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

Prepared by:

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May 13, 2011

Project ID# ace049

Outline of Presentation

- **Overview**
- Objectives and Relevance
- Milestones
- Approach
- Accomplishments
  - System for lab scale production of modules completed
  - Lab scale production of couples and modules demonstrated
  - Advantages of aerogel insulation system demonstrated
  - 50/100/200W Generation 1, 2 and 3 TEGs have been constructed and tested
  - Un-insulated single couple temperature cycling test successful
  - Couple Bypass Technology invented and successfully demonstrated
  - Important remaining technical barriers identified
- Future Work
- Summary

Overview

Timeline

Start – January 2005
Finish – March 31, 2011

Budget

	DOE	Contractors
• Phase 1	215K	
• Phase 2	3,508K[1]	1,185K
• Phase 3	700K[2]	231K
• Phase 4	1,029K[3]	

[1] Received a total 4,423K from DOE over 5.5 years

[2] Phase 3 funded received on 4/10 involves a hardware demonstration of TEG. Phase 3 original was 1,078K

[3] Phase 4 was eliminated.

Barriers

- Utilize waste heat to reduce fuel consumption: DOE goal 10% reduction in bsfc …leading to diesel engines with a 55% thermal efficiency
- Develop cost effective solutions for reducing fuel consumption – For an over the road truck, engine idle reduction reduces fuel consumption and emissions while lowering capital costs
- After testing approximately 100 – 5/10 watt modules in 50 and 100 watt TEGs, a remaining unsolved technical barrier is mechanical integrity of interfaces

Partners

- Cummins, Purdue, NASA-JPL, Northwestern and Tellurex
- Office of Naval Research
- DOE Oak Ridge High Temperature Materials Laboratory
- Materials and Manufacturing Directorate, Air Force Research Laboratory, WPAFB

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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% bsfc improvement possible based on segmented couples for a 2007 engine, at cruise operating conditions)
- Demonstrate steps necessary to develop 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
  - ➢ Specify unresolved issues which impede TEG implementation

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Milestones
(Phase 2/3, 2009-2010)

Milestones described in previous merit review:

- Completed Phase 2 and started Phase 3 on December 31, 2009
- Skutterudite has been down-selected for a Phase 3 demonstration because of its thermoelectric and mechanical performance and estimated cost of production
- Methods for laboratory scale mass production of skutterudite (SKD) unicouples has been demonstrated at MSU (TE legs for 150 couples in two days, maximum theoretical output ~300W based on performance of best couples at a ΔT of 600C)
- 5, 25, 50 and 100 watt TEGs have been fabricated and tested at MSU, including a second generation 100W TEG
- Heat transfer issues for a 1kW – TEG have been identified and solutions proposed
- Major technical barrier to 1kW – TEG appears to be developing effective integrity at TE interfaces

Milestones since last merit review:

- Couple Bypass Technology has been proposed and demonstrated permitting high levels of series configurations for couples and modules in TEGs
- A Generation 3 100/200 W generator has been constructed and operated ~1W per cubic inch possible (200W is the power that would be produced at a ΔT of 600C given performance of best couples of the size used in the Gen 3 TEG)
- A graded layer system for hot side interfaces has been developed and demonstrated with partial success …more work required
- Highly insulated modules have been demonstrated …greater thermal stresses exhibited in well insulated modules

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Approach: Use Expertise of Experienced Groups to Integrate Numerical and Experimental Studies into a Practical Thermoelectric Generator Design based on High Efficiency TE Materials

Engine-TEG Simulation and Experimental Verification
MSU / Cummins

- Complete engine system- f (x,t)
- Temperatures and heat flux
- EGR energy
- Energy in exhaust (T, P, *m*)
- Turbine work, inlet/outlet temperatures

3D CFD Analysis
Purdue / MSU

- Couple and Module Issues

  Convection and radiation between legs with and without insulation

  Current distribution, Joule heating, Heat fluxes
- Electrical energy production
- Unsteady heat transfer analysis to and from modules (3D, pulsatile, comp.)

6 Cyl. Engine Test Data
Cummins

ERS-APU Demonstration Phase 3-4
MSU

TEG Design and Construction
MSU / JPL / NWU / Tellurex

- Generator design
- TEG materials selection
- Mechanical and TE material property characterization including Weibull analysis
- FEA analysis
- Leg and module fabrication methods

Systems for Utilization of Electrical Power Recovered
MSU

- Design of electrical energy conditioning and utilization system
- Control system design and construction
- Inverter, Belt Integrated Starter-Generator Selection

Other Significant Collaborations

- Oak Ridge National Laboratory, High Temperature Material Laboratory(Drs. Edgar Lara-Cuzio and Hsin Wang): Mechanical property characterization of materials over the temperature range of interest
- Materials and Manufacturing Directorate, Wright Patterson Air Force Base (Dr. Mike Cinibulk): SPS of LAST/T segmented legs with different compositions for optimum efficiency

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TEG Construction at MSU

High Vacuum Sealing Line

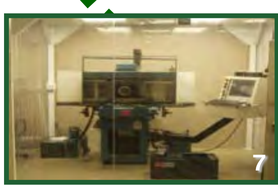
Furnace

Rocking Furnace

Double Glove Box – Powder Processing

Hot Press

N and P Hot Pressed Pucks

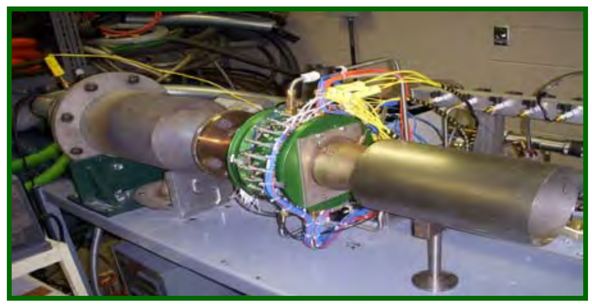


Grinder/Slicing Machine

N and P Hot Pressed Pucks After Slicing

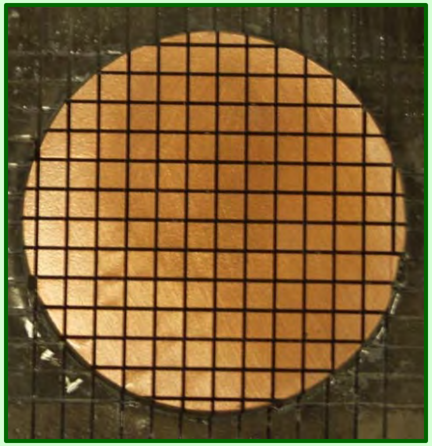
5-Watt TE Module

25-Watt TE Generator


Second Generation 100-Watt TEG Under Test

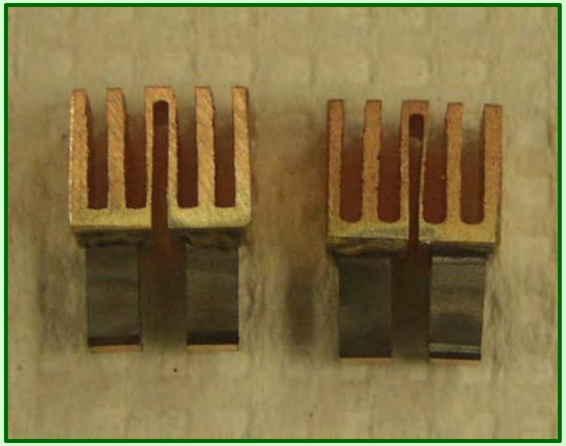
MSU Hot Pressing and Unicouple Fabricating Capabilities

