Thermoelectric Conversion of Waste Heat to Electricity in an IC Engine Powered Vehicle

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Prepared by:

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Energy Efficiency Renewable Energy (EERE)

John Fairbanks and Samuel Taylor, Contract Monitors

Objectives and Relevance to DOE Goals

- Use a TEG for improving the fuel economy by converting waste heat to electricity used by the OTR truck
- Show how advanced thermoelectric materials can provide a cost effective solution for improving fuel economy and idle reduction for an OTR truck (3-5% possible based on segmented couples)
- Determine and demonstrate steps necessary to achieve kW level TEGs
  - ➢ Develop TEG fabrication protocol for module and system demonstration using non-heritage, high-efficiency TE materials
  - ➢ Determine heat exchanger requirements needed for building efficient TEGs
  - ➢ Design and demonstrate power electronics for voltage boost and module fault by-pass in a TEG

TEG Construction at MSU

High Vacuum Sealing Line

Furnace

Rocking Furnace

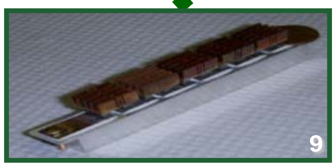
Double Glove Box – Powder Processing

Hot Press

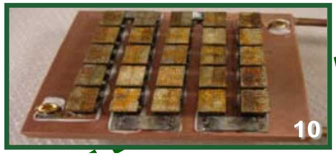
N and P Hot Pressed Pucks

Grinder/Slicing Machine

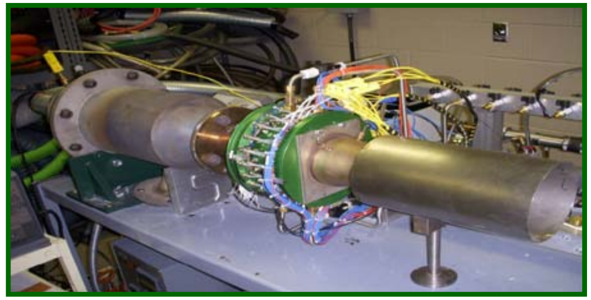
N and P Hot Pressed Pucks After Slicing



5-Watt TE Module

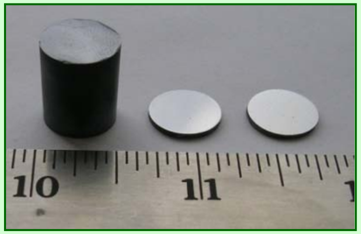


25-Watt TE Generator

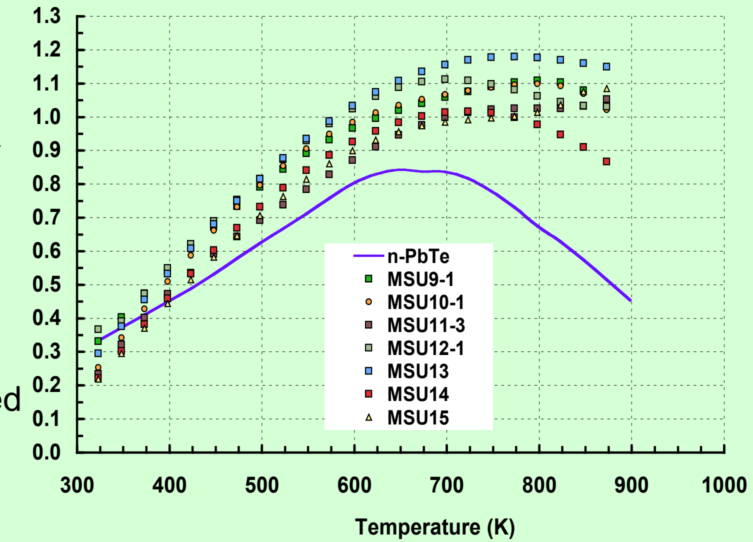

Second Generation 100-Watt TEG Under Test

Skutterudite Materials and Metallization at JPL

- N-type: $Ba_xYb_yCo_4Sb_{12}$
  - Further established TE properties repeatability
  - ~ 40% improvement in ZT over n-type PbTe in the 873K-373K temperature range

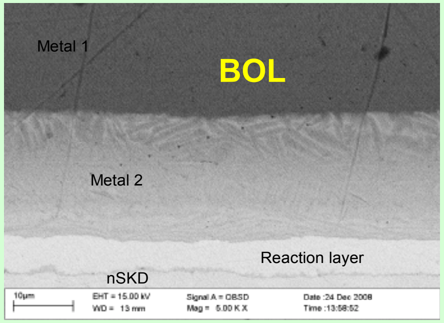


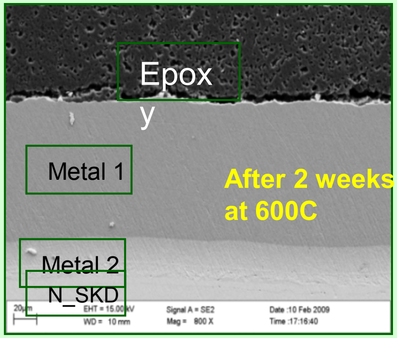
Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$



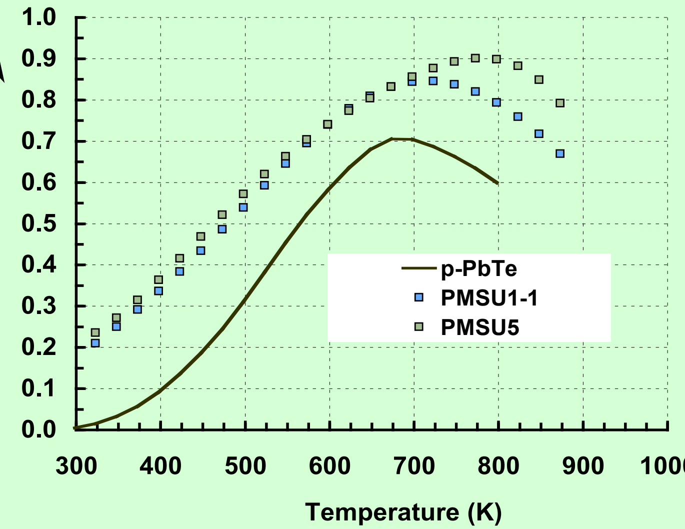
ZT values for n-type $Ba_xYb_yCo_4Sb_{12}$ ball milled materials. Each set of data corresponds to a separate 100 g batch.

- P-type: $Ce_xFe_{4-y}Co_ySb_{12}$
  - Established ball milling synthesis conditions for 50 g batches
  - Established initial TE properties for ball milled and hot-pressed materials; full repeatability demonstration in progress
- **Metallization**
  - Developed a new metallization for n-type $Ba_xYb_yCo_4Sb_{12}$
  - Demonstrated stability of low-electrical contact resistance metallization for up to 2 weeks up to 600C; additional stability testing in progress
  - Similar metallization development in progress for p-type





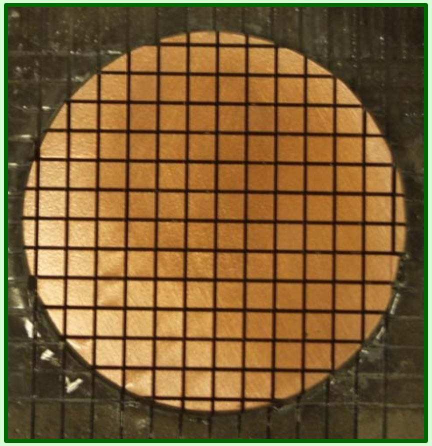
SEM images showing the SKD/metallization interface at beginning of life (BOL) and after 2 weeks aging at 600C. After aging, no degradation of the interface and no significant metal/SKD diffusion is observed.



