U.S. Army Research, Development and Engineering Command

Thermoelectric Materials and Device Research at the Army Research Laboratory

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TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

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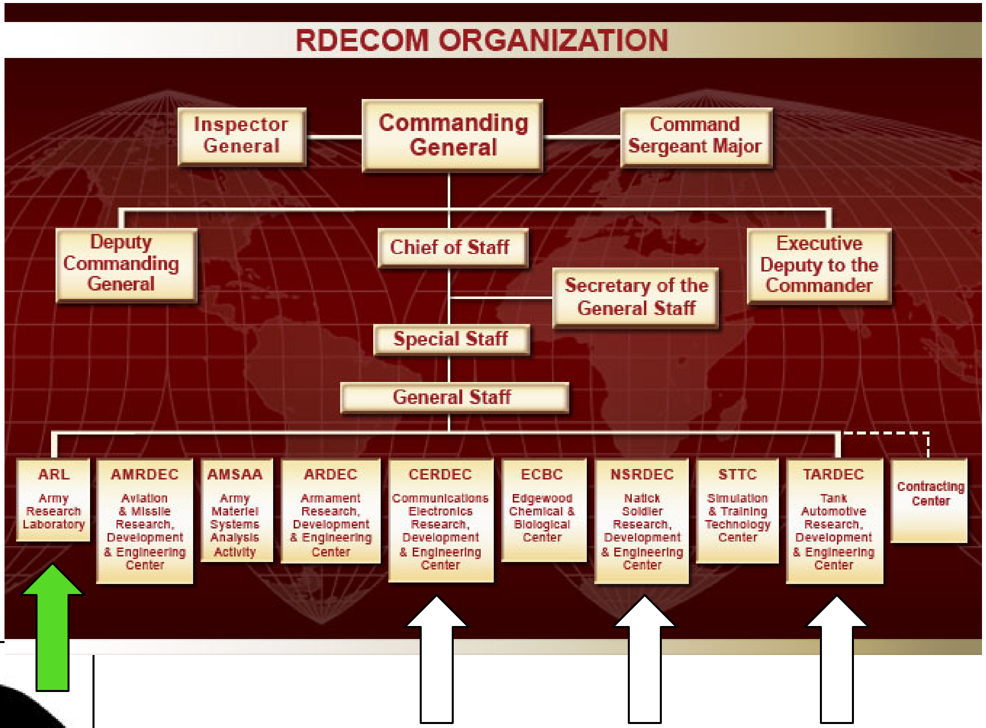
Outline

- Army Interest and Applications
- External Program (RTI)
- Internal Programs
  - *Cooling Devices*
  - Remote Power Devices
  - Thin-Film Thermoelectric Materials
  - Low-Parasitic TE measurments
  - Seedling
- Four Focus Areas - Partnering
- Summary

Army Interests and Applications

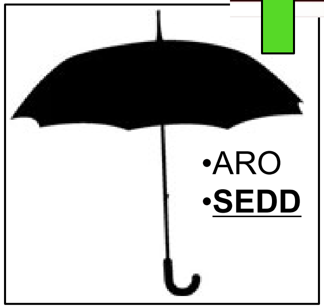
- **ARL is the Army's R&D lab**

✓University Outreach
✓Fundamental Research
✓Applied Research



ARL Directorates:

C4ISR
Human Dimension
Vehicle Technology
Sensors & Electron Devices
Survivability & Lethality Analysis
WMRD
ARO



Overlap - DOE Freedom Car

- Army Systems (usually) don't:
  - access cold sea water to reject heat
  - have access to deep space to reject heat (sometimes can provide robust air flow)
  - offer choice of fuel (**JP-8**)

- Army considers options:
  - Solar cells
  - Fuel cells
  - Batteries
  - detectability

<u>SEDD INTEREST:</u>

- TE Power Generation:
  - Direct generation for soldier power (rchg batteries)
  - Fuel utilization for vehicles
  - Energy scavenging for small sensors

- TE Cooling:
  - Cooling of infrared detectors
  - Temperature control for emitters