Hot Pressing
2” or 3”
~ 7 hours/puck



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

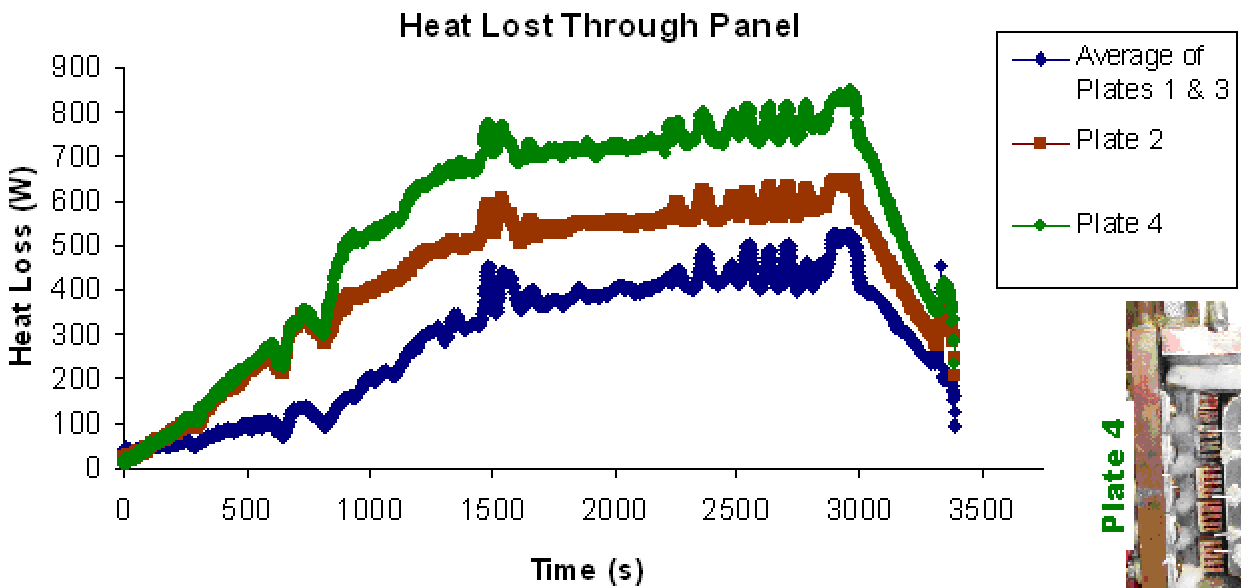
In 2010 MSU hot pressed
25 N-type and 25 P-type skutterudite 2” pucks

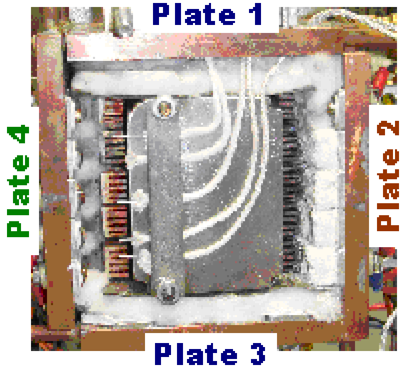


Unicouple fabrication 20 per batch run, ~80 per 8 hr day, 200-360 Watts per week

Aerogel vs High Temp Wool Insulation

(>25% Heat transfer reduction through insulation)



