Thermoelectric Energy Harvesting with Carbon Nanotube Systems

Presented by Thomas C. Van Vechten, Ph.D.
At the New England Nanomanufacturing Summit at UMass Lowell, June 2010
Outline

• Carbon Nanotubes
  – Synthesis
  – Applications

• Energy

• Thermoelectrics
  – History
  – Physics

• CNT based Thermoelectrics
  – Material Progress
  – Fabrication Technologies
Carbon Nanotubes

Smalley

UNH
Synthesis

Continuous Nanotube Growth

Fuel

Reaction Gas
 Formats

Sheet 132 cm by 234 cm

2 Kilometers of 4 ply Cable
Safety of Articles

Products
DO NOT SHED

Confirmed by outside testing of lots of raw sheets and yarns to 1nm sensitivity.

No carcinogenic catalysts.

Products generally coated prior to shipping for increased handling safety.
Light-Weight Performance Materials:

- Electrical Conductors
- Structural Composites
- Thermal Management

Pre-Preggs Armor

- EMI Shielding
- Antennas
- Data Cables
- Power Cables
- Windings

Heaters
De-icers

Heat Spreaders

Solar Thermoelectric Waste Heat

Thermoelectrics
Waste Energy Availability

On average, 44% of fuel’s energy is exhausted through radiator, a tens of kWs heat flux from ~90 °C to air temperature.

In the U.S. total loss equivalent to ~ 40 Billion Gallons per Year.

DOE
History of Thermoelectric Applications
In 1826 T. J. Seebeck Discovered:

Voltage  \[ V = \alpha \Delta T \]

Thermoelectrics
p-type Semiconductors have opposite sign:

\[ T_C < T_H \]

p-type

n-type
Power Generation

Heat In

Heat Out

Electrical Work
Done
## Generators: Commercial and NCTI CNT Experimental

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value at $\Delta T$ of 200 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power / Mass</td>
<td>0.166 W/g</td>
</tr>
<tr>
<td>Power / Volume</td>
<td>0.665 W/cm³</td>
</tr>
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Ranking of Thermoelectric Generators / Materials

Dimensionless Figure of Merit, ZT

\[ ZT = \frac{\alpha^2 T}{\rho \kappa} \]

- Power per Unit Weight
- Power per Unit Volume
- Power per Area
- Efficiency
Electron Band Structure

\[ Z\bar{T} = \frac{\alpha^2\bar{T}}{\rho\kappa} \]

- Good Seebeck Semiconductor-Doped
- Good Electrical Resistivity Metal
- Good Thermal Conductivity Insulator
CNT Surface Doping – Charge Carriers

Polyethyleneimine (donor)  Tetracyanoquinodimethane (acceptor)

Dai
### ZT Results so far.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bi$_2$Te$_3$</th>
<th>CNT Felt</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seebeck Coefficient</td>
<td>195</td>
<td>80</td>
<td>μV/K</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>$1 \times 10^{-5}$</td>
<td>$4 \times 10^{-5}$</td>
<td>Ωm</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>2</td>
<td>2</td>
<td>W/mK</td>
</tr>
<tr>
<td>ZT</td>
<td>0.60</td>
<td>0.011</td>
<td>none</td>
</tr>
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</table>
Print and Fold Technology
Self Supporting, Felt Only Thermoelectric Device
Deploy for Maximum $\Delta T$
# Results and Goals

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<tr>
<th>Parameter</th>
<th>Commercially Available</th>
<th>CNT Current</th>
<th>CNT Target</th>
</tr>
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<tr>
<td>$\Delta T = 200$ K</td>
<td></td>
<td></td>
<td></td>
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</tr>
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<td>Dollars / Watt</td>
<td>$5 / W</td>
<td>$133 / W</td>
<td>$1 / W</td>
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<tr>
<td>ZT</td>
<td>0.6</td>
<td>0.01</td>
<td>0.2</td>
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</table>
Conclusions

- Lots of waste energy and “low grade” heat is available to harvest.
- Wide dispersal of heat in space and time coupled with low conversion efficiency has in the past confined thermoelectrics to niche markets.
- Improved CNT materials can expand these opportunities.
- Carbon Nanotube based Thermoelectrics may be competitive in applications very sensitive to power to weight.
- Printing and folding fabrication of abundant raw material means price can be competitive with semiconductor technologies, if CNT manufacturing becomes large scale.
- Significant improvements in electrical conductivity and Seebeck coefficient are an object of our research at Nanocomp.