Cost-Effective Fabrication Routes for the Production of Quantum Well Type Structures and Recovery of Waste Heat from Heavy Duty Trucks

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Energy Efficiency and Renewable Energy

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Outline

- Department of Energy (DoE) Waste Heat Recovery Programs
- Program overview of UTRC-led team
- Thermoelectric Generator Design (Phase I)
- Progress-to-date (Phase II):
  - Thermal-to-Electric Conversion Efficiency Rig
  - Fabrication of Quantum Well (QW) Couples for Efficiency Testing
  - Fabrication of Heterogeneous Nanocomposites

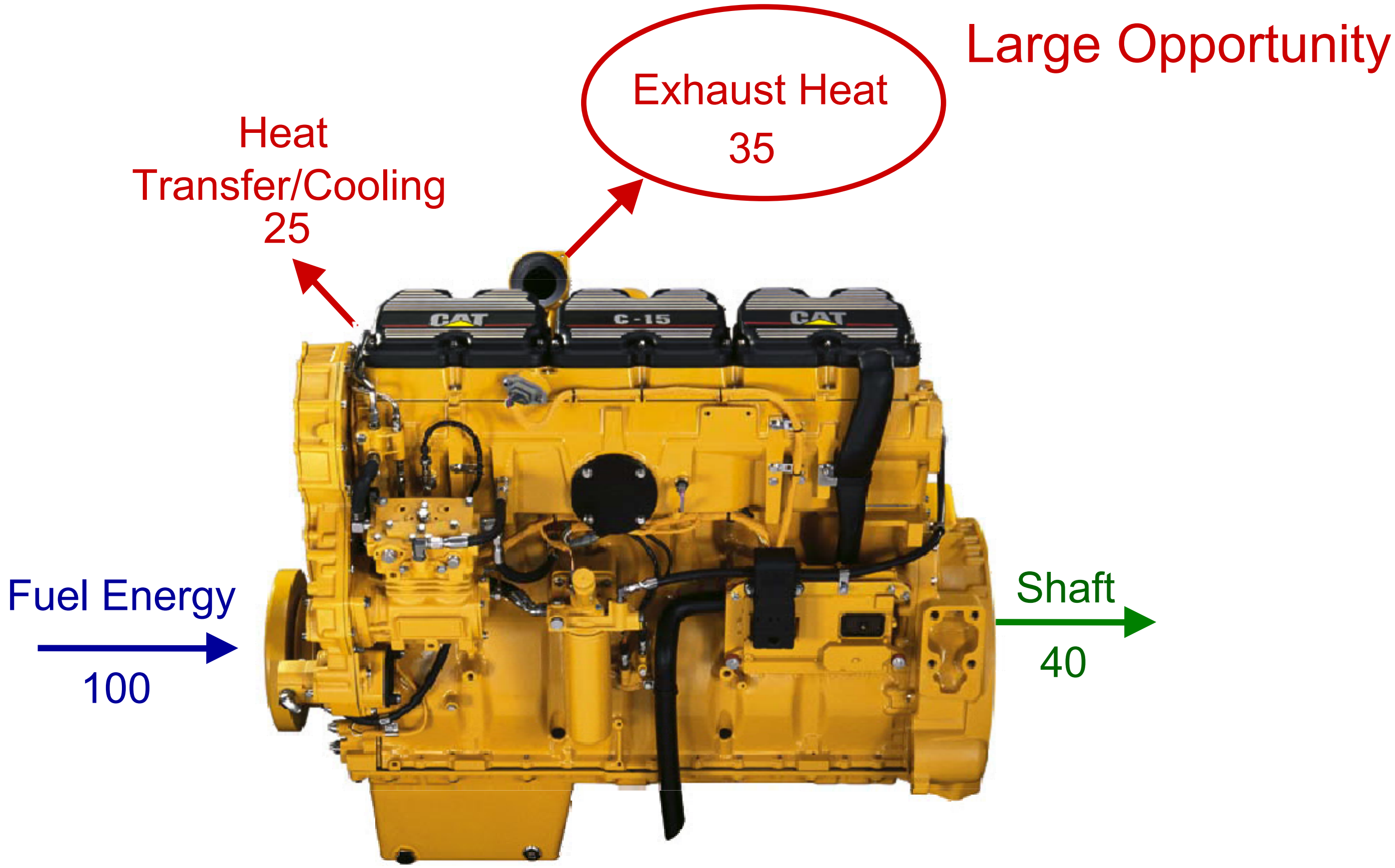
DOE Waste Heat Recovery & Utilization Program

Program Overview

- Four-phase program focused on the development of thermoelectric (TE) materials, devices and systems for waste heat recovery from automotive exhaust
- Team is currently in Phase II of IV
- Specific focus is on QW film technology for Class 8 on-highway trucks
- Exploration of alternative deposition routes to reduce cost
- Exploration of alternative form factors (bulk nanocomposites) to reduce cost