ZT values for p-type $Ce_xFe_{4-y}Co_ySb_{12}$ ball milled materials. Each set of data corresponds to a separate 50 g batch.

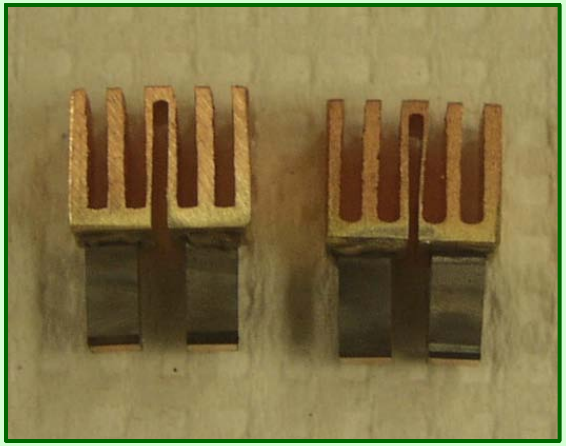
MSU Hot Pressing and Unicouple Fabricating Capabilities

Hot Pressing
2” or 3”
~ 7 hours/puck



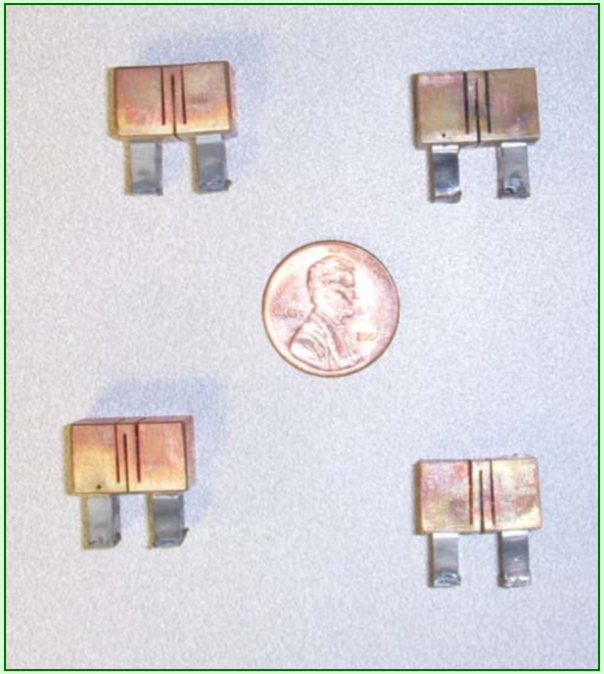
Dicing 2” puck
Yields 112 legs
3.5 mm x 3.5 mm