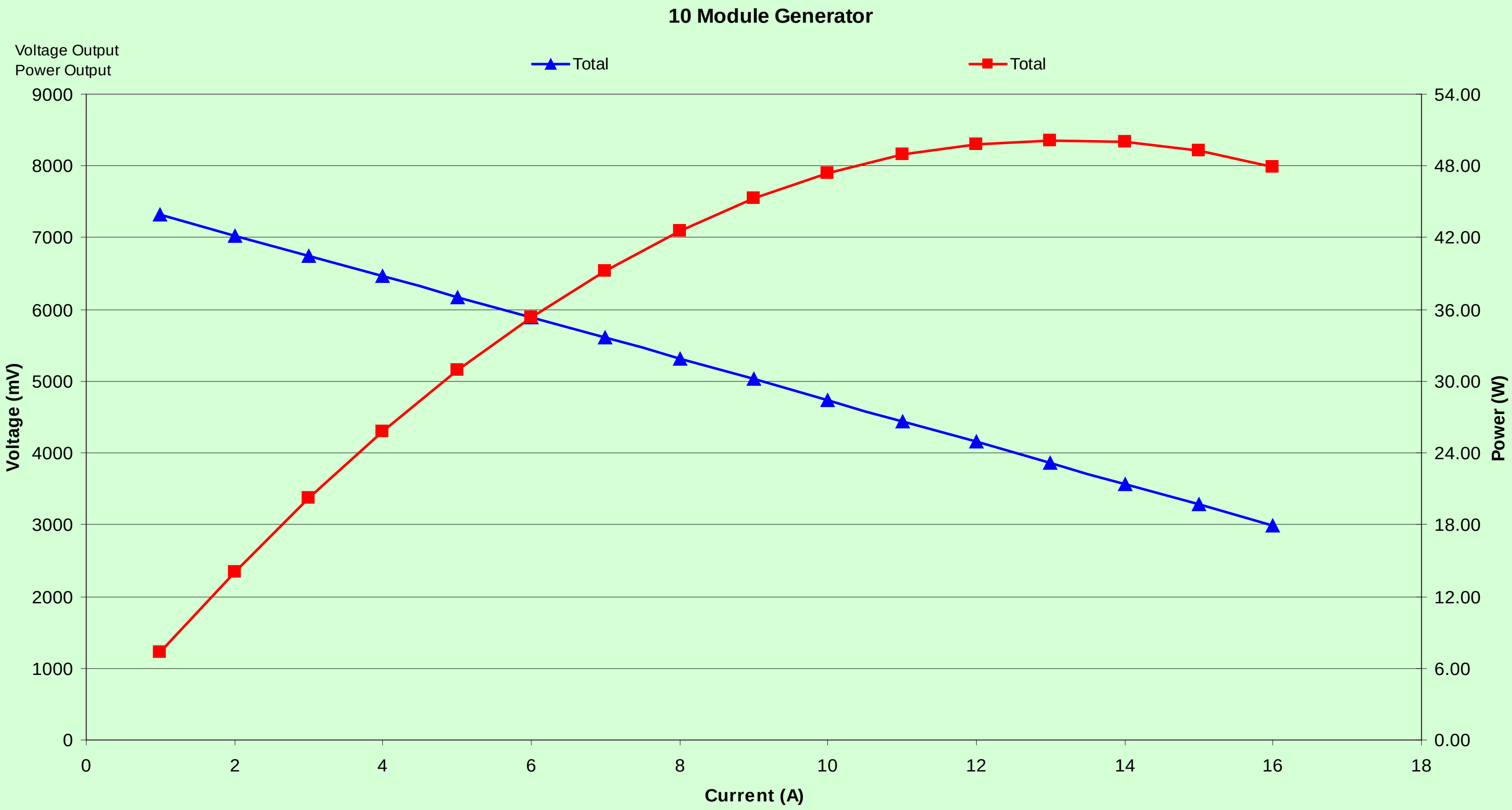


Average of Plates 1 & 3: high-temp wool with mica sheet, no modules

Plate 2: Modules, aerogel insulation

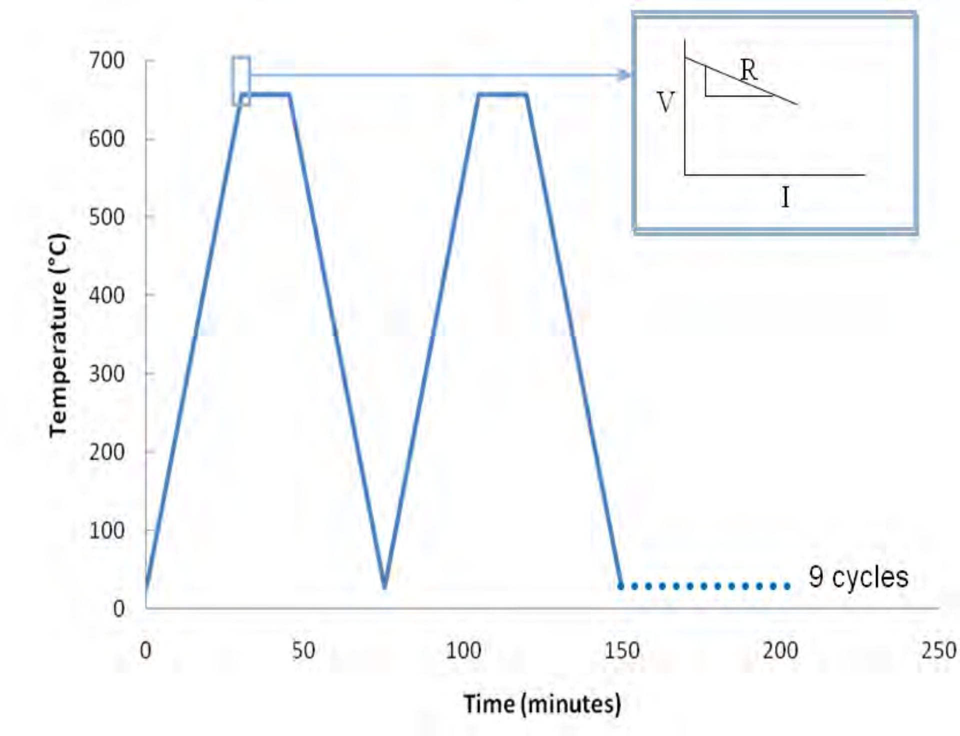
Plate 4: Modules, high-temp wool

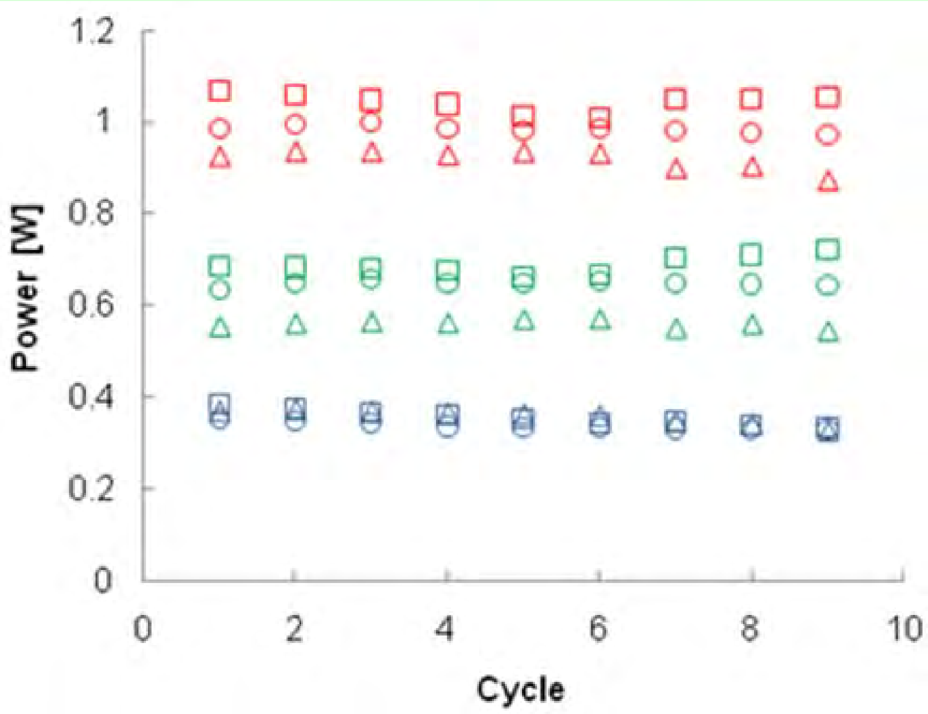
10-Module TEG output ~50.12W, ΔT~550ºC (8/4/09)
Best Result at MSU to Date from 50/100W Generators
(50W nominal produced 50.12W, Gen 1 100W nom. – 73W, Gen 2 100W nom. – 70W)