Motivation for Waste Heat Recovery from Diesel Engines

Large opportunity to improve fuel economy and engine efficiency

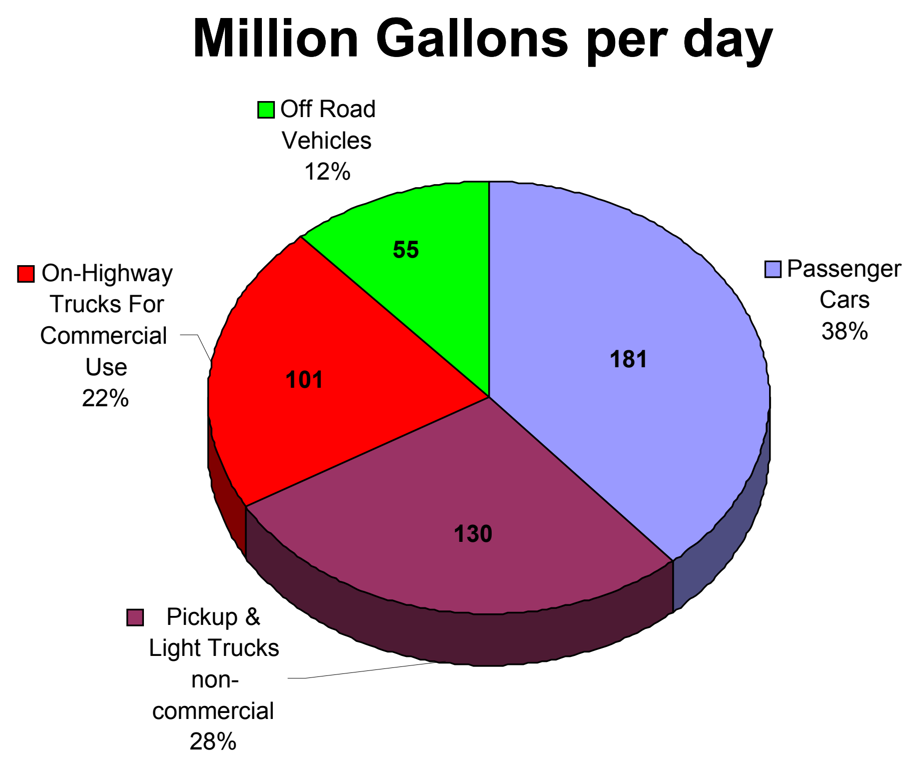


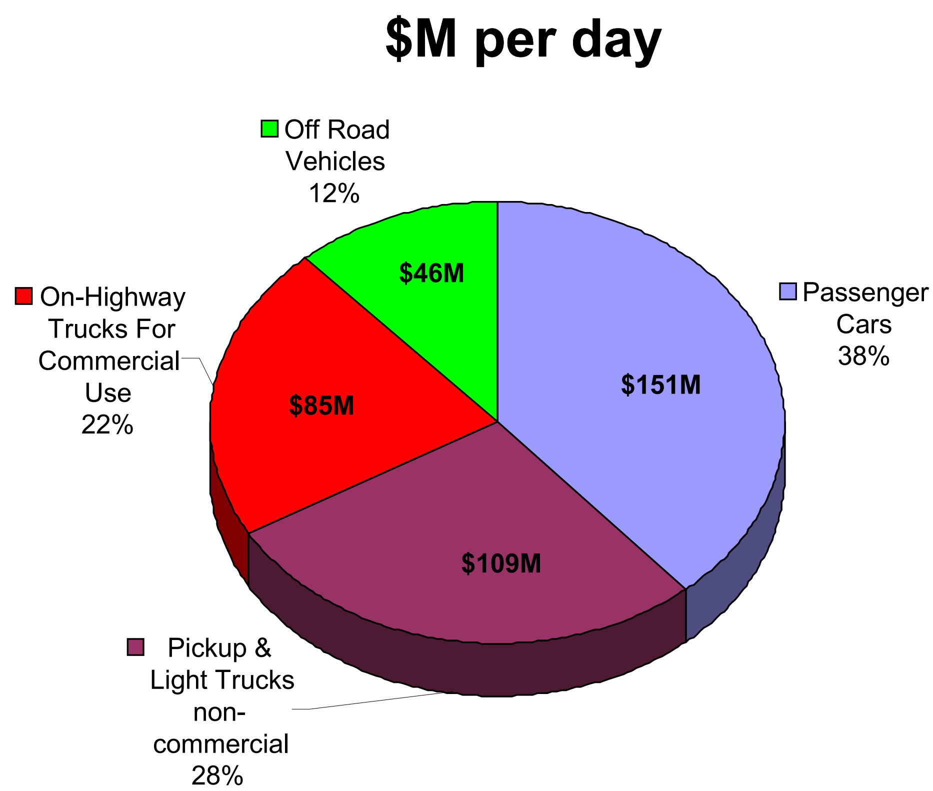
Class 8 Truck Engine Energy Audit

Motivation for Waste Heat Recovery from Diesel Engines

Large opportunity to improve fuel economy with early payback

Daily Fuel Consumption and Potential Opportunity

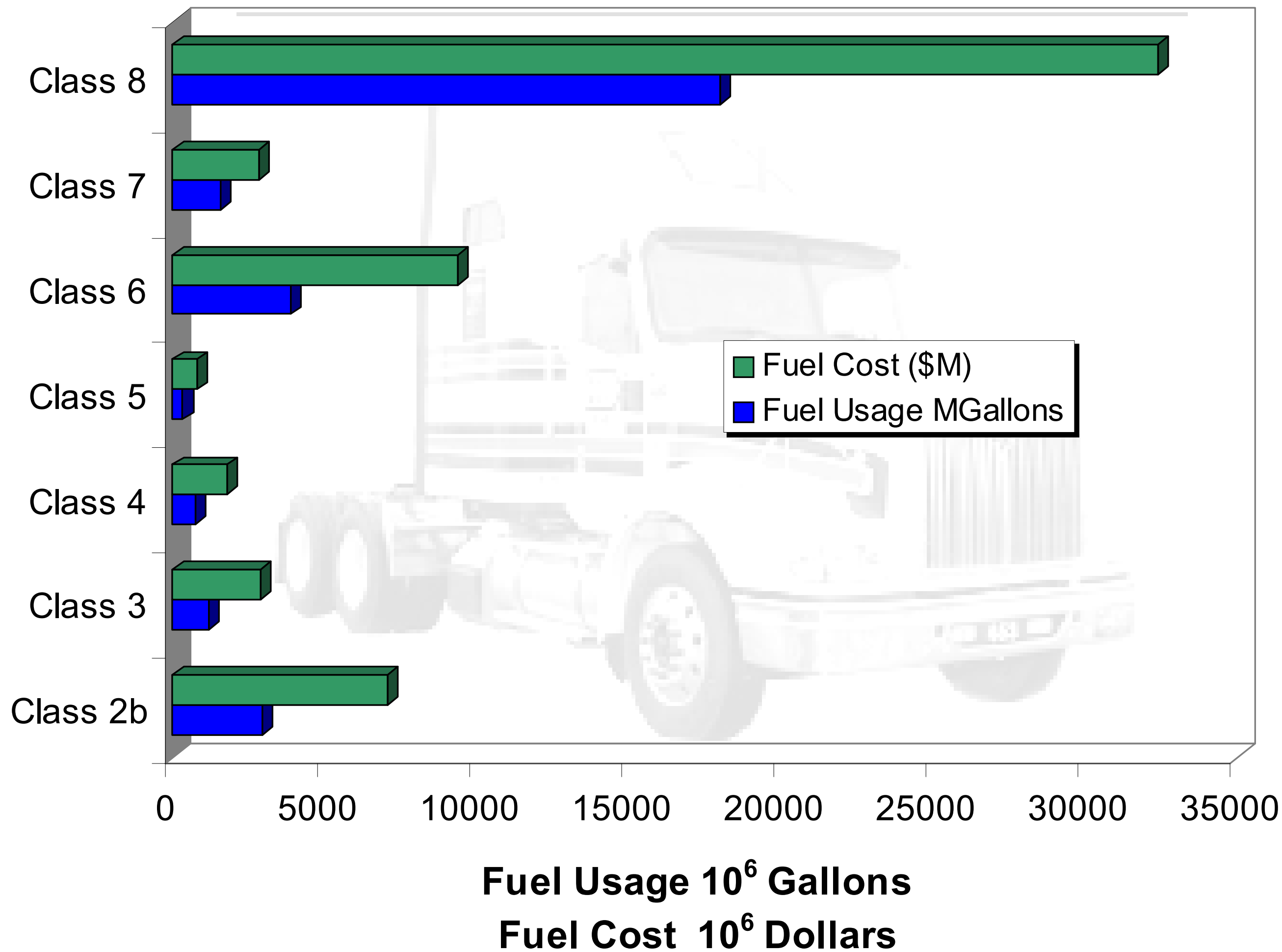




35% waste heat amounts to

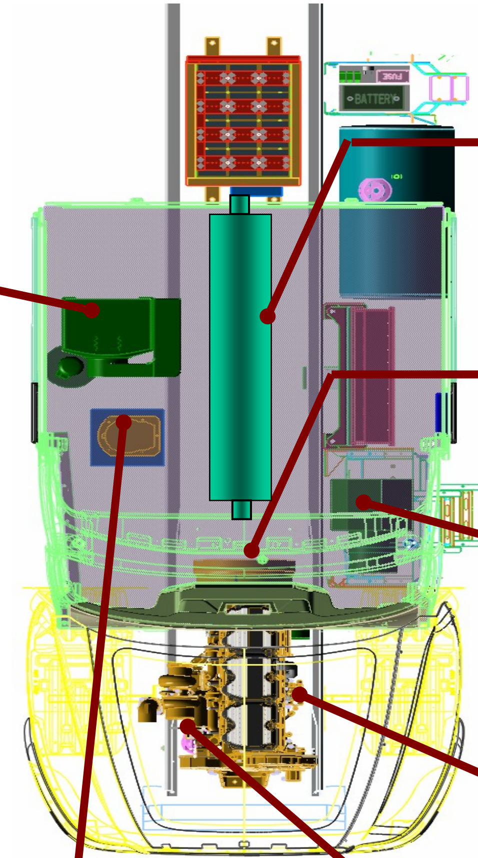
Motivation for Waste Heat Recovery from Diesel Engines

Class-8 diesel trucks represent significant portion of fuel consumed



Caterpillar's MorElectric Truck Platform

Effective "Decoupling" of Essential Power Systems from Engine Gear-Drive



Thermoelectric Generator (TEG)

Modular HVAC

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

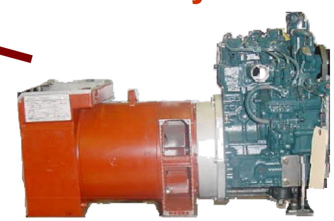
Starter/Generator Motor

Belt less engine, product differentiation, improve systems design flexibility, more efficient & reliable accessories

Shore Power and inverter

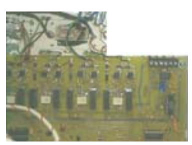
Supplies DC Bus Voltage from 120/240 VAC 5060 Hz Input and Supplies 120 VAC outlets from battery or generator power