Last 12 months we have hot pressed
25 N and 25 P-type skutterudite 2” pucks

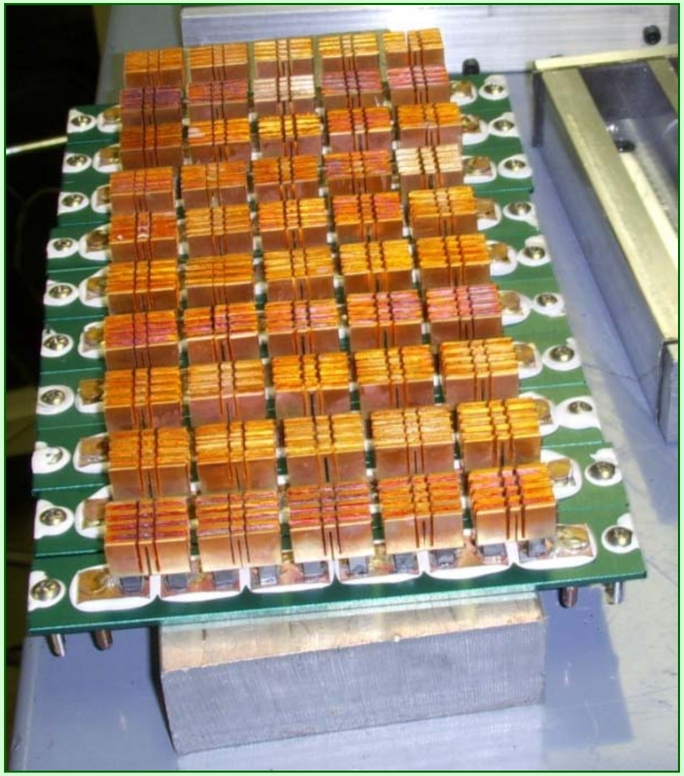


Unicouple fabrication 20 per batch run, ~80 per 8 hr day, 200-360 Watts per week

MSU Fabricated Unicouples and Modules

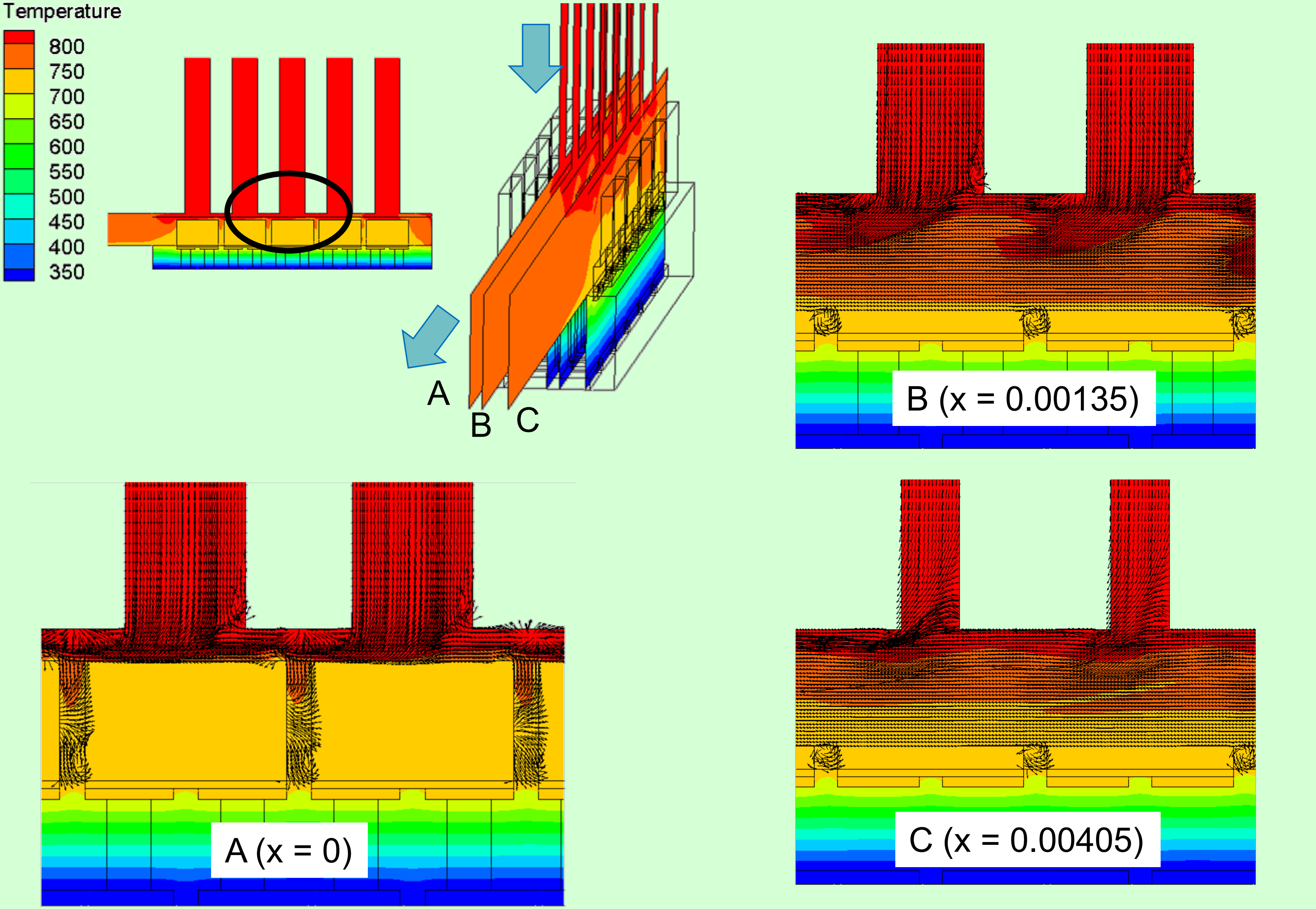


Unicouples ready to be made into modules with MSU expansion joint design



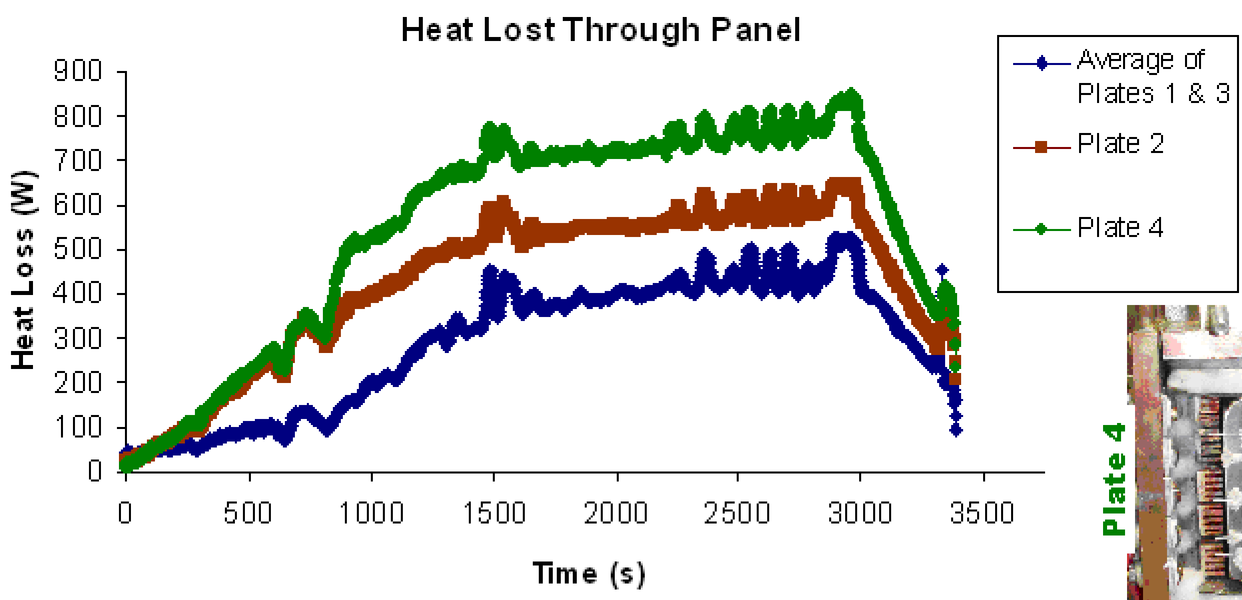
Multiple 5-Couple modules assembled and ready for aerogel insulation

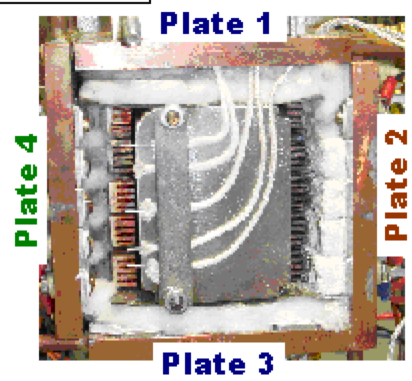
CFD Flow Calculations for Optimum Heat Transfer



Aerogel vs High Temp Wool Insulation

(>25% Heat transfer reduction through insulation)



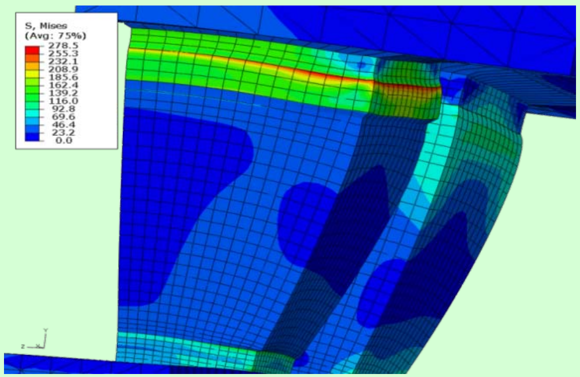


Average of Plates 1 & 3: high-temp wool with mica sheet, no modules

Plate 2: Modules, aerogel insulation

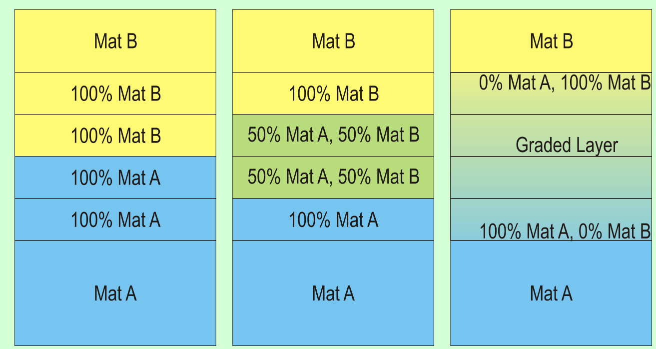
Plate 4: Modules, high-temp wool

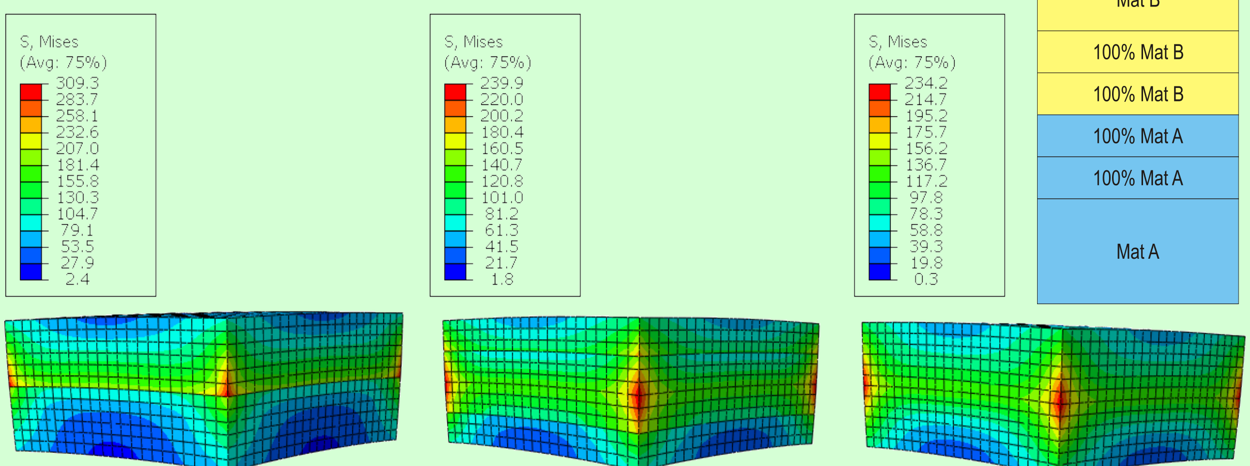
Stress Distribution in Couples and Methods of Stress Reduction