Single Couple, 9 Cycle Power Test

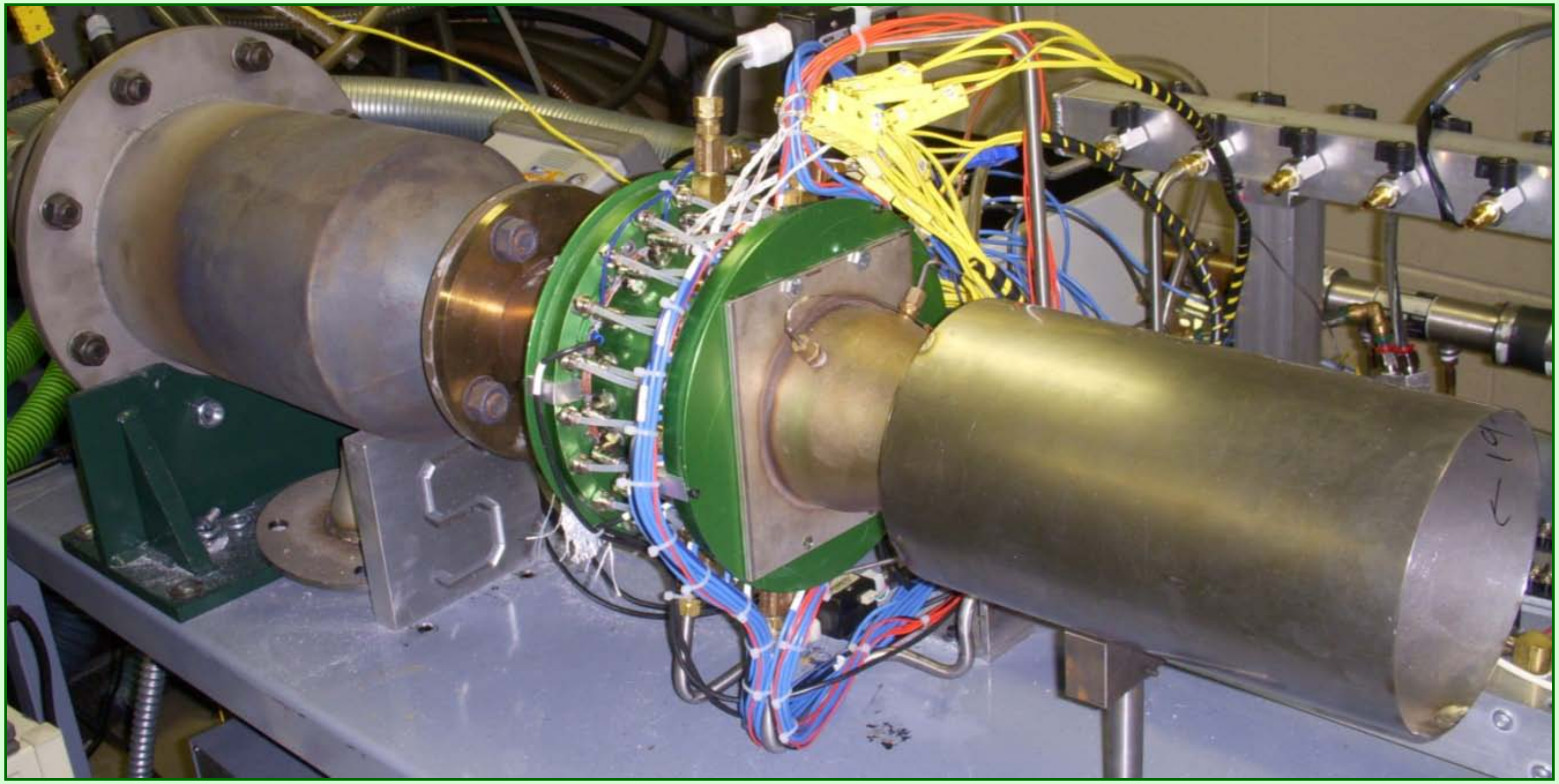
- Hot side Temp: 650°C
- Dwell Time: 15 m

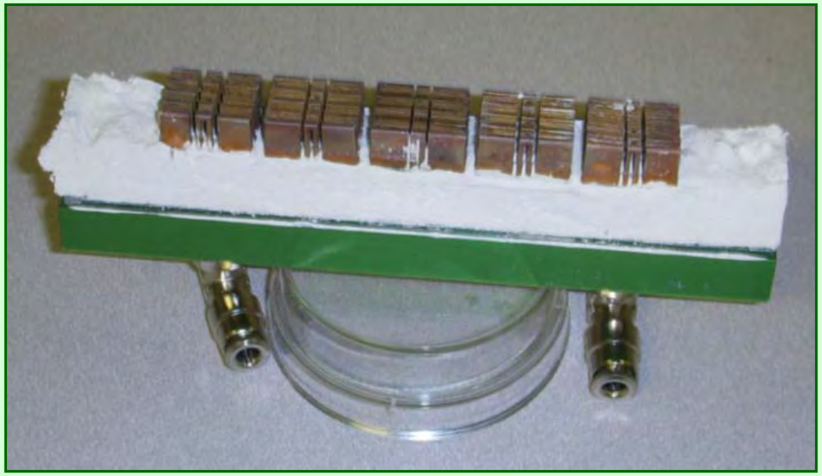




- Red: Total Power
- Green: N-Leg Power
- Blue: P-Leg Power

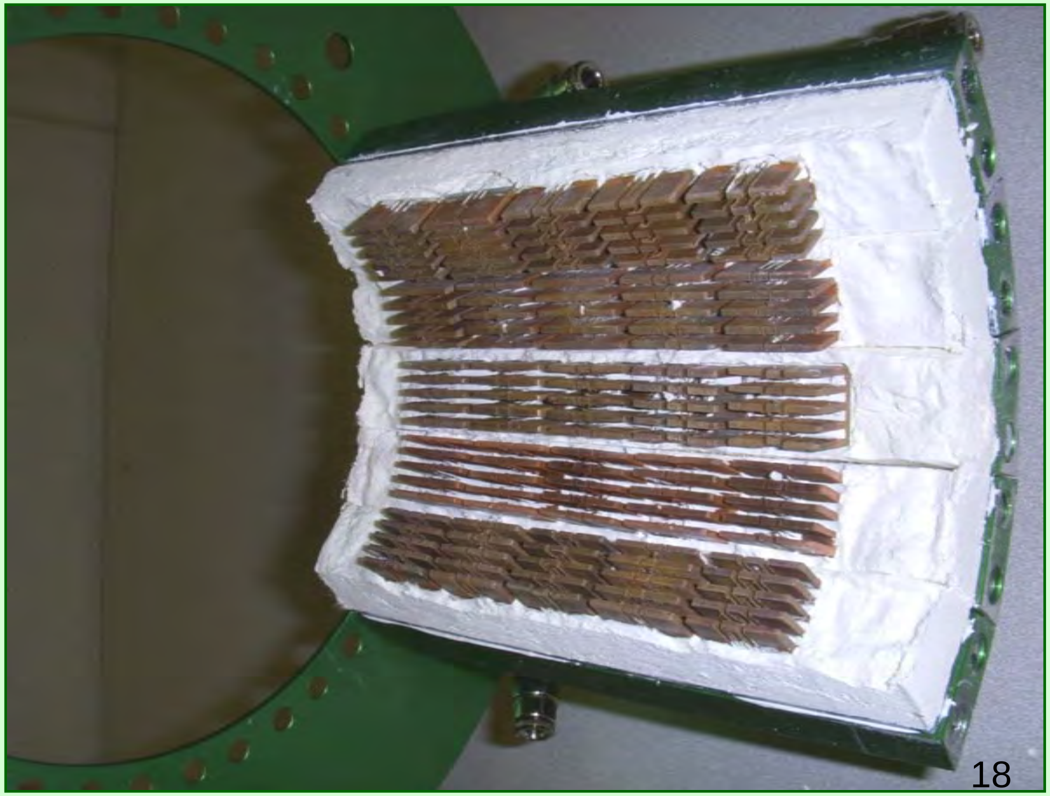
Gen 2 100 Watt TEG Assembled and Instrumented with Air Torch for Testing





