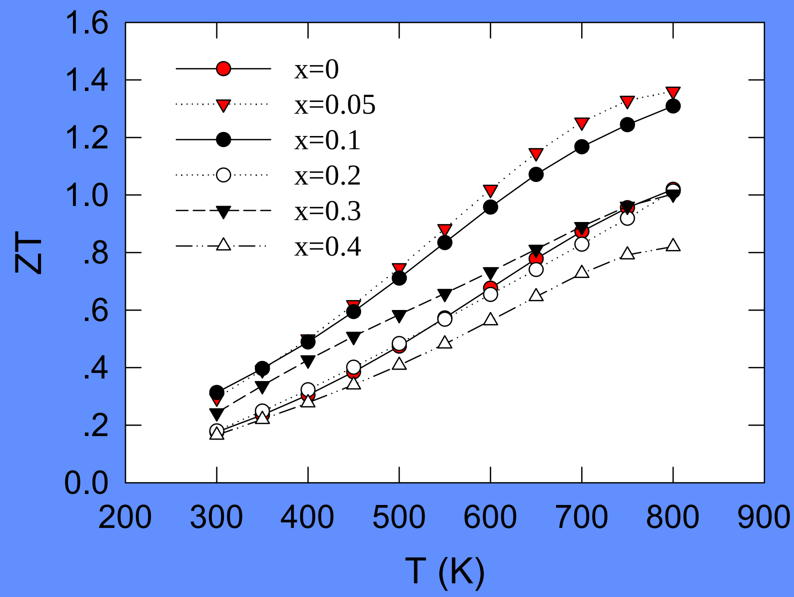
- **Non-conglomerated nanocrystals within the bulk matrix**
- **Power Factor enhancement of 30% at room temperature**
- **Three weeks at 600 K with preservation of nanostructure**

NOVEL MATERIALS LABORATORY
UNIVERSITY OF SOUTH FLORIDA

Filled Skutterudite Nanocomposites

$Yb_{0.2}Ba_xCo_4Sb_{12}$





ZT = 1.36 for x=0.05

HTML at Oak Ridge Natioanl Lab

ORNL efforts will focus on the following areas:

- High temperature transport properties testing
- Utilizing ORNL capabilities to continue the search for high ZT materials
- Start mechanical properties testing on selected materials
- Continue to develop and expand measurement capabilities for TE materials

Environmental Impact of R134a Containing Automobile AC: Global Warming

- Direct and Indirect Global Warming Impact of R-134a

  Direct leakage R-134a:

  345 gm/yr * 1,400 = 483 kg/yr

  Indirect increase in emissions due to AC R-134a:

  23.5 gallons/yr * 8.9 kg CO_2/gal = 209 kg/yr

- Total Global Warming Impact of R-134a, and Entire Gas-Powered Vehicle

  R-134a: 483 + 209 = 692 kg/yr

  Entire Vehicle: avg. 696 gal/yr * 8.9 kgCO_2/gal = 6194 kg/yr

* M. S. Bhatti, "A critical look at R-744 and R-134a mobile air-conditioning systems", SAE SAE-970527

Summary

- Automotive TE waste heat recovery is promising for FE improvement
- \$/W or \$/Δmpg needs to used to assess its commercial feasibility
- Major challenges in materials and engineering
- Automotive TE cooling needs to be evaluated