External Program

“High-Performance Thermoelectric Energy Conversion and Energy Scavenging Demonstration”

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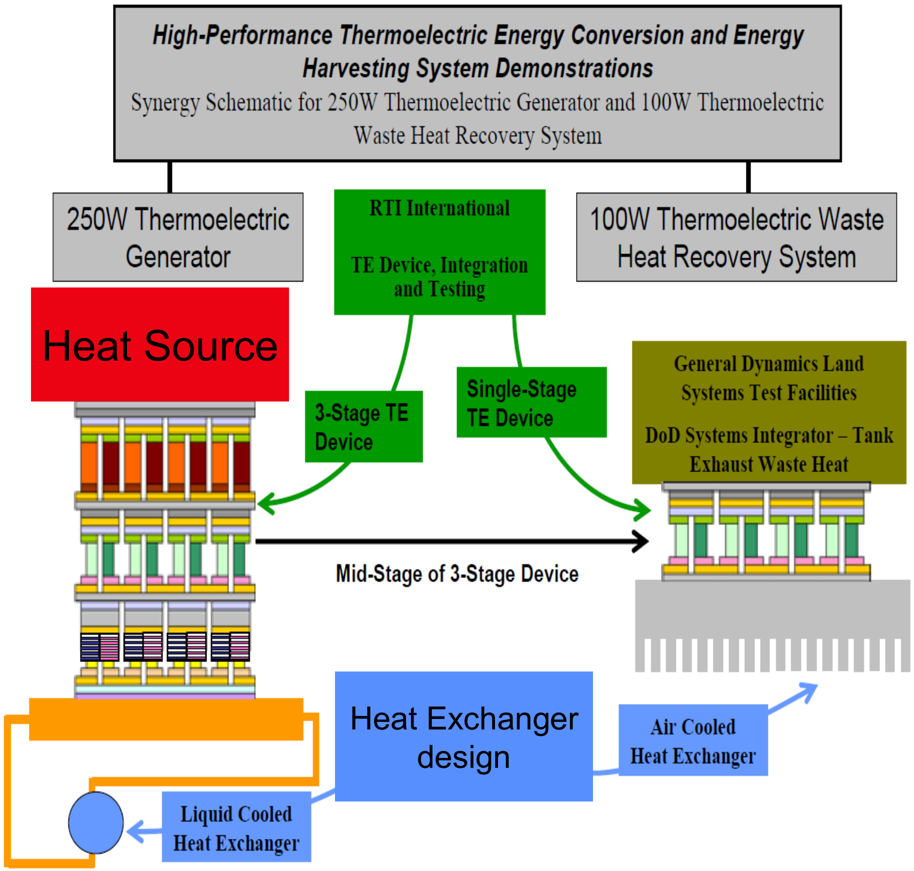


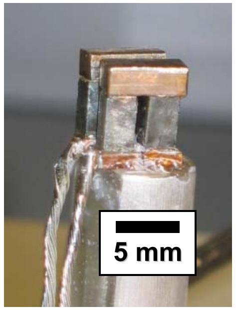
- **Goals**
  - ➢ **Y1: 3-stage 50 W_e (15%)**
    1-stage 25 W_e (collection)
  - ➢ **Y2: 3-stage 250 W_e (15%)**
    >exchanger integration
    1-stage 100 W_e
    <u>Design 1kWatt</u>

GENERAL DYNAMICS
Strength On Your Side®

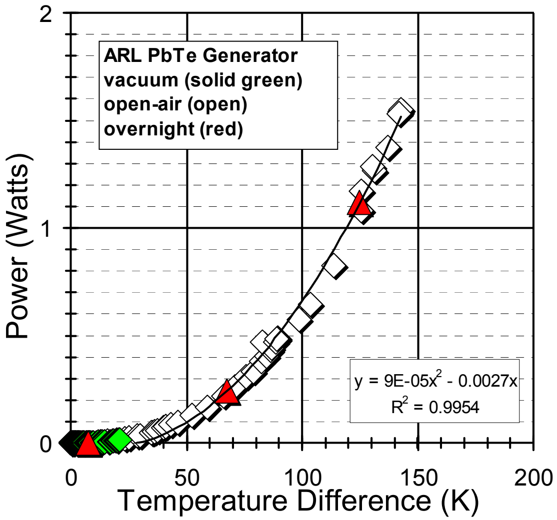
- **Hard Deliverables**
  - ➢250 W_e unit demo from fuel burner
  - ➢100 W_e unit from exhaust or Army utilities
  - ➢Path to scale to 1 kilowatt for widespread use