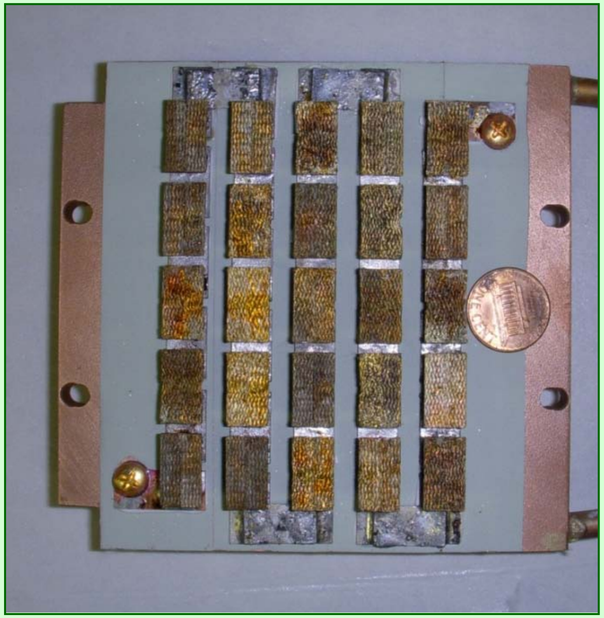


High stresses high at hot side interfaces

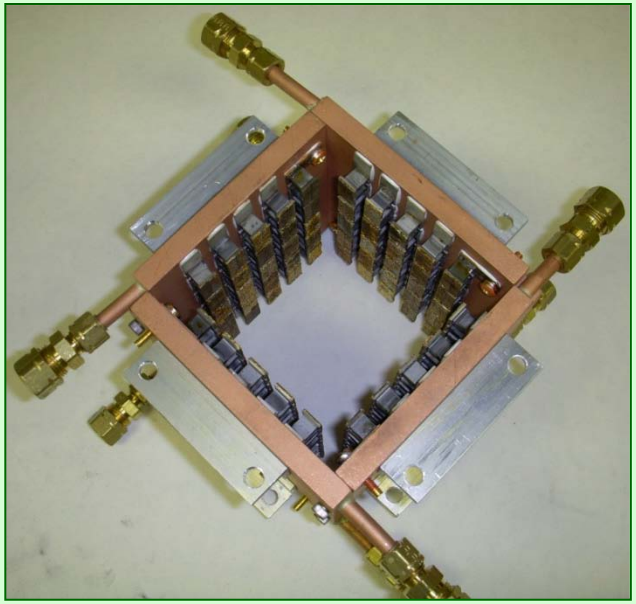
Stress distributions at Layers 1 through 4, pure layers at the left, 50-50 layer in the middle, and graded layer at the right. … (25% stress reduction)