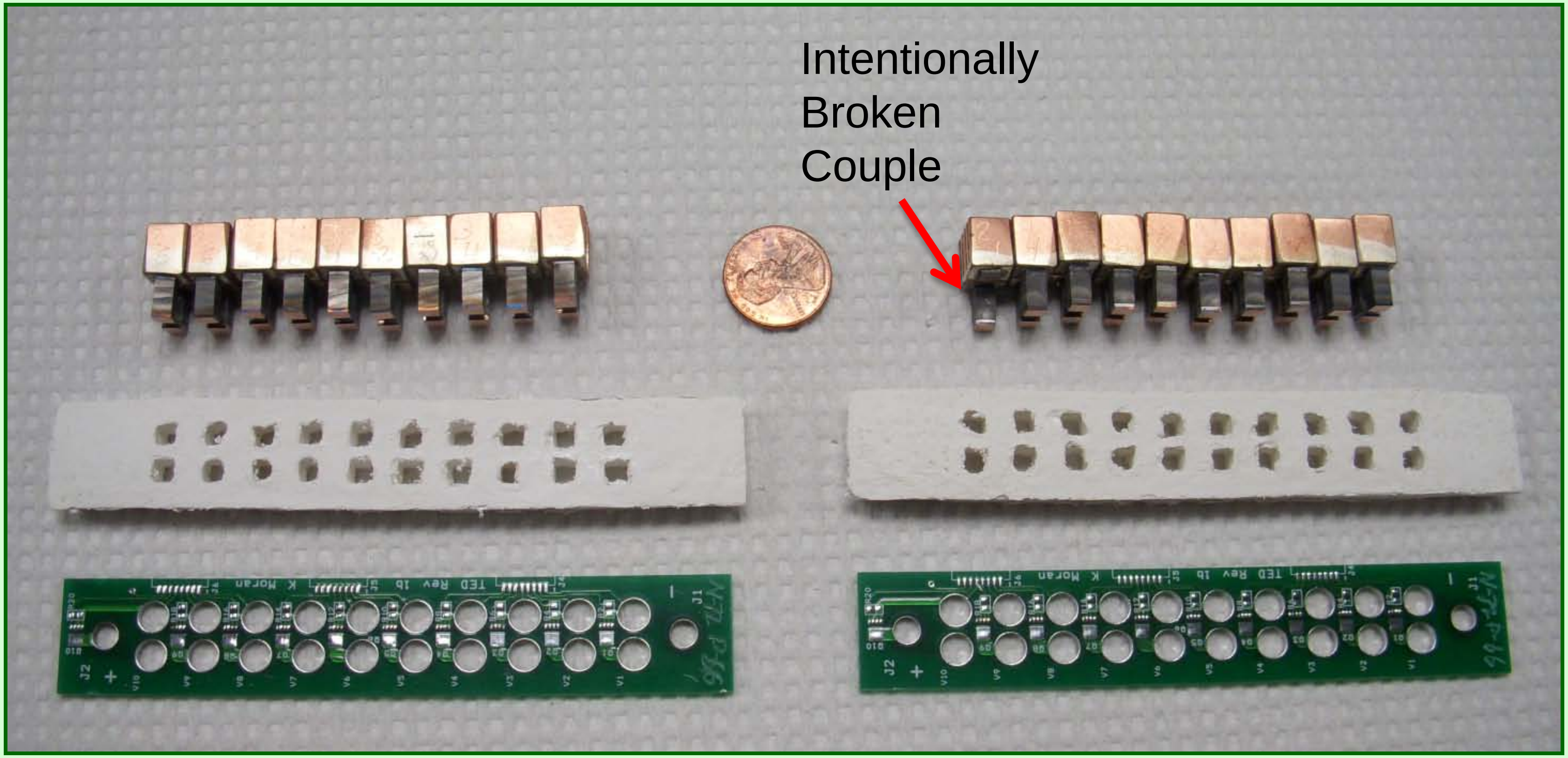
Module with aerogel insulation mounted to cooling plate

Five insulated modules and cooling plates assembled into circular generator



Module with Couple Bypass Technology (CBT)

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



CBT Module Experimental Results and Projections

Module Power Measurements (modules shown on previous slide)

- 10-Couple Power (550C ΔT) Module Experiment: **4.75 Watts** at 0.75V and 6.35 Amps
- 10-Couple Power (550C ΔT) 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

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

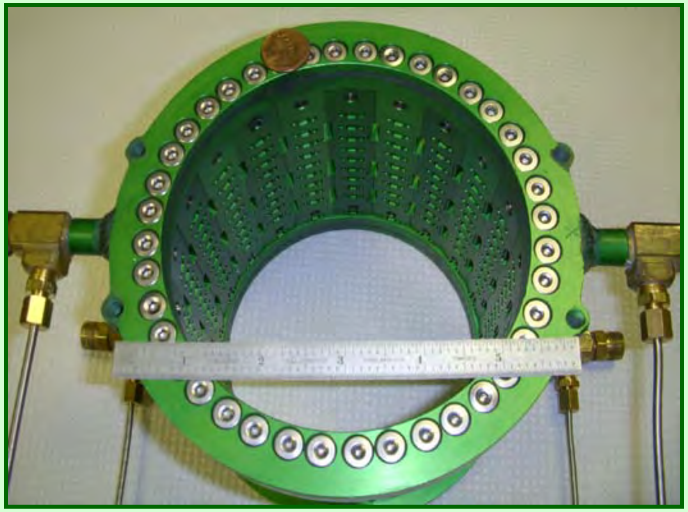
95W – Based on module demonstrated (TEG, 15V and 6.35Amps, each module 4.75W, 0.75V)

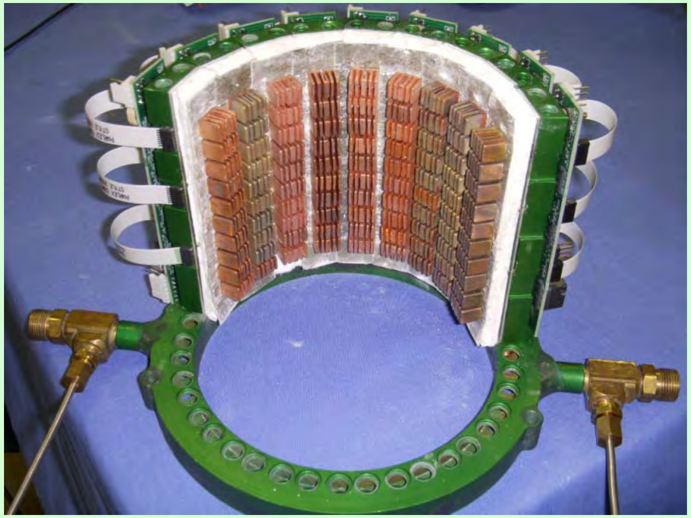
122W – Based on best couple taken from puck used to fabricate module describes above

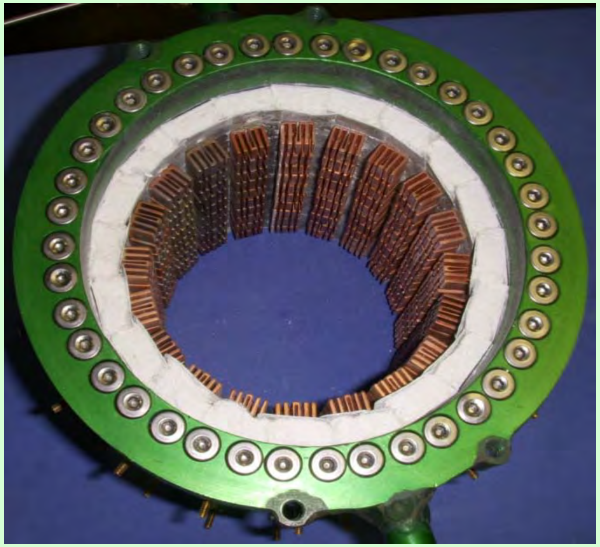
200W – Based on best couple measured of this Size (3.5x3.5x7mm)