Internal Work

- **Small Devices for Remote Power**



  - Goal: scalable (tandem), cost-effective, covert, small
  - Device Fabrication:
    - PbTe
    - Burner **(Ivan Lee)**
    - Heat-sink **(Brian Morgan)**
  - State-of-the-art performance
    - >2 Watts/cm^2
  - **Issues:**
    - **HJ electrical contacts**
    - **Better materials**
    - **Thermal management (heat-sink)**



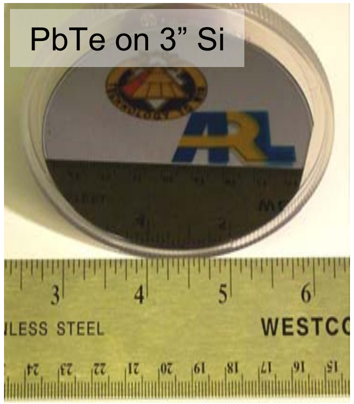
• Thin-Film TE Materials and Devices (Morgan)

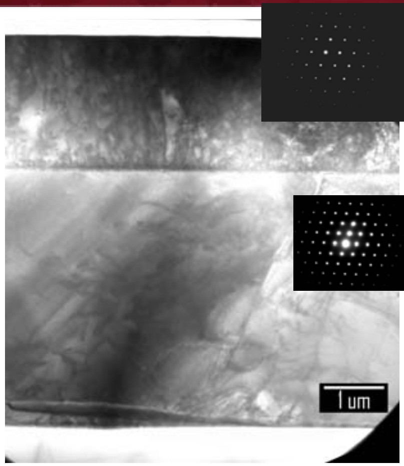
- Goal: MEMS integration (UGS)
  - *–MBE/nanostructuring*
  - *–Low-power levels*
  - *–Infrared cloaking (?)*

- Single-crystal IV-VI (PbTe) and V-VI (Bi_2Te_3) epilayers on silicon

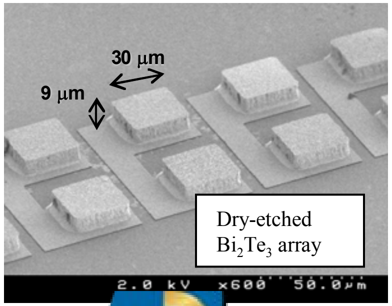
- Shown:
  - –Excellent crystallinity (Journ. Elec. Mat.)
  - –Doping
  - –Good TE properties
  - –Dry-etching

- **Issues:**
  - **–Thermal Expansion**
  - **–Device Fabrication (metals)**
  - **–Contact resistance**





TEM PbTe/PbSeTe NDSL *unpublished*: Moiré fringe analysis of nanodots, 2003



B. Morgan
P.J. Taylor

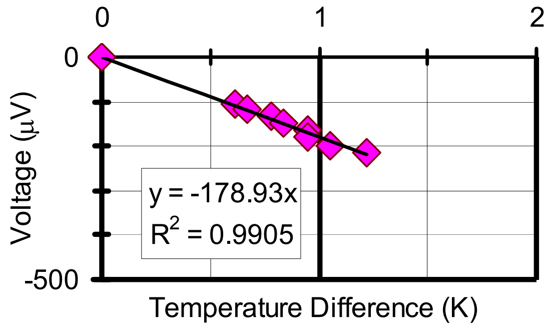
- **Thermoelectric Measurements**

BULK

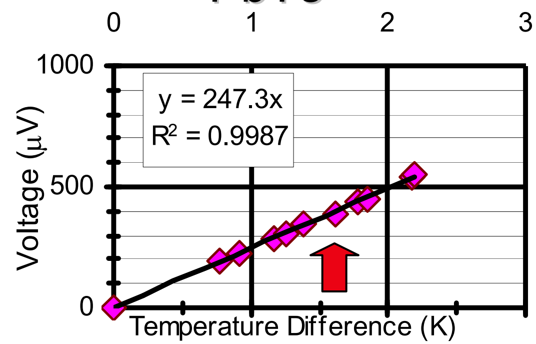
Goal:
- -Simplify
- -parasitics
- -device fab.