Auxiliary Power Unit



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

Down Converter



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

Electric Oil Pump

Variable speed, higher efficiency

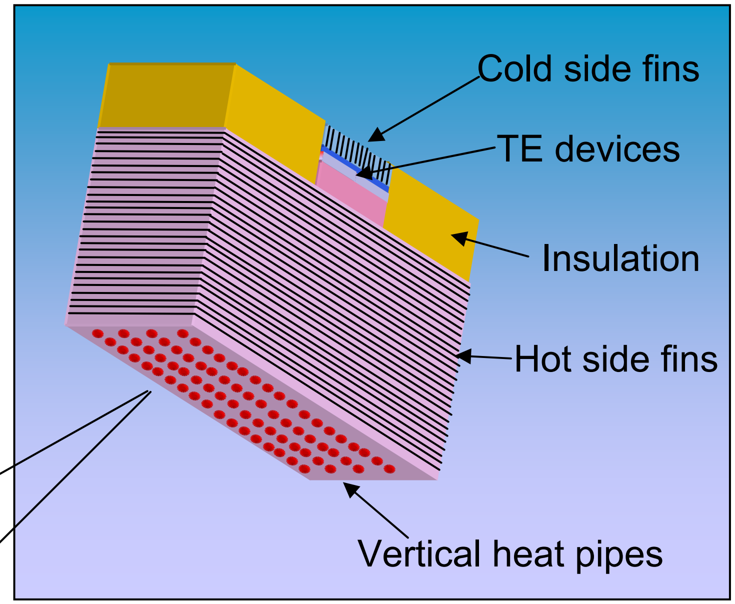
Thermoelectric Generator (TEG) Design

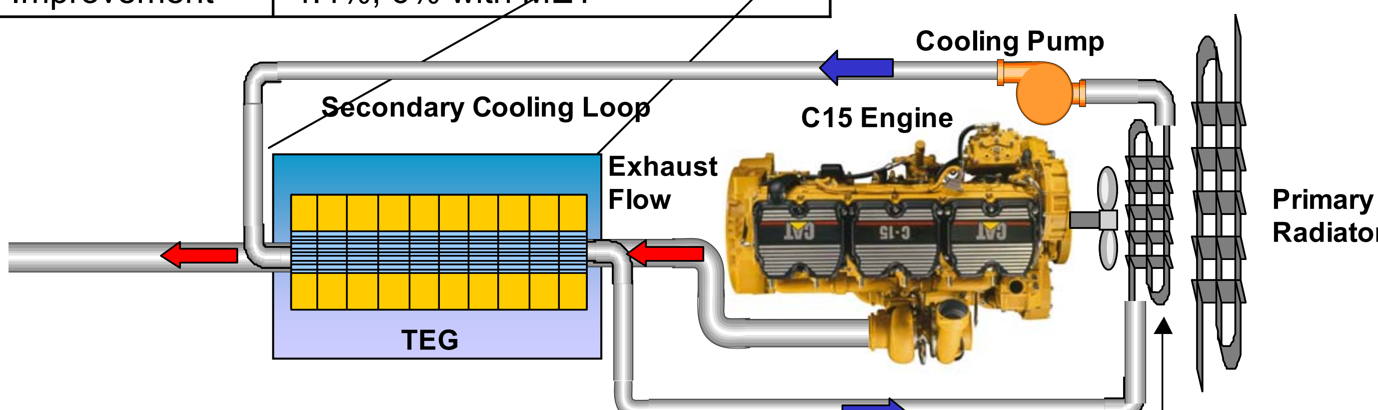
TEG heat exchanger design determined as part of Phase I of program

KEY FEATURES

TEG location	Under the truck chassis
Exhaust temperature	420ºC, direct to TEG
Heat Exchange Design	10-stage counterflow
Hot side delivery	Vertical heat pipes
Cold side rejection	Ethylene glycol / water coolant
TEG cold side temperature	50C, dedicated cooling loop
Δ T across TE Device	265ºC
Load design point	62%
Drive Cycle	Cruise
Thermal Power Extracted	67 kWatts (34% of heat flow out)
Conversion Efficiency	17%
TEG power output	12 kW
Fuel Economy Improvement	4.4%, 6% with MET

Thermoelectric Heat Exchanger





"Thermoelectric Generator" Patent Pending, Caterpillar Inc, filed October 2005

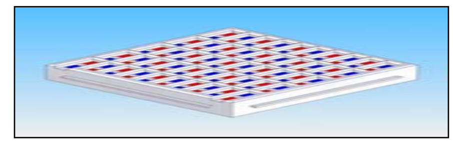
Thermoelectric Device Design

TEG device design determined as part of Phase I of program

KEY FEATURES

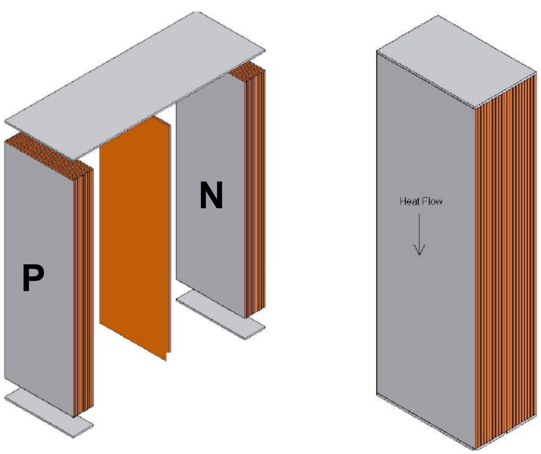
TE Material Form(s)	Up to 350C, QW films > 350C, QW nanocomposites
TE Material Composition(s)	Silicon Germanium; Boron Carbide
Substrate Material (if film)	Kapton™
Heat Flux through Device	25 W/cm^2
Specific Power (W/g)	~1.0 (Films), ~3.0 (Nanocomposites)