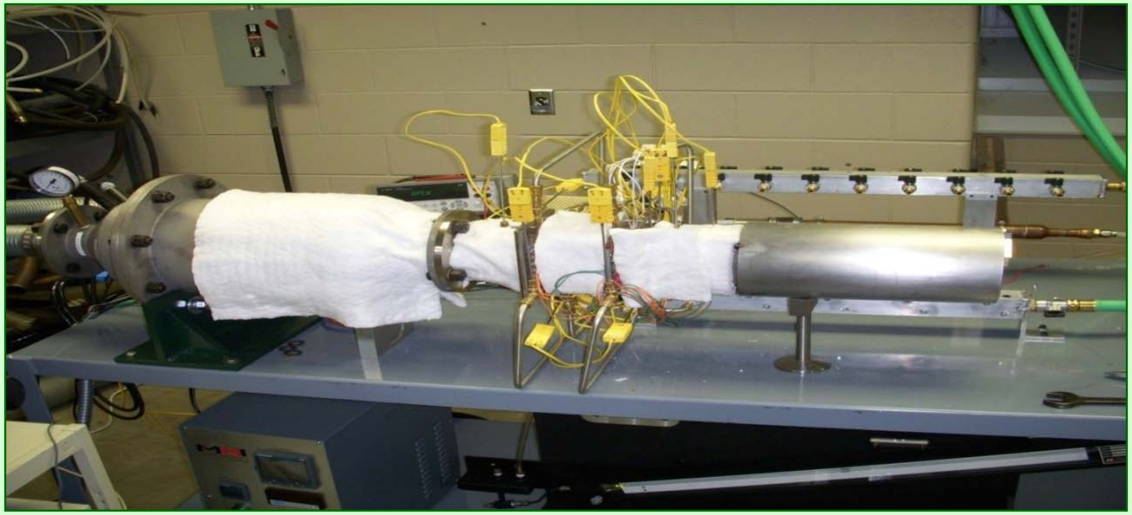




5 - 13W Modules (theoretical @ ΔT=600C) before Insulation

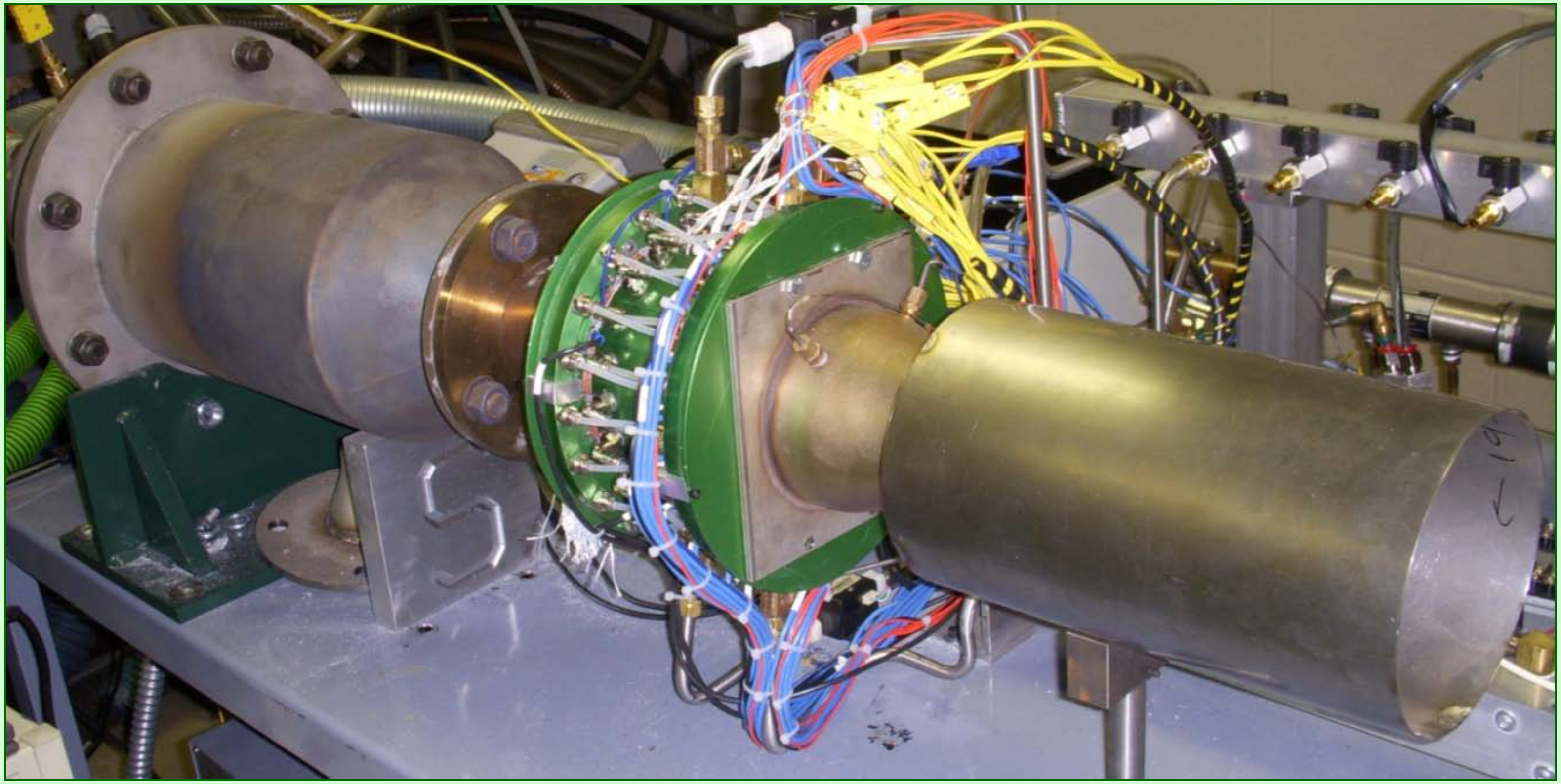


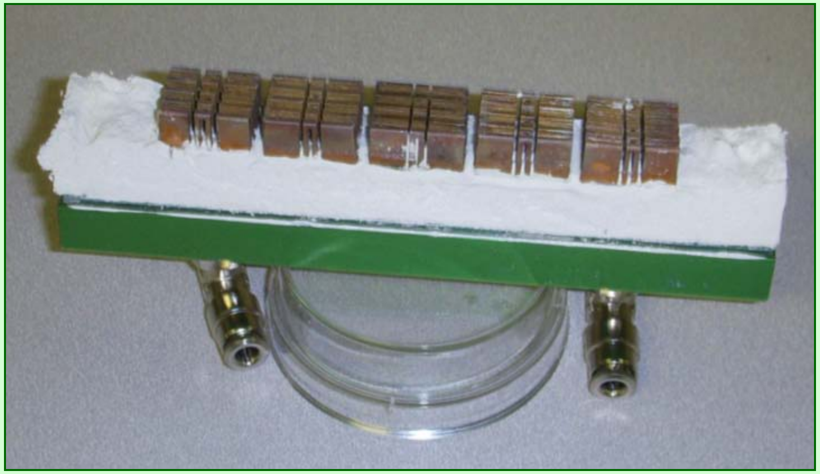
TEG – 260W (theoretical @ ΔT=600C) 20 – 13W Modules