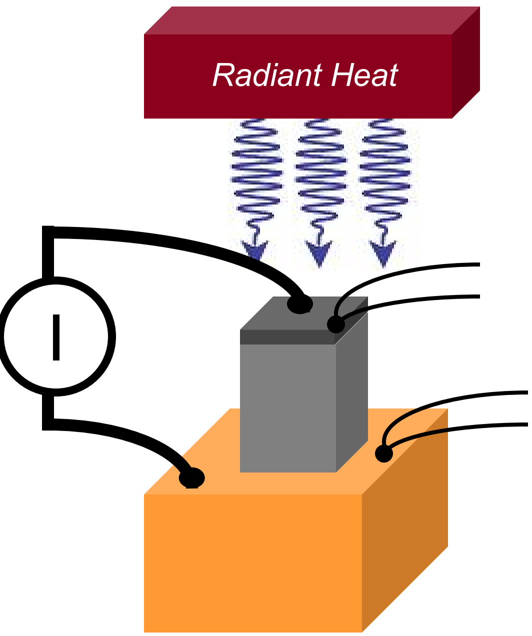
Radiant Heat (Seebeck)

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



PbTe





Apply D.C. $\Delta T \rightarrow 0$

$@\Delta T=0 \quad Q_{Pelt.} = Q_{rad.} \quad Q_{wire} \,\&\, Q_{tc}=0$

(Know $Q_{rad.}$ heat flow at $\Delta T \neq 0$)

Solve for κ (geometry)

I = 0.087 amperes
***Seebeck Coefficient* (meas)**
A/l = 0.405 cm²/cm
κ = 0.0149 W/cm-K

I = 0.057 amperes
***Seebeck Coefficient* (meas)**
A/l = 0.081 cm²/cm
κ = 0.0285 W/cm-K

Measure Resistivity

$@\Delta T=0$ …*No Seebeck error*

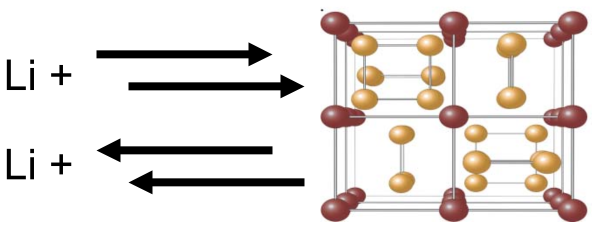
POC: Dr. Jeff Wolfenstine (301)-394-0317

w/ Prof. Jeff Sakamoto, Michigan State University

- **Seedling**

Objectives:

Develop nanostructured $CoSb_3$ skutterudites by lithium ion transport



Desired Impact

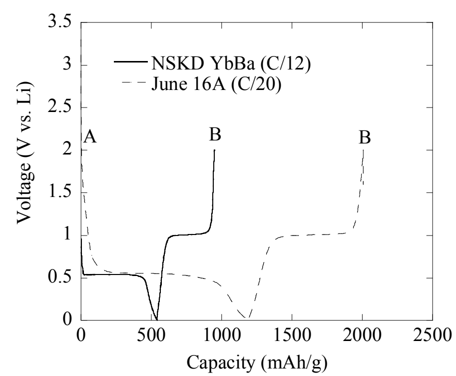
•Higher efficiency.