<u>TE Device (QW Nanocomposite)</u>



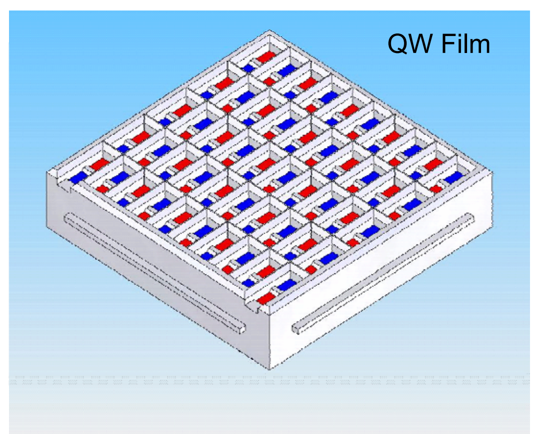
<u>QW Film P-N Couple</u>

Exploded View *Collapsed View*

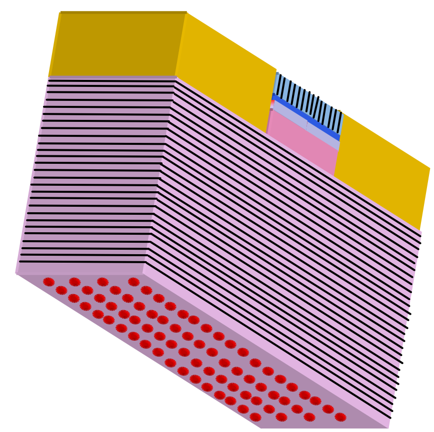


1.5 cm x 0.5 cm x 0.3 cm

<u>TE Device (QW Film)</u>



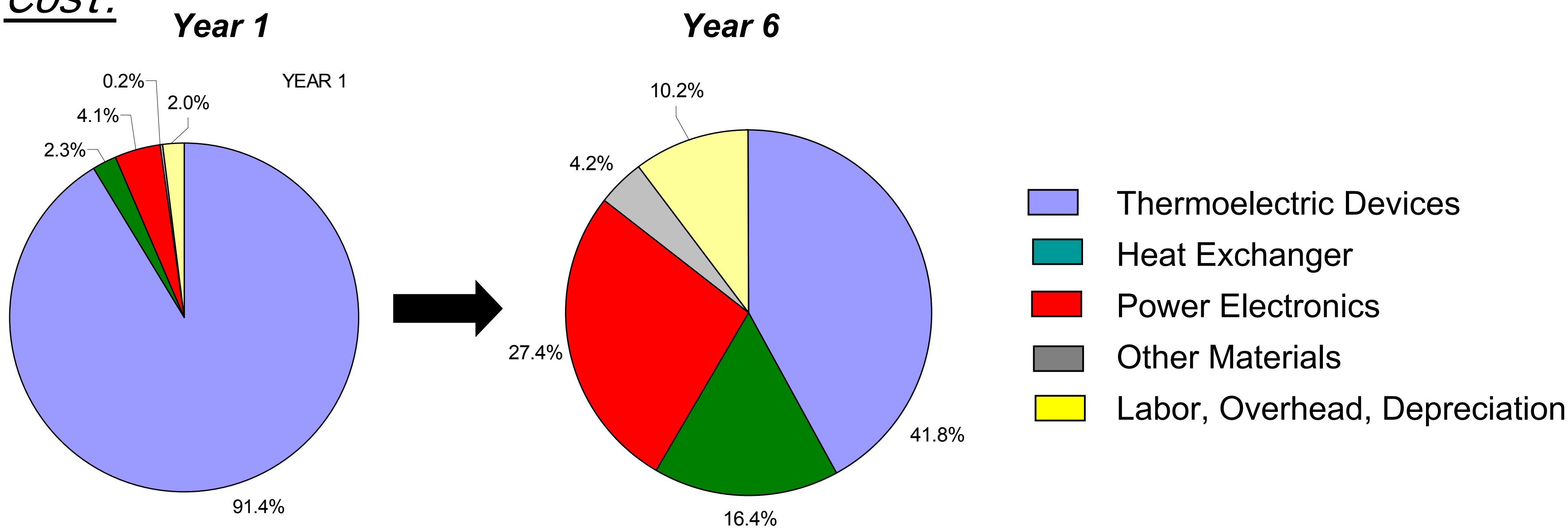
<u>TE Heat Exchanger</u>



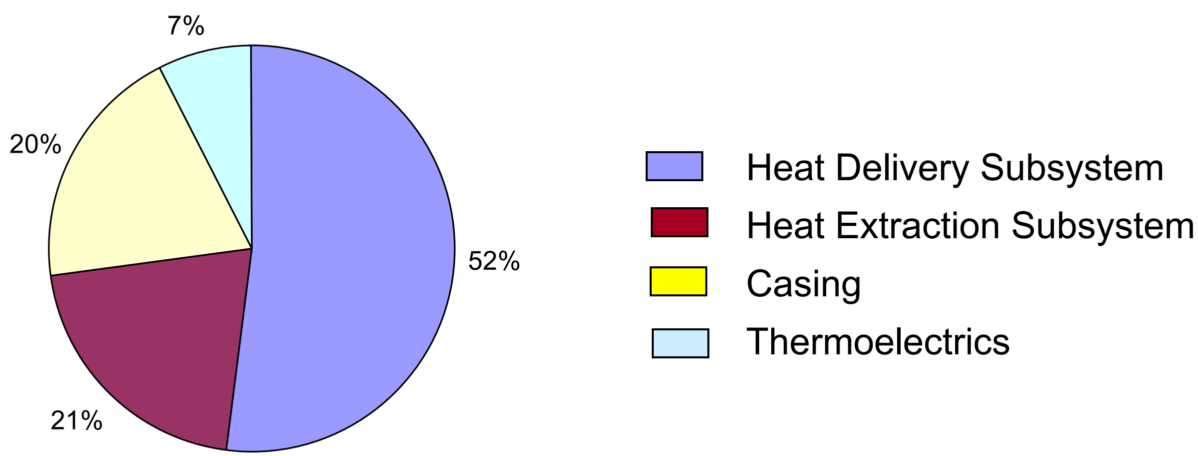
Cost and Weight Breakdowns

TE devices constitute the largest cost of the TEG system; Heat delivery system constitutes the largest weight

Cost:



Weight:

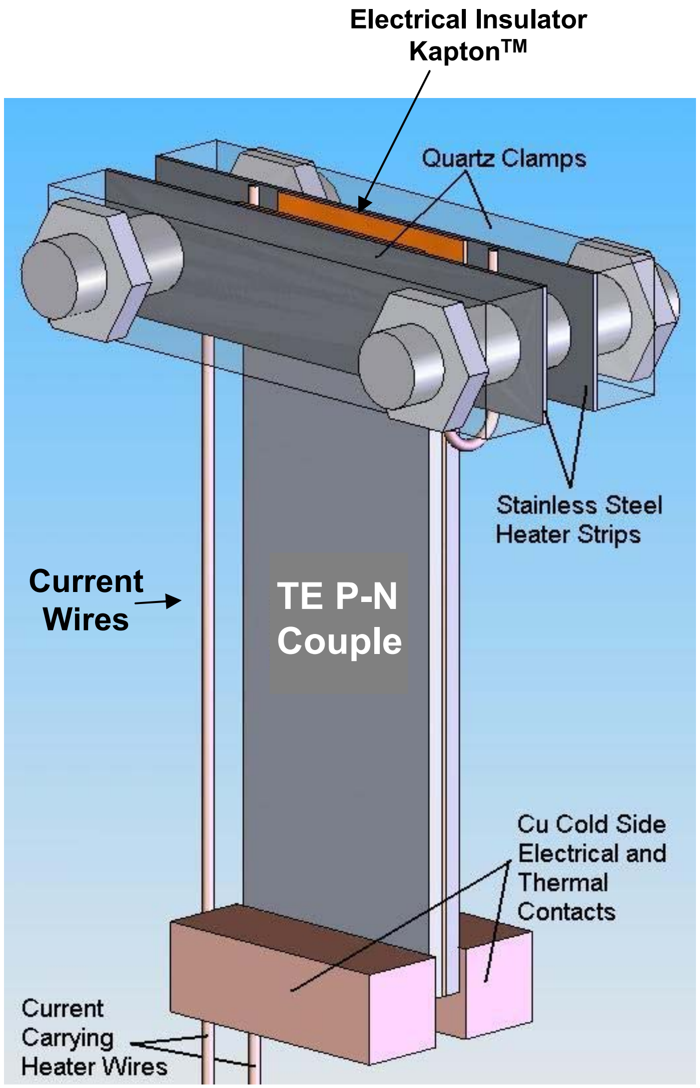


Phase II Objectives

- Determine thermal stability of the fabricated QW- type structures
- Identify and overcome key risks associated with the integration of thermoelectric materials into a subsystem level device
- Define requirements and design the TE device – TEG interface
- Develop a technical path for fabricating a prototype subsystem level heat management unit

Thermal-to-Electric Conversion Efficiency Rig

Inner wire heater design



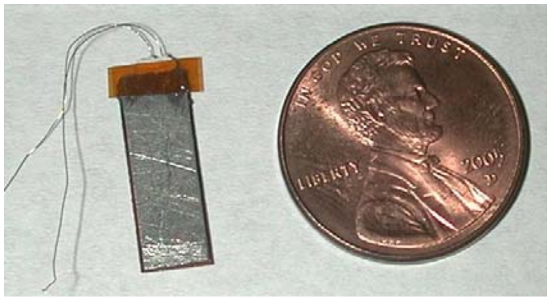
Inner Wire Heater Design

- Easy to assemble / reassemble
- Heat load applied directly to sample hot side, minimizing heat losses
- Heat losses can be predicted and accounted for
- Heater compressed against sample, aiding in thermal contact and transfer
- Minimizes electrical and thermal contact resistance