Gen 1 TEG Testing Assembly at MSU

Gen 2 100 Watt TEG Assembled and Instrumented with Air Torch for Testing

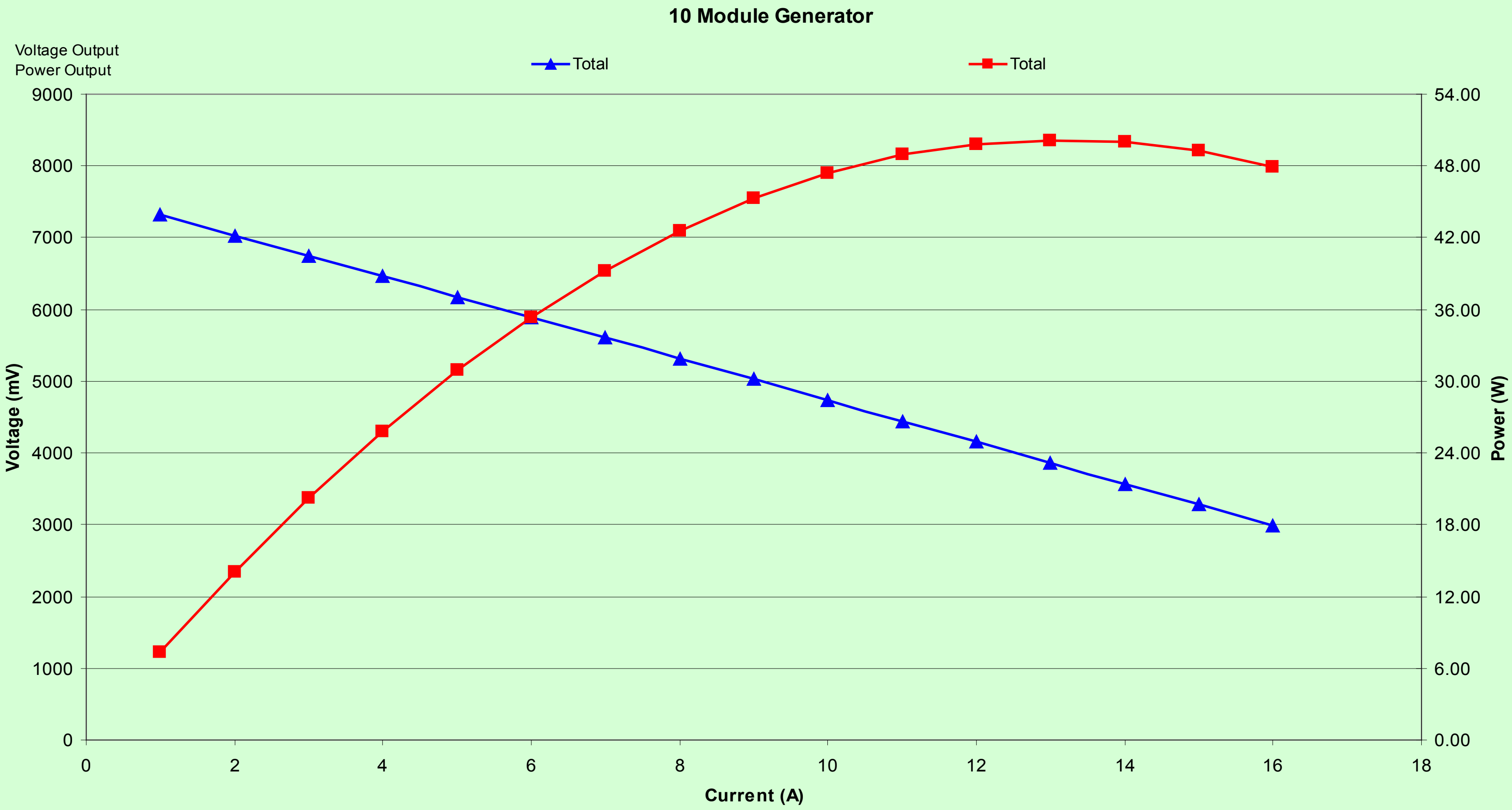




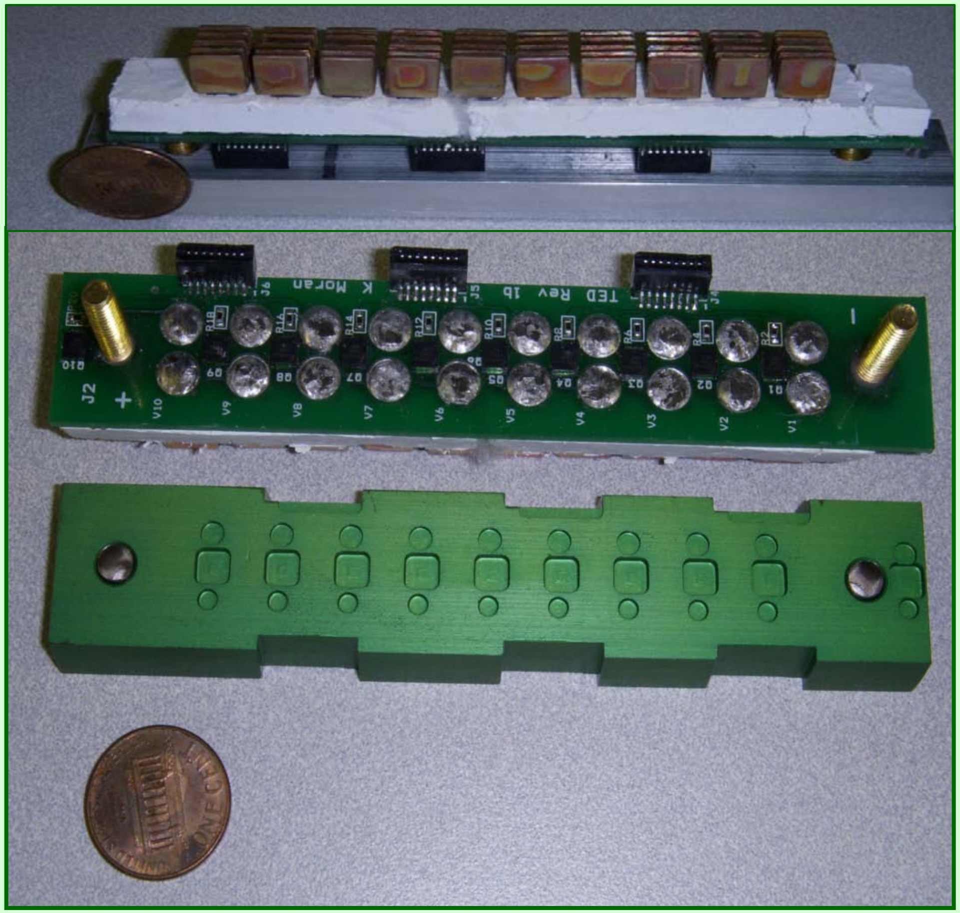
Module with aerogel insulation mounted to cooling plate

Five insulated modules and cooling plates assembled into circular generator

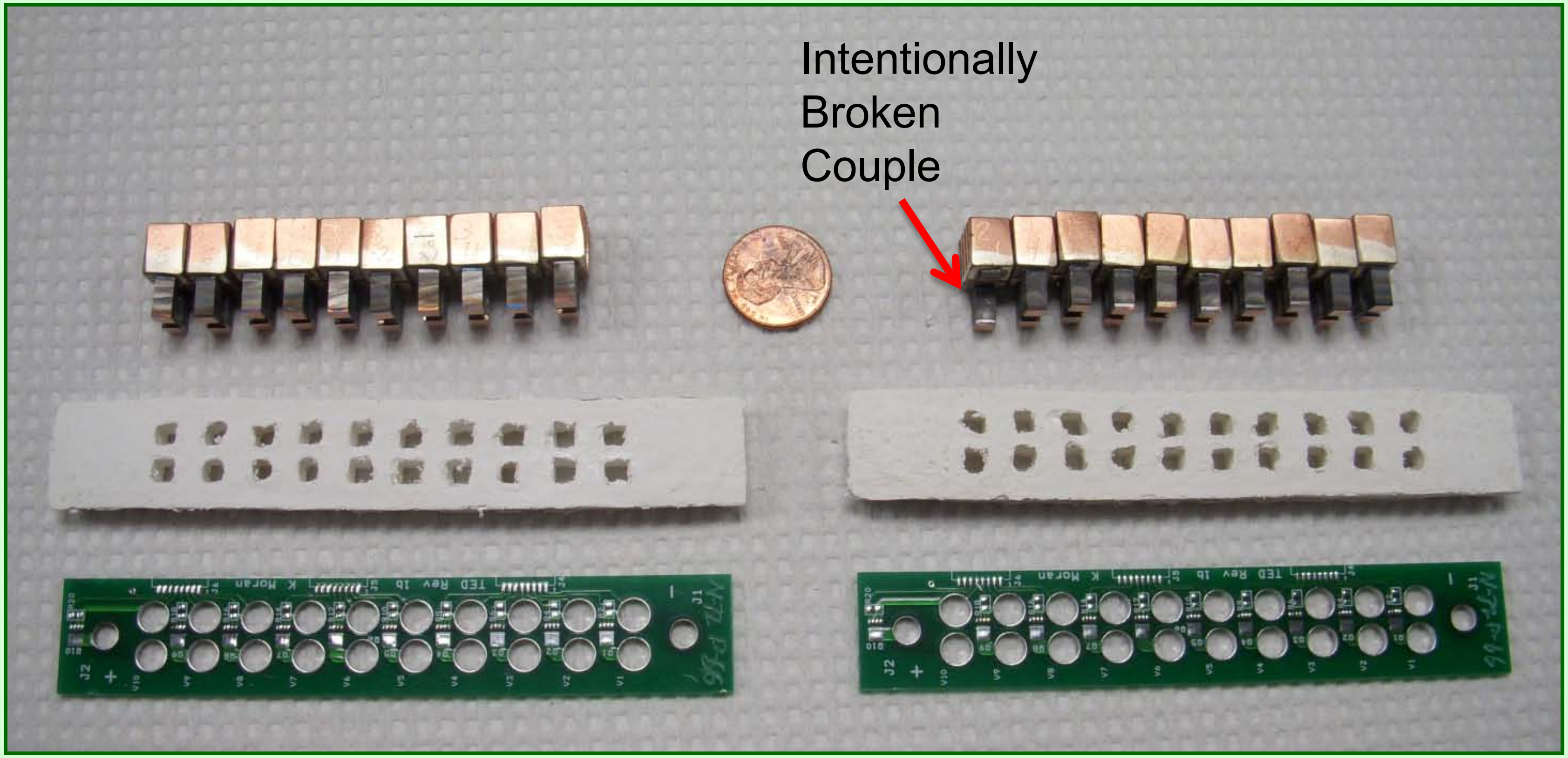
10-Module TEG output ~50.12W, ΔT~550ºC (8/4/09)
Best Result at MSU to Date from 50/100W Generators
(50W nominal produced 50.12W, Gen 1 100W nom. – 73W, Gen 2 100W nom. – 70W)



Module with Couple Bypass Technology (CBT)



CBT Modules Tested: Broken and Non-Broken – All Legs taken from Single P and Single N-type Puck



CBT Module Experimental Results and Projections

Module Power Measurements (modules shown on previous slide)

- 10-Couple Power (550C ΔT) based on Module Experiment: **4.75 Watts at 0.75V and 6.35 Amps**
- 10-Couple Power (550C ΔT) based on Module Experiment: **3.40 Watts at 0.68V and 6.35 Amps** (One couple INTENTIONALLY broken)