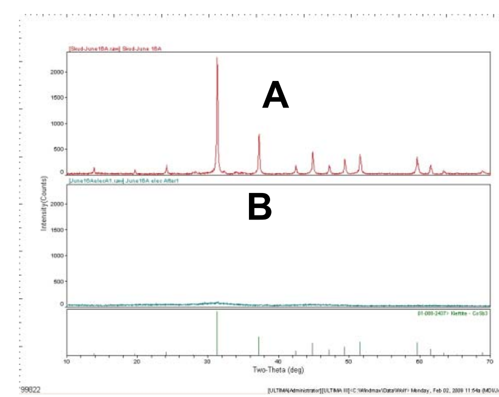
•Long-Term: improved energy conversion for Army mobile power and energy recovery

Technical Challenge

•Use electrochemical means to form amorphous/nanostructured n-type $CoSb_3$

Accomplishments





A: As-prepared: -Crystalline $CoSb_3$
B: After Electrochemical processing:
(one cycle discharge/charge) –Amorphous $CoSb_3$

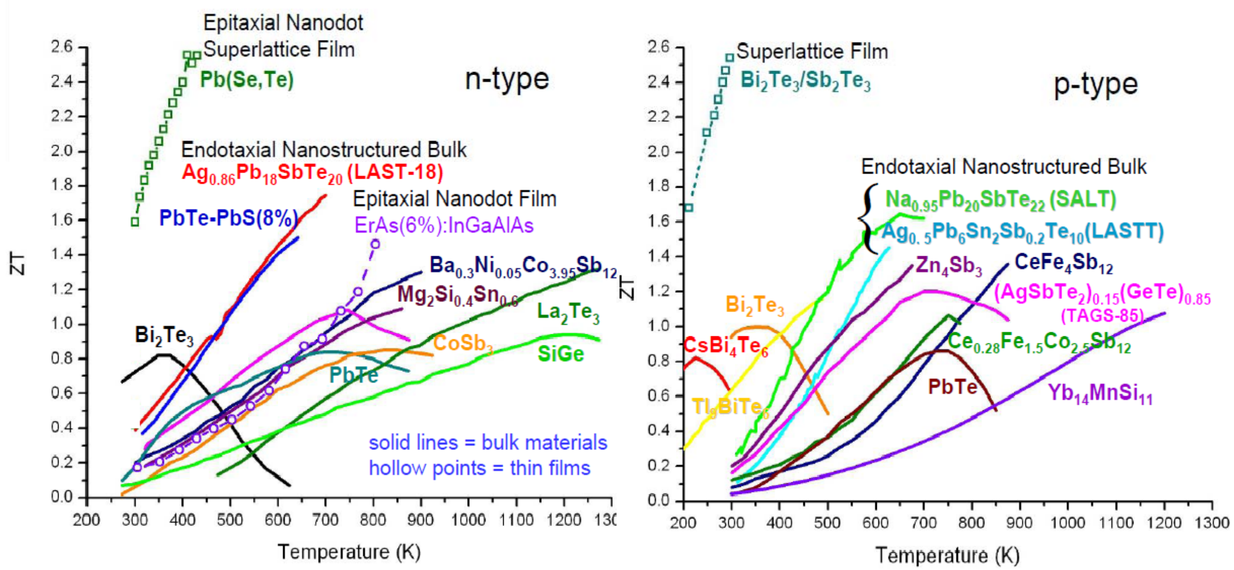
Research Challenge 1: TE Materials

- **Materials**
  - ➢ (Gross, Pazik, Rosker, DARPA, ARO)
  - ➢ ***Relevancy (devices)***

