Review of Interests and Activities in Thermoelectrics

DoE Thermoelectrics Applications Workshop: Jan 3-6, 2011

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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OUTLINE

- Army Rationale
- Thermoelectric Power Generation
  - Soldier power
  - UAV power
- Materials Research
  - Bulk
- Thermoelectric Cooling
  - DARPA/MTO: ACM
  - NEA device idea
  - Where would these help?
- Summary
• 3 x $10^5$ barrels per Day!

• JP-8:
  • Base cost $3$/Gallon
  • “Fully burdened cost” $42$/Gallon
  • Human cost 1 US casualty per 24 trips
• 3 x 10^5 barrels per Day!

• JP-8:
  • Base cost $3/Gallon
  • “Fully burdened cost” $42/Gallon
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Batteries require **more supply trips**!

POINT: Power-Generation opportunities that ARL is looking at:
  1. reduce batteries (soldier power)
  2. reduce demand (UAV)
OEF – AFGHANISTAN (72 Hour Mission)

Base Approach Load = 77 lbs
Max Approach Load = 170 lbs

Total: 7 types of batteries, 70 batteries, 16 lbs; 9.17 watts
1. Direct Power Generation

**Goal:**
- Develop small light weight power sources for the Warfighter that maximize specific energy for Soldier systems and sensors.
- High efficiency thermoelectrics could compete with fuel cells, while likely using logistic fuels.

**Research Areas:**
- Burner development
- TE materials
- TE packaging / interconnects
- Thermal management
- Balance of plant (pumps, valves, etc)

\[
\text{Energy Density} = \frac{900 \text{ W-hr/kg}}{12,000 \text{ W-hr/kg}} \times 15\% \times 600 \text{ W-hr/kg} \times 10\% \times 300 \text{ W-hr/kg} \times 5\% \times \text{System Overhead}
\]
Total weight (14.2 kg)
Main payload is imaging pod (intel)
UEL AR 741 Wankel (air-cooled)
  -28 kW power, 50 kW max (* 1:1)
28 Volt/900-1500 We generator (3.5 kg)

Say…only 1/3 goes to heat…

@28 kW, then 10 kW heat
  -5% TE then 500 We
  -10% TE then 1000 We
  -15% TE then 1500 We

@50 kW, then 16 kW heat
  -5% TE then 800 We
  -10% TE then 1600 We
  -15% TE then 2400 We

Opportunity? weight, cost, reliability, performance
BULK
Basic theory:

- Efficiency $\propto f(1/\kappa)$

As $\kappa \downarrow$...efficiency $\uparrow$

Low $\kappa$ bulk (450º C)

- $\text{(Tl,Bi)Te}_2 \sim \text{PbTe}$

"Pseudo-PbTe"


$$Q_\kappa = \kappa \left( \frac{A}{\ell} \right) \left( \Delta T_{ss} \right)$$

- Room-Temp. $\kappa \sim 0.6 \text{ W/m-K}$. 3X better than PbTe
TE Cooling
Active Cooling Modules

DARPA/MTO: ACM
(Kenny → Bar-Cohen)

- PROG: Develop high-COP devices
- ARL: Revolutionary Improvement in Contact Resistivity

Metal (Bi,Sb)$_2$(Se,Te)$_3$

\[ W_t = \sqrt{\frac{2\varepsilon(E_b - kT)}{qN_d}} \]

\[ W_t \propto R_c \propto \frac{1}{\sqrt{N_d}} \]

Impact of Contact Resistivity on COP
- Intrinsic Material ZT = 3; Film Thickness = 16 µm
- \( T_{heat} = 313K, \Delta T = 29K, T_{source} = 300.9K \)
- Film Resistivity = 0.8e-30hm·cm
- Film Resistivity = 1.0e-30hm·cm
- Film Resistivity = 1.2e-30hm·cm

Contact Resistivity (Ohm·cm$^2$)

COP

\( N_d (/cm^3) \)

\( R_c \cdot \Omega \cdot cm^2 \)

\( N_d (/cm^3) \)
Thermodynamics:

\[ Q_c = -(\alpha_n + \alpha_p)TI + (\kappa_n + \kappa_p)\Delta T(A/l) + \frac{1}{2}I^2(\rho_n + \rho_p)(1/A) \]

\[ \Delta T_{\text{max}} = \frac{1}{2} ZT^2 \]

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

Anything else that can be done?
“What if…. ”
- we incorporate a gap

1. Heat cannot be conducted
2. Current cannot flow

Is there something that we can do to induce the electrical current to cross?
“Negative Electron Affinity”
- Phenomenon in p-GaAs
- Surface treatment → severe band-bending
- e⁻ source at Stanford Linear Accelerator (SLAC)

**Key:** Cs metal on GaAs
“Negative Electron Affinity”

- How would this work?
- Incorporate GaAs e⁻ emitter within gap

**Physics:**

Child’s Law: current density across gap:

\[ J = K \frac{V_d^{3/2}}{d^2} \]

where

- \( J \) = current density
- \( d \) = gap spacing
- \( V_d \) = Potential across \( d \)
- \( K \) is a constant = \((4/9) \varepsilon_0 (-2q/m)^{1/2}\)

10 V ~ “\( d \)” in mm range
“Negative Electron Affinity”

- Role for thin-film TE in practical devices
- Maybe:
  - (Bi,Sb)$_2$(Se,Te)$_3$/GaAs NEA Cooler
  - PbTe/GaAs NEA Power

At this stage:
Form Analysis
Risk is OK
Thermoelectric Cooling

Unmanned Assets (UAV/UGV):
• High-performance IR would be nice
• High-performance IR needs coolers
• SADA is…

<table>
<thead>
<tr>
<th>Attribute</th>
<th>TE 6-stage</th>
<th>SADA (Stir.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>7 cm³</td>
<td>986 cm³</td>
</tr>
<tr>
<td>Weight</td>
<td>100 g</td>
<td>2500 g</td>
</tr>
<tr>
<td>Cost</td>
<td>$800</td>
<td>$10,000</td>
</tr>
<tr>
<td>$\Delta T_{\text{max}}$</td>
<td>133 K</td>
<td>235 K</td>
</tr>
<tr>
<td>Input Power</td>
<td>22.7 Watts</td>
<td>20 W (60 W_{\text{max}})</td>
</tr>
<tr>
<td>Heat Load</td>
<td>0.58 Watts</td>
<td>1.5 Watts</td>
</tr>
<tr>
<td>MTTF</td>
<td>unlimited</td>
<td>~ 10,000 Hrs.</td>
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</tbody>
</table>
Funding:

MDA:

Army I²WD: Passive infrared threat warning

Collaboration:

RTI
Brimrose
Northrop-Grumman
Summary

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