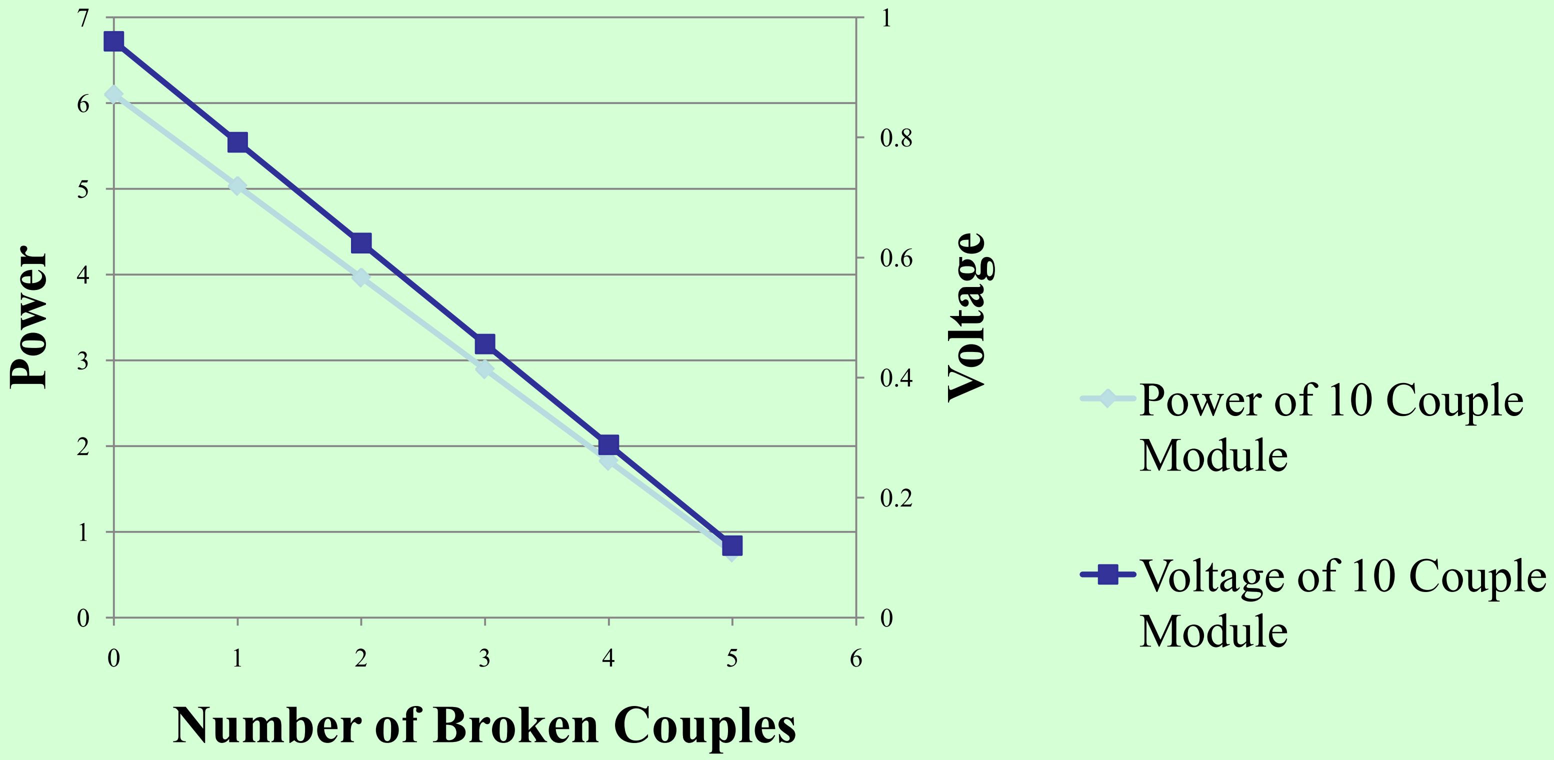
Module Power *Estimates* based on Best Single Couple Measurements from same puck used to fabricate module above

- Estimate of Module Performance Based on Best Couple in above module: Module Power (550C ΔT) 6.1 Watts at .96 Volts and 6.35 Amps, Greater than 1 watt/couple at ΔT = 600C would produce over 10 Watts per module

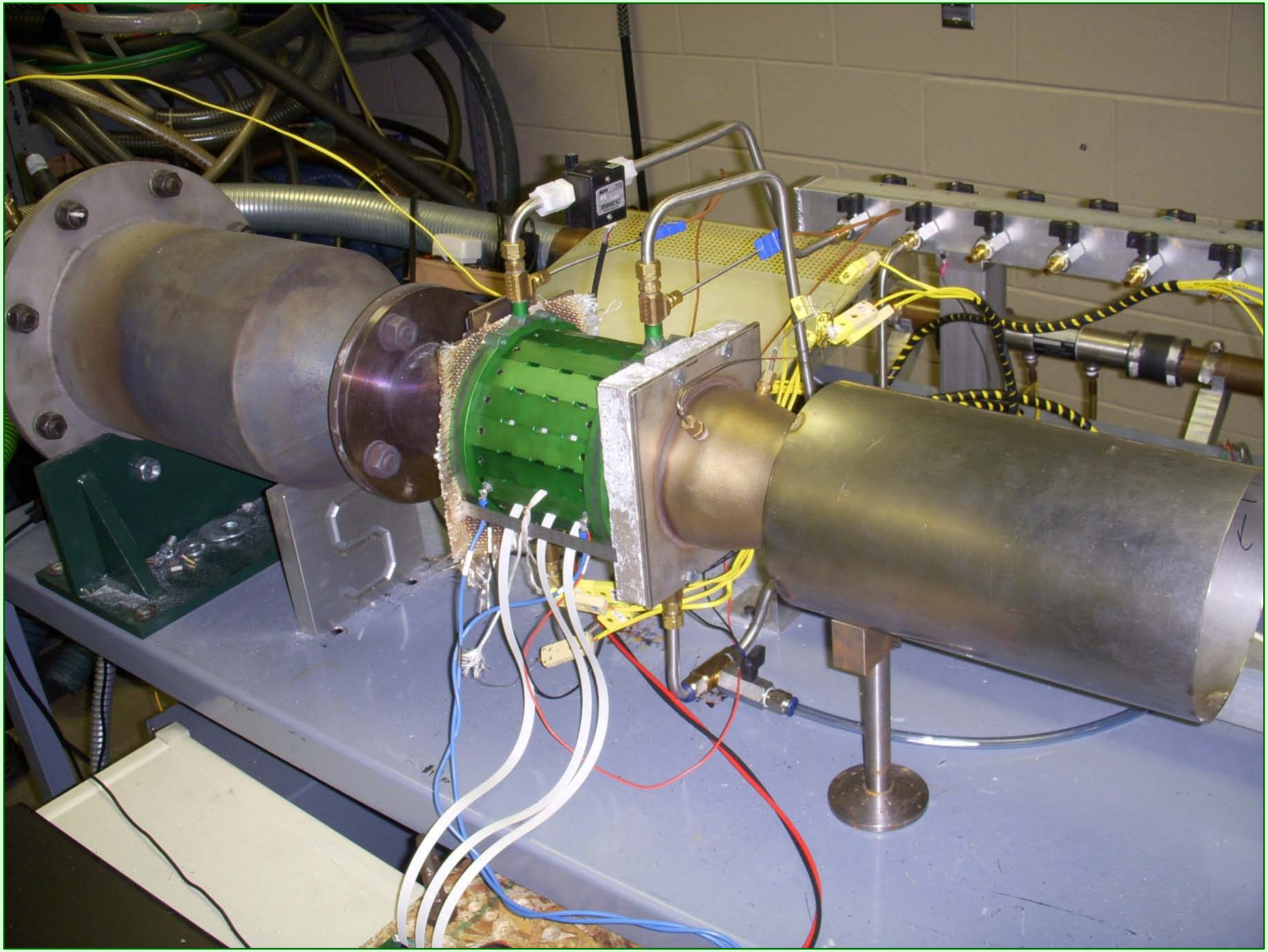
Other Benefits

- Excellent test bed for couples, update rate on performance every 500ms

Power and Voltage of 10-Couple, CBT Module with Broken Couples



Gen 3 - TEG (100-200 Watts) Under Test



Estimated Results for a Gen 3 CBT 20 Module Generator Test* at ΔT = ~550C

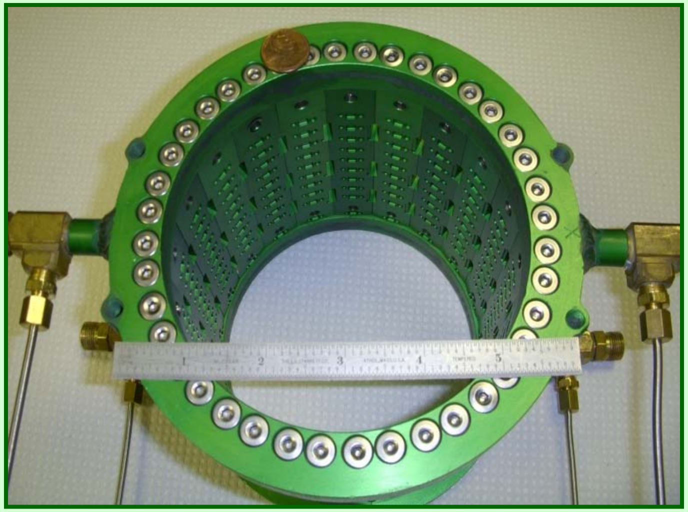
95W – Based on module demonstrated (TEG, 15V and 6.35Amps, each module 4.75W, 0.75V)