ONR

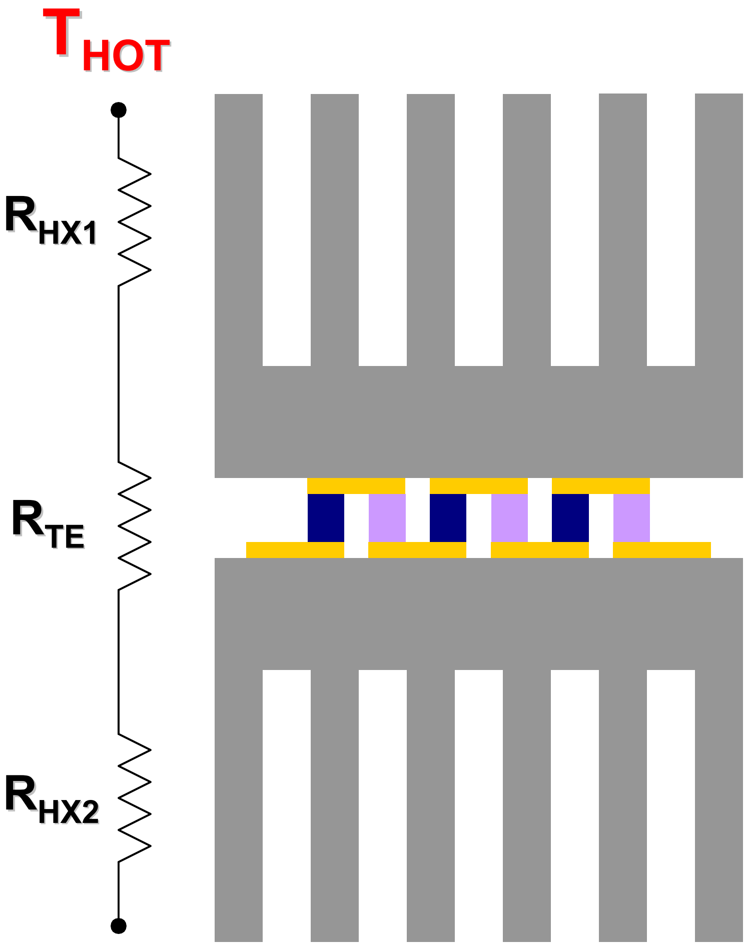
State-of-the-Art Thermoelectrics

A highly efficient power generation system will require a series of n-p couples, each with optimum performance over a given section of the overall temperature range.



Curves adapted from compilation by Tim Hogan (http://www.egr.msu.edu/%7Ehogant/Group%20Web%20Page/Research%20page.htm#thermoelectrics)