*** P and N legs csa not optimized for heat flow, Outside dimensions of Gen 3-TEG: Diameter = 165mm, Length = 150mm ~200 cubic inches**

Gen 3 - 20 Module TEG with CBT



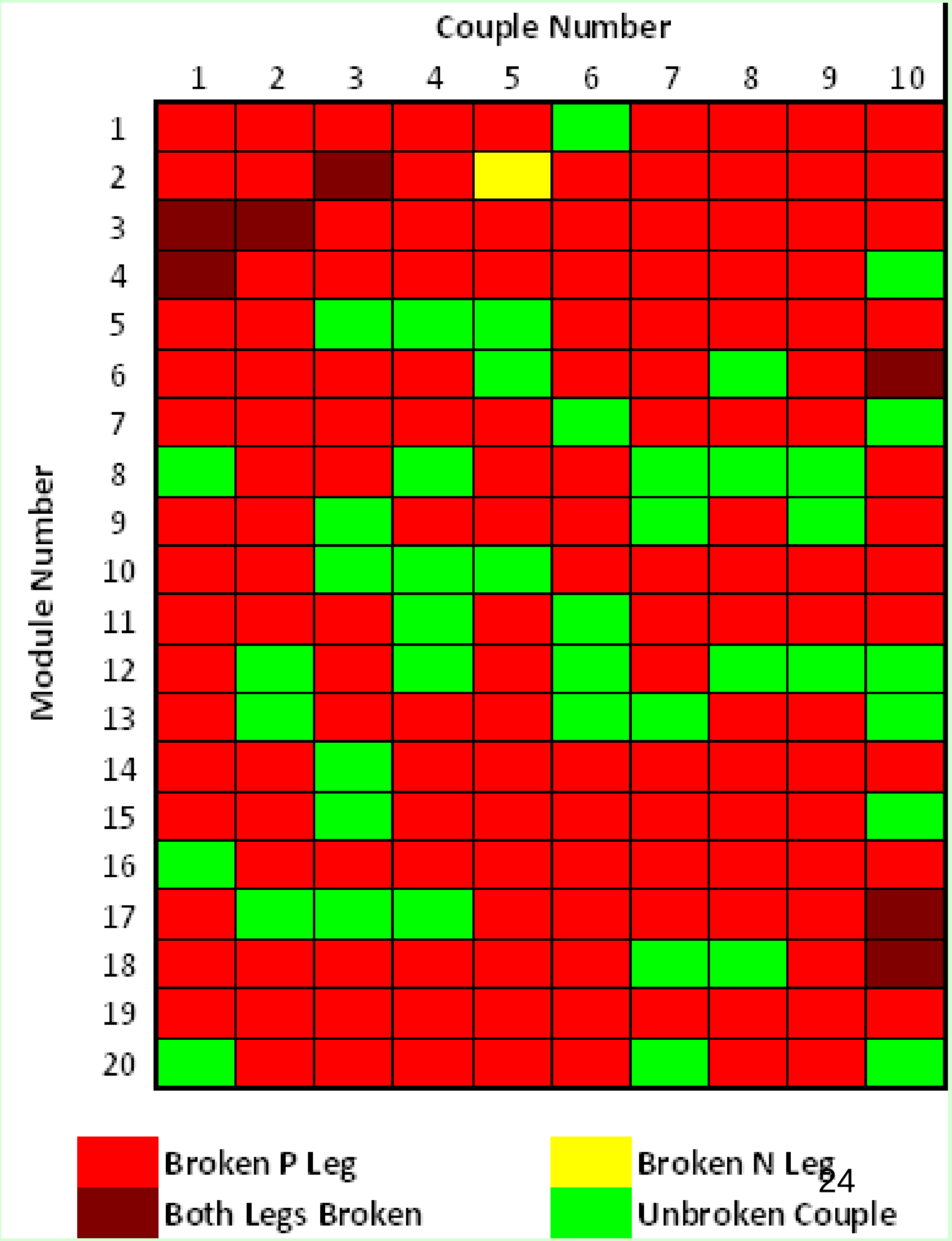


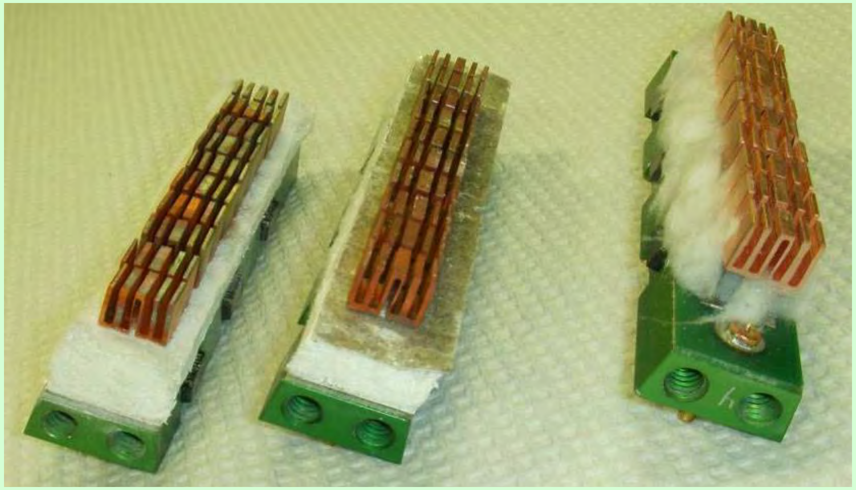


Couple Failure Grid – Gen 3 TEG

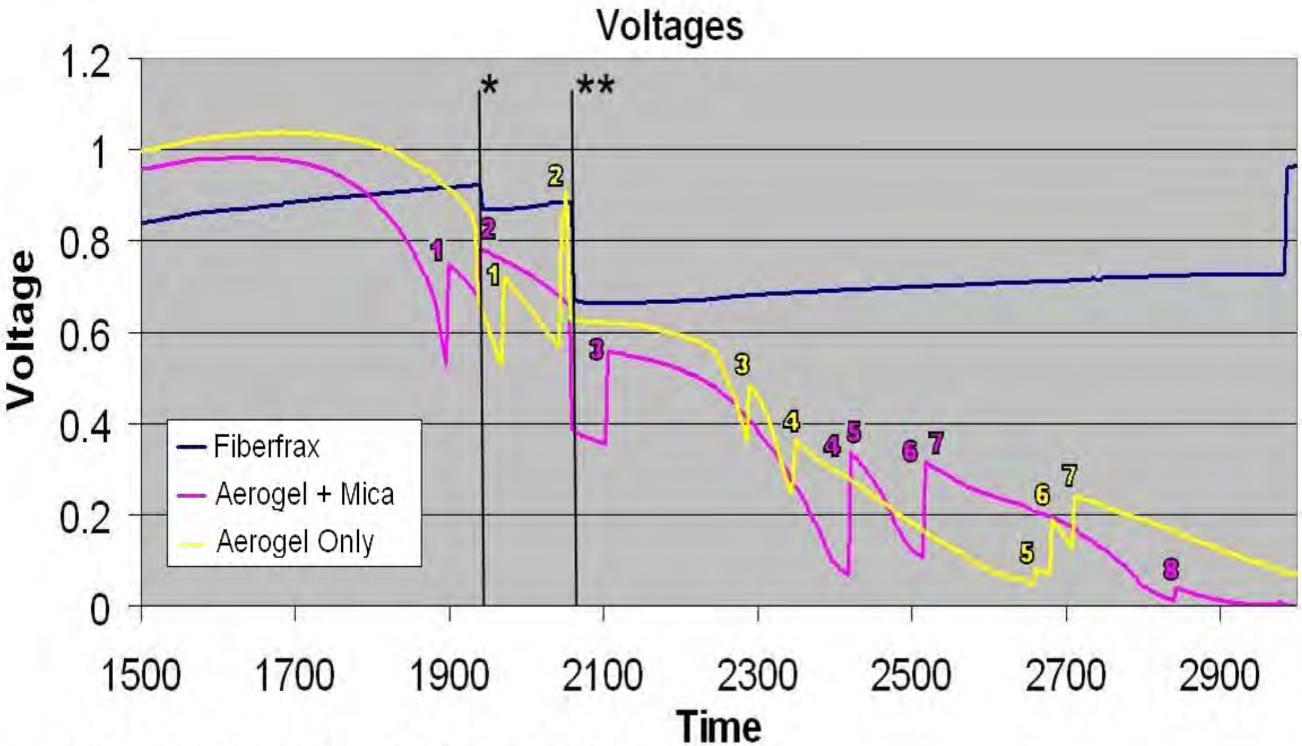
- **Number of Broken Couples: 156/200**
  - P-Leg Breaks: 155 (78%)
  - N-Leg Breaks: 8 (4%)

- **CBT system validation by measuring couples from disassembled modules:**
  - Best Case: 100% accurate
  - Worst Case: 91.6% (some may have been broken during disassembly)





What caused Gen 3 TEG couples to fail? 3, 5W Module Insulation Test



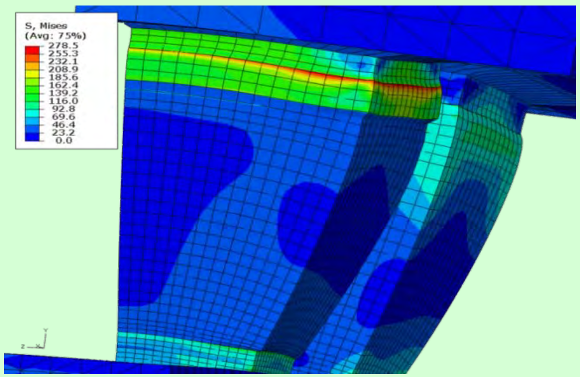
* Modules Loaded with External Resistance (0.11 ohms)

** Modules Loaded with External Resistance (0.44 ohms)

Number of Broken Couples

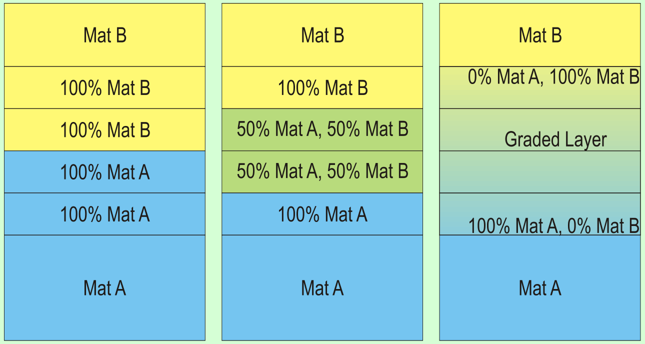
- **No insulation: 8 cycles completed without failure** (see previously described single couple test, slide 16)
- **Commercial Wool Insulation: 2/10**
- **Aerogel(k_{wool}/2): 7/10**
- **Aerogel with Mica Film: 8/10 <(k_{wool}/2)**

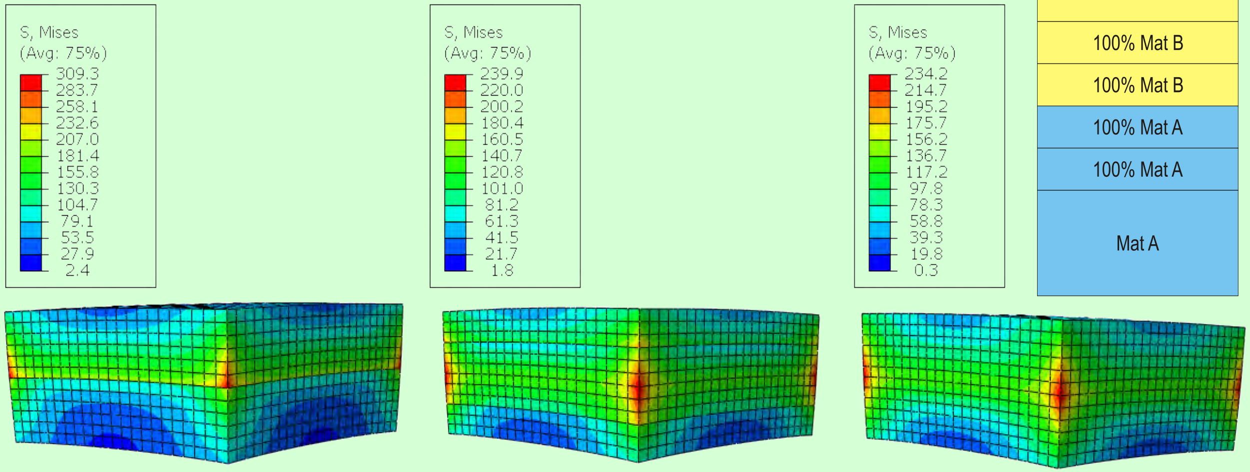
Stress Distribution in Couples and Methods of Stress Reduction



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)





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- **Future Work – New proposals/projects and collaborations**
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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 of couples and modules demonstrated
- Major Issues that Impede Advanced TEG Implementation Understood
- Couple Bypass Technology(CBT) developed and demonstrated permits electrical series configuration for couples and modules. CBT facilitates couple and module development.
- A 2% improvement in bsfc for 2010 Class 8 trucks (at cruise load) will require 4kWe TEG/s…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, see backup slide)
- Additional engineering work needed for :
  - Resolve hot side interface issues: **Performance vs reliability issue**
  - Develop manufacturing processes for viable mass production of couples and modules

Acknowledgements

US Department of Energy, Energy Efficiency Renewable Energy (EERE): John Fairbanks and Samuel Taylor project managers

Oak Ridge National Laboratory, High Temperature Material Laboratory: Drs. Edgar Lara-Cuzio and Hsin Wang