Thermal-to-Electric Conversion Efficiency Rig

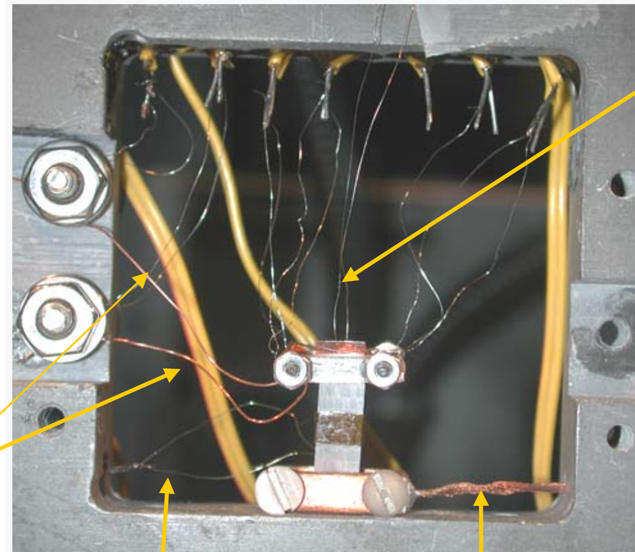
Baseline testing using bulk Bi_2Te_3 gives expected values for S, ρ and η

Baseline Bi_2Te_3 Sample



Sample Dimensions
15 x 5 x 5 mm^3

Conversion Efficiency Rig



T_{hot} = 169°C
T_{cold} = 35°C
ΔT = 134°C
ZT = 0.685

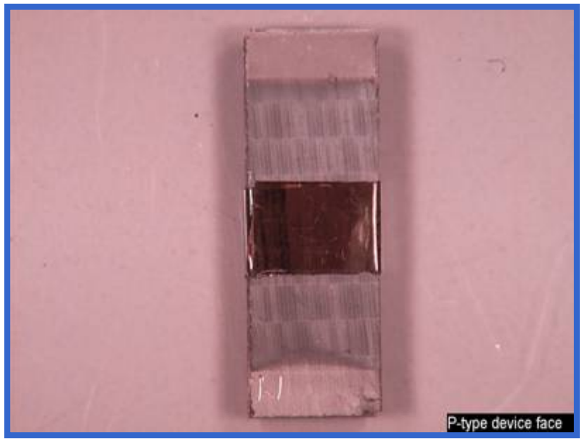
Baseline Test Results for P-N Couple

		Literature	Experimental	Percent Difference
Conversion Efficiency	η (%)	4.6	4.5	2.2
Seebeck Coefficent	S (μV/K)	365	328	10.7
Electrical Resistivity	ρ (mohm-cm)	1.33	1.30	1.9

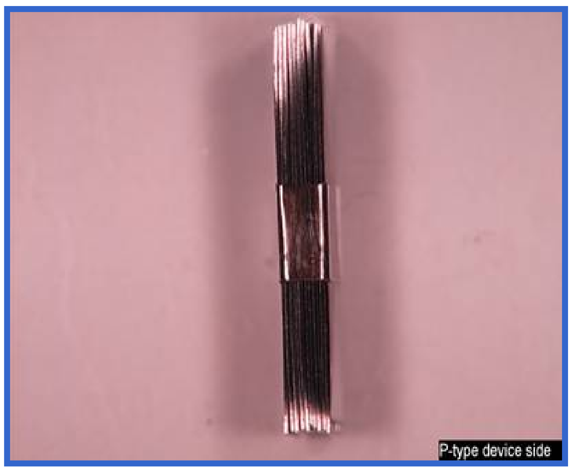
Fabrication of QW film couple for testing