Research Challenge 2: Thermal Management



$$Q_{Heat} = \frac{\Delta T}{R_{Total}}$$

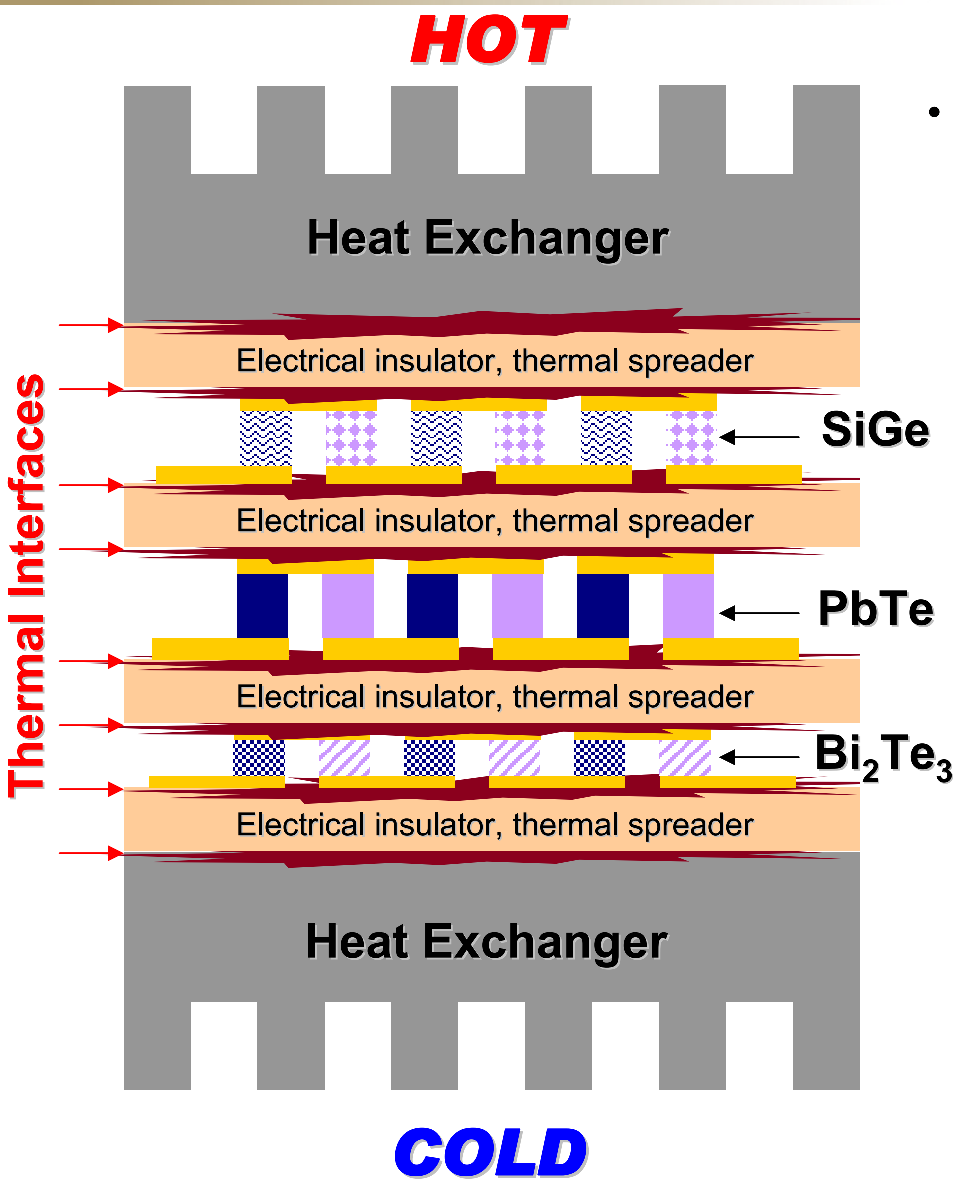
Power $\propto (\Delta T_{TE})^2$

The result of managing the heat *FLOW*

- Heat Exchangers (HX) are critical:
  - HX thermal resistance (R_{HX}) limits total heat flow (& Power)
  - Relative R_{HX}'s change temperature at thermoelectric device
  - Potentially dominates system size
- Research paths:
  - System specific trade studies for Active vs Passive air and liquid cooling
  - Efficient heat spreading

(Morgan)

Research Challenge 3: Packaging-Multistage



(Morgan)

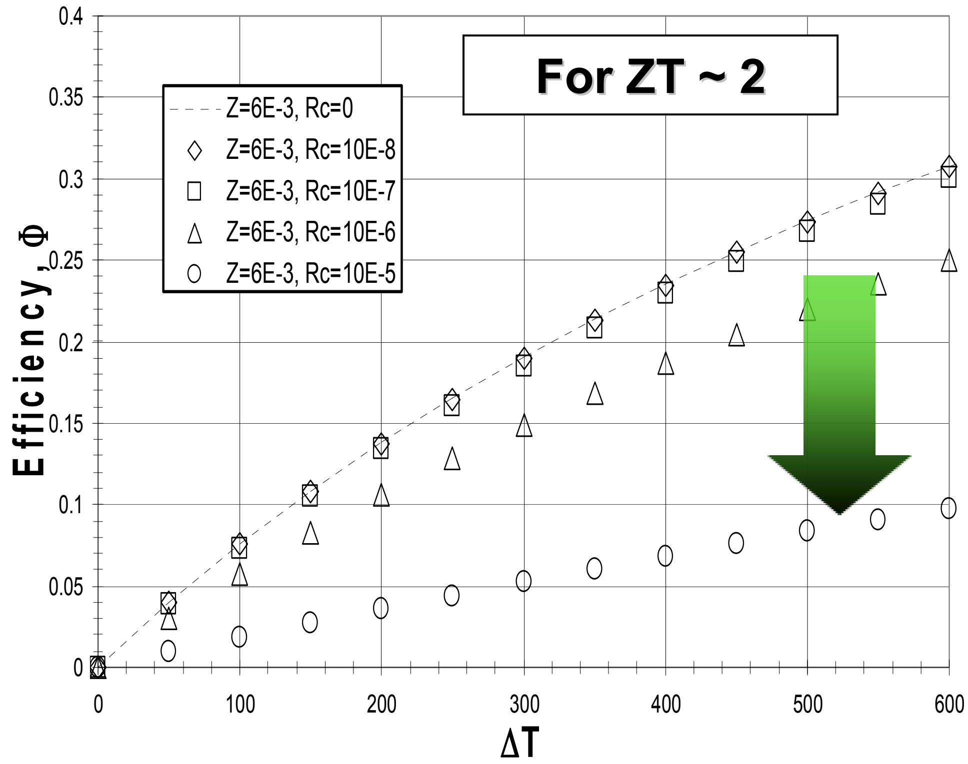
- Many Thermal interfaces:
  - Typically involve a grease
  - Diminishing returns in cascaded devices targeting large ΔT & high efficiency
  - Grease or solders must survive high temperature