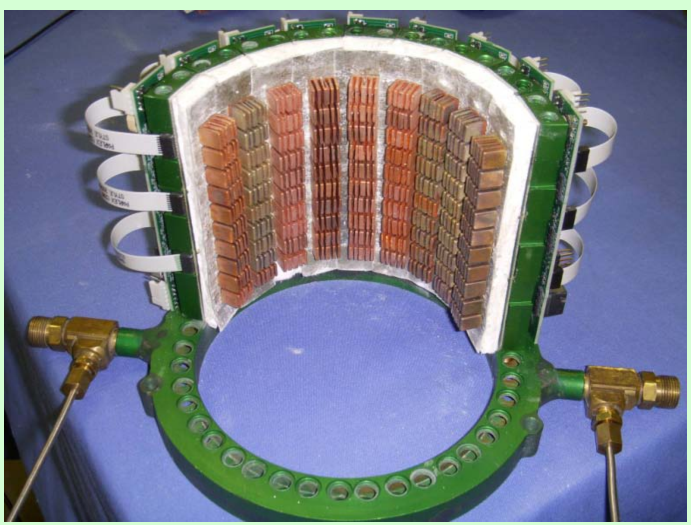
122W – Based on best couple taken from puck used to fabricate module describes above

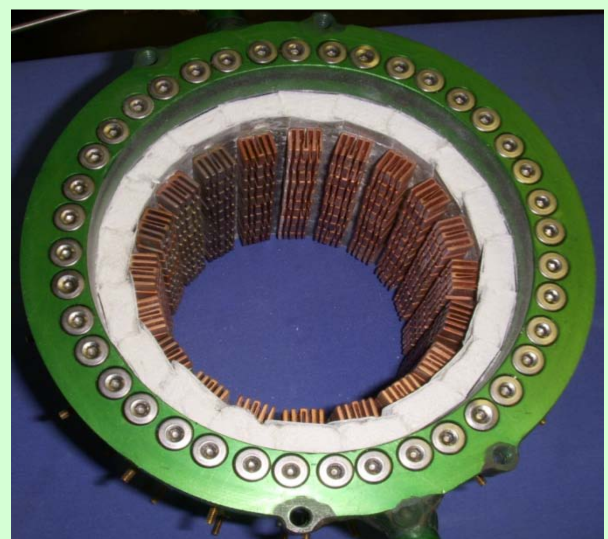
200W – Based on best couple measured of this Size (3.5x3.5x7mm)

*** P and N legs csa not optimized for heat flow, Outside dimensions of Gen 3-TEG: Diameter = 165mm, Length = 150mm**

Gen 3 - 20 Module TEG with CBT (To be tested January, 2011)



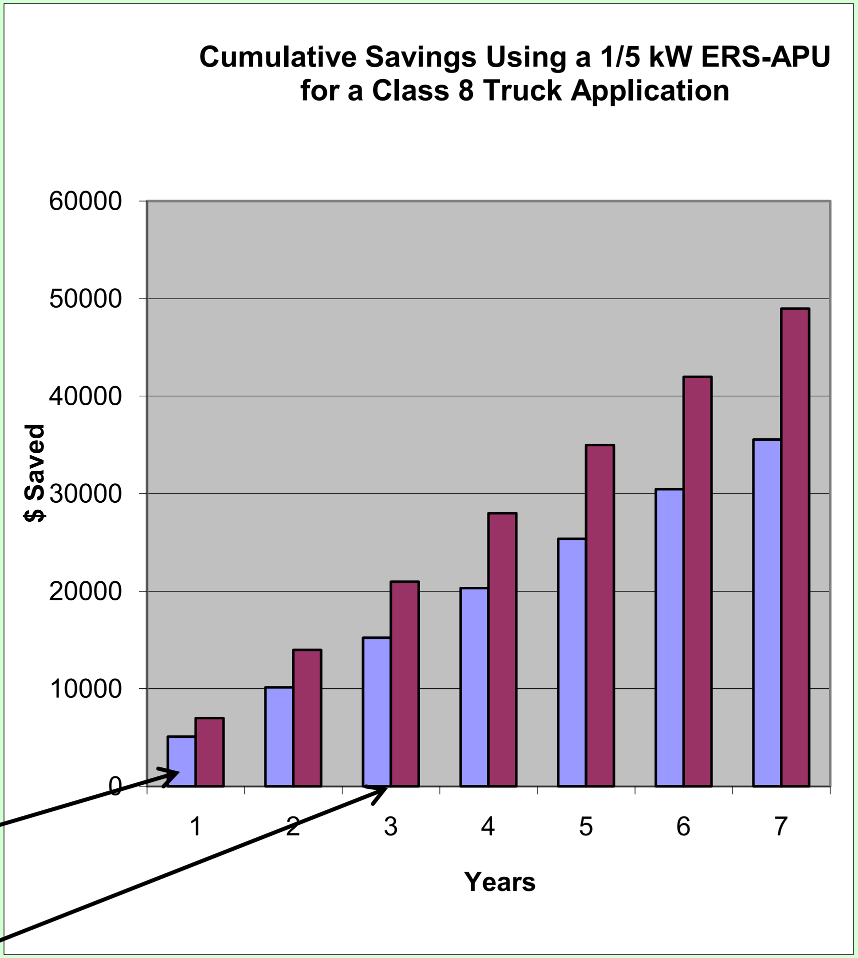




TEG Cost to Benefit for a 1/5kW ERS-APU Updated September, 2010

Total 1 kW System Price Based on Four Subsystems

• Electrical/Electronics	~~$943.28~~
	$471.64
• TEG Subsystem	
– TE Materials	$1200.00
– Module Assembly	~~$1124.85~~
	562.43
– Housing	$400.00
• Burner	$717.00
• Cooling Subsystem	$388.64
Total Price	~~$4773.77~~
	$3339.71 *
Total 5 kW System Price	~~$19276.13~~*
(* Arrows point to payback date)	**$16698.56**



Experiments at the Energy and Automotive Research Lab – 1MW Dynamic Absorption

Vehicle arrived 21 January 2010 - 1800 hrs.

Vehicle departed 2 February 2010 - 1800 hrs

Summary

- Systems for material synthesis, powder processing, hot pressing, leg and SKD module fabrication are operational at MSU (ingot to couple 95% mtl. utilization) …lab scale mass production shown
- Major Issues that Impede Advanced TEG Implementation Understood
- Couple Bypass Technology developed and demonstrated...permits electrical series configuration for numerous modules and facilitates couple development
- Using available TEG technology, a 2% improvement in bsfc will require a 5kW TEG…first viable application may be as an ERS-APU for trucks and buses (1 and 2.5 year payoffs for 1 and 5kW units, respectively)
- During Phase 3, the MSU led team will build a TEG from using advanced skutterudite material with areogel insulated modules …Output > 100 Watts, Voltage > 15 V, Modules will feature couple bypass technology

Acknowledgements

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