10 segments of each P and N make up the TE couple

Face view



Side view



QW Film P-N Couple

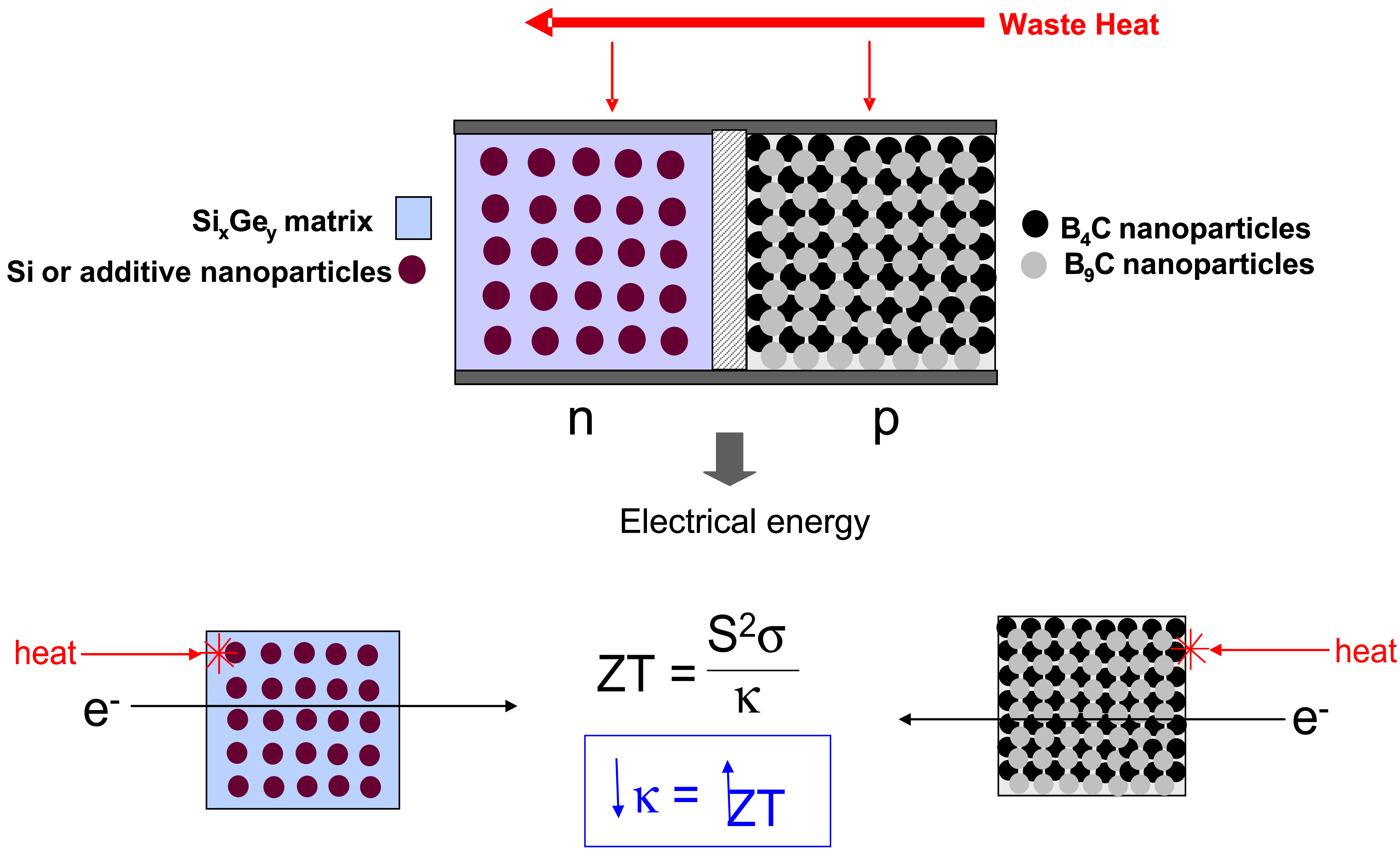
- P and N films deposited on Kapton™
- Deposition area 1.25” x 1.25”
- 12 microns thick
- Deposited film laser sectioned into 12 smaller segments: 1.5 x 0.5 cm^2
- 10 segments of each P and N film stacked to form the couple
- Films masked and contacts made via magnetron sputtering (Mo, Ag)
- Kapton spacer placed between P and N stack

Status To Date

- First QW film couple built / Testing underway
- Two additional QW film couples being built for test

Fabrication of Heterogeneous Nanocomposites

Material Approach



Fabrication of Heterogeneous Nanocomposites

N-type Silicon Germanium

Fabrication Approach

2 fabrication approaches being pursued in parallel:

1. Mechanical mixing of Si nanoparticles into coarse $Si_{0.8}Ge_{0.2}$ powder matrix
   → **$Si/Si_{0.8}Ge_{0.2}$**

2. Precipitation of insoluble additive phase from molten mixture of silicon and germanium
   → **$X/Si_{0.8}Ge_{0.2}$**

Status to Date

- Mixing technique optimized to give high dispersion of nanoparticle phase (> 90%) into coarse powder
- Phase precipitation of select additives observed, however, at micron scale
- Initial ZT testing underway

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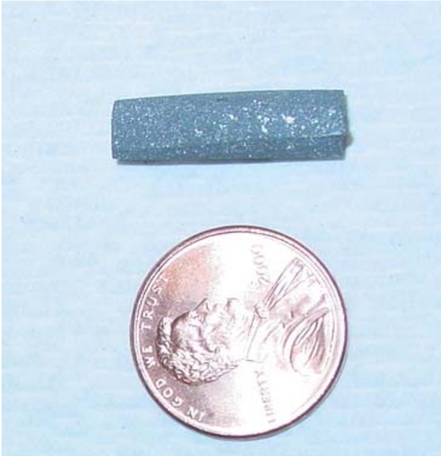
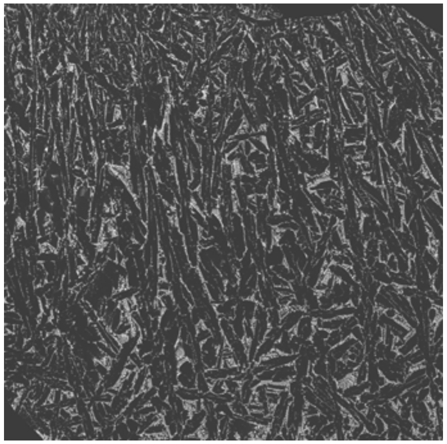


Compacted mixture of Si / $Si_{0.8}Ge_{0.2}$

(2)



Scanning Electron Micrograph of $X-Si_{0.8}Ge_{0.2}$ Composite

Fabrication of Heterogeneous Nanocomposites

P-type Boron Carbide

Fabrication Approach
2-step process developed:

1. Thermal decomposition of phenolic resin with amorphous boron creates nanostructured boron carbide; material ground and sieved prior to densification via hot pressing

2. Moderate crystal growth (still nanostructured) at higher temperatures during hot press compaction step

→ **B_4C/B_9C**
→ **B_7C**

Status to Date

- Several composite panels fabricated from various starting formulations targeting different product stoichiometries

- Nanostructured B_4C, B_7C and B_9C formed

- Initial ZT testing underway

Nanostructured boron carbide

Ground / Sieved
boron carbide powder

Hot pressed
boron carbide panel

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Fuel, Fuel Cost and Fuel Efficiency Savings

Caterpillar On-Highway Truck