Scaling to large area / power:

- High thermal gradients create large stress as area increases
- Huge CTE mismatches
  - Bi_2Te_3 ~19 ppm/K
  - SiGe ~4 ppm/K
  - Thermal spreader ~4 ppm/K
  - Heat Exchanger ~23 ppm/K
- Need improvements in package design & materials

Research Challenge 4: Electrical Contact Resistance

- **Contacts - Interconnects**
  - Bad contacts can degrade perf.
  - Need:
    - Cost-effective, producable
    - temporally stable
  - Goal: $R_c > 10^{-7}\ \Omega\text{-cm}^2$ (*films*)
  - Shoes/interconnect integration:
    - Efficient heat transfer
    - managing CTE mismatch
    - manufacturable



Take Aways…

- ARL is acutely interested in TE technologies

- Power Generation:
  - Small power devices > 2 W/cm^2
  - Thin-film Materials (MEMS$\rightarrow$UGS)
    - **Crystalline Bi_2Te_3/Si**
    - **Crystalline (Pb,Sn)(Se,Te)/Si**
  - Fast, simple κ meas. using radiative heat
  - Seedling effort for $CoSb_3$

- Challenges/ Focus Areas:
  - Higher Z
  - Thermal management (heat sinking)
  - Packaging
  - Electrical contacts

Partnering
Collaboration

US ARMY RDECOM

Back-up

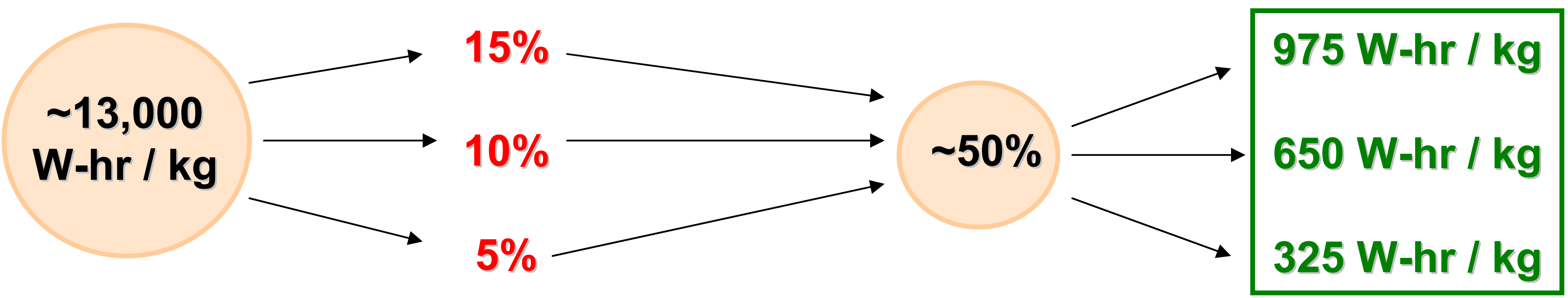
Direct Soldier Power Generation

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)



JP-8 x TE Efficiency x System Overhead = Energy Density