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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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
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

Million Gallons per day
- Off Road Vehicles: 12%
- On-Highway Trucks For Commercial Use: 22%
- Pickup & Light Trucks non-commercial: 28%
- Passenger Cars: 38%

$M per day
- Off Road Vehicles: 12%
- On-Highway Trucks For Commercial Use: 22%
- Pickup & Light Trucks non-commercial: 28%
- Passenger Cars: 38%

35% waste heat amounts to

$46M
$151M
$109M
$85M
$101
$130
$181
$55
Motivation for Waste Heat Recovery from Diesel Engines

Class-8 diesel trucks represent a significant portion of fuel consumed.
Caterpillar’s MorElectric Truck Platform

Effective “Decoupling” of Essential Power Systems from Engine Gear-Drive

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

Shore Power and inverter
- Supplies DC Bus
- Voltage from 120/240 VAC 50/60 Hz Input and Supplies 120 VAC outlets from battery or generator power

Down Converter
- 12 V Battery from DC Bus

Compressed Air Module
- Supplies compressed air for brakes and ride control

Thermoelectric Generator (TEG)
- Supplies DC Bus Voltage when engine is not running, fulfills hotel loads without main engine overnight

Starter/Generator Motor
- Belt less 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 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
Thermoelectric Generator (TEG) Design

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

### KEY FEATURES

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

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**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**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE Material Form(s)</td>
<td>Up to 350°C, QW films</td>
</tr>
<tr>
<td></td>
<td>&gt; 350°C, QW nanocomposites</td>
</tr>
<tr>
<td>TE Material Composition(s)</td>
<td>Silicon Germanium; Boron Carbide</td>
</tr>
<tr>
<td>Substrate Material (if film)</td>
<td>Kapton™</td>
</tr>
<tr>
<td>Heat Flux through Device</td>
<td>25 W/cm²</td>
</tr>
<tr>
<td>Specific Power (W/g)</td>
<td>~1.0 (Films), ~3.0 (Nanocomposites)</td>
</tr>
</tbody>
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QW Film P-N Couple

**TE Device (QW Nanocomposite)**

**TE Device (QW Film)**

TE Heat Exchanger

1.5 cm x 0.5 cm x 0.3 cm
Cost and Weight Breakdowns

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

### Cost:

**Year 1**
- Thermoelectric Devices: 91.4%
- Heat Exchanger: 2.3%
- Power Electronics: 4.1%
- Other Materials: 0.2%
- Labor, Overhead, Depreciation: 2.0%

**Year 6**
- Thermoelectric Devices: 41.8%
- Heat Exchanger: 16.4%
- Power Electronics: 10.2%
- Other Materials: 7%
- Labor, Overhead, Depreciation: 4.2%

### Weight:

- Heat Delivery Subsystem: 52%
- Heat Extraction Subsystem: 21%
- Casing: 20%
- Thermoelectrics: 7%
Phase II Objectives

- Evaluate performance of QW films on Kapton
- Evaluate cost-effective fabrication approaches for high efficiency TE materials
- 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
**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$_2$Te$_3$ gives expected values for $S$, $\rho$ and $\eta$

Baseline Bi$_2$Te$_3$ Sample

Sample Dimensions
15 x 5 x 5 mm$^3$

Conversion Efficiency Rig

Current Wires

Hot side thermocouple

Hot side
$T_{\text{hot}} = 169^\circ\text{C}$

Cold side
$T_{\text{cold}} = 35^\circ\text{C}$

Sample Voltage

$\Delta T = 134^\circ\text{C}$

ZT = 0.685

Baseline Test Results for P-N Couple

<table>
<thead>
<tr>
<th></th>
<th>Literature</th>
<th>Experimental</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conversion Efficiency</td>
<td>$\eta$ (%)</td>
<td>4.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Seebeck Coefficient</td>
<td>$S$ (\mu V/K)</td>
<td>365</td>
<td>328</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>$\rho$ (mohm-cm)</td>
<td>1.33</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Fabrication of QW film couple for testing

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

**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 cm²
- 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

\[ ZT = \frac{S^2\sigma}{\kappa} \]

\[ \kappa = \frac{1}{ZT} \]
Fabrication of Heterogeneous Nanocomposites

\textit{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  
   \[ \rightarrow \text{Si/Si}_{0.8}\text{Ge}_{0.2} \]

2. Precipitation of insoluble additive phase from molten mixture of silicon and germanium  
   \[ \rightarrow \text{X/Si}_{0.8}\text{Ge}_{0.2} \]

**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
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

   \[ \rightarrow \text{B}_4\text{C}/\text{B}_9\text{C} \]

   \[ \rightarrow \text{B}_7\text{C} \]

**Status to Date**

- Several composite panels fabricated from various starting formulations targeting different product stoichiometries
- Nanostructured B\(_4\)C, B\(_7\)C and B\(_9\)C formed
- Initial ZT testing underway
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Fuel, Fuel Cost and Fuel Efficiency Savings

Caterpillar On-Highway Truck

**101 Million gallons / day consumed** → **annual** → **36,865 Million gallons / year consumed**

35% not utilized

12,903 Million gallons / year not utilized → 38,708 Millions $ / year lost

$3.00 / gallon

34% extracted to TEG

4,387 Million gallons / year (TE processed)

18% converted to electrical energy

249 kWatt Engine Horsepower

196 kWatt thermal @ 62% load

34% extracted to TEG

67 kWatt thermal @ 62% load

18% converted to electrical energy

12 kWatt electrical @ 62% load

12 kW / 249 kW = 4.8%

= 4.4%

after accounting for fan and pump power

790 Million gallons / year recovered

2,369 Millions $ / year recovered

$3.00 / gallon

6.12% of wasted fuel and dollars recovered