Office of Naval Research, MURI Program that supported our early activities in thermoelectrics

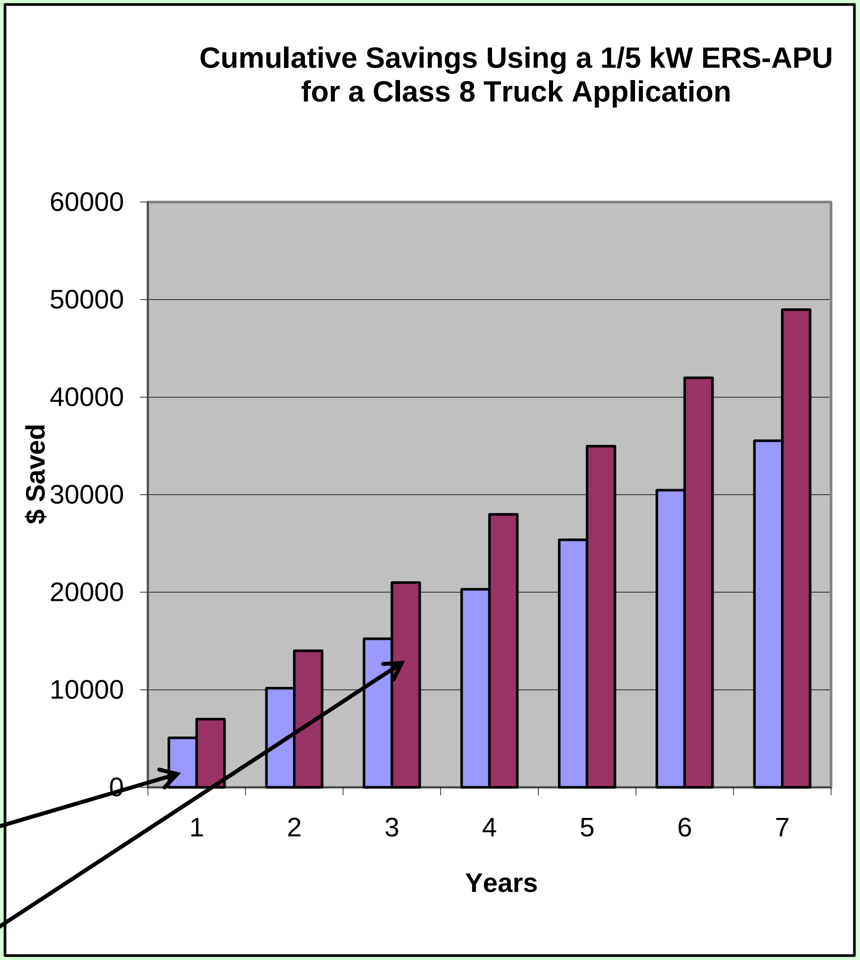
Our partners: NASA-JPL, Cummins, Purdue/Iowa State, Tellurex and Northwestern

Backup Slides

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

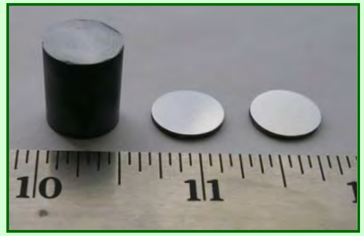
Total 1 kW System Price Based on Four Subsystems

• 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~~
	$3739.71 *
Total 5 kW System Price	~~$19276.13~~*
(* Arrows point to payback date)	**$13464.63**

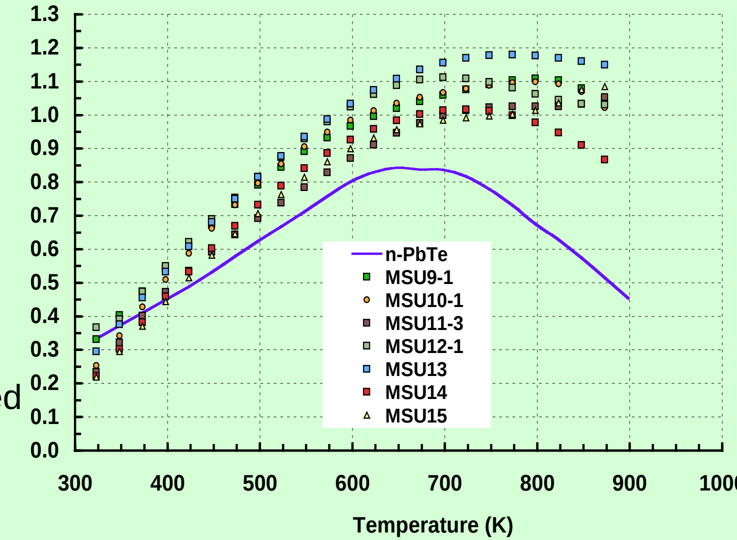


Skutterudite Materials and Metallization at JPL

- 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

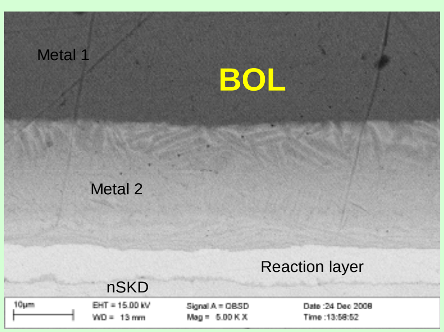


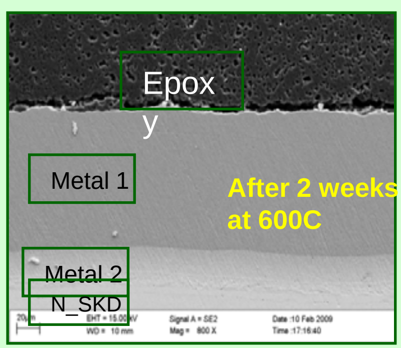
Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$



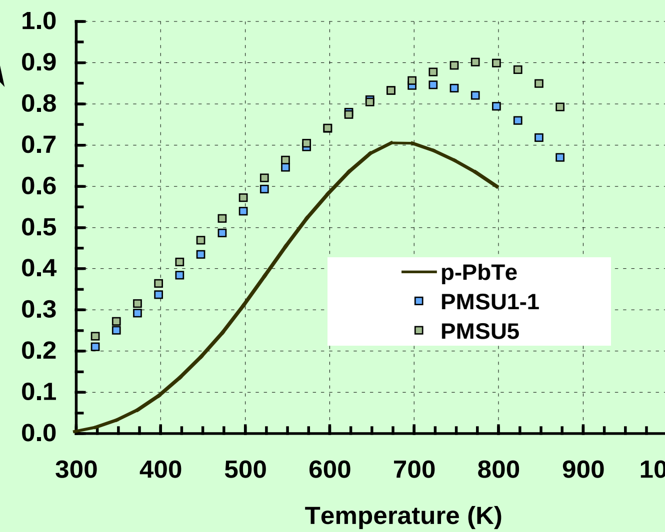
ZT values for n-type $Ba_xYb_yCo_4Sb_{12}$ ball milled materials. Each set of data corresponds to a separate 100 g batch.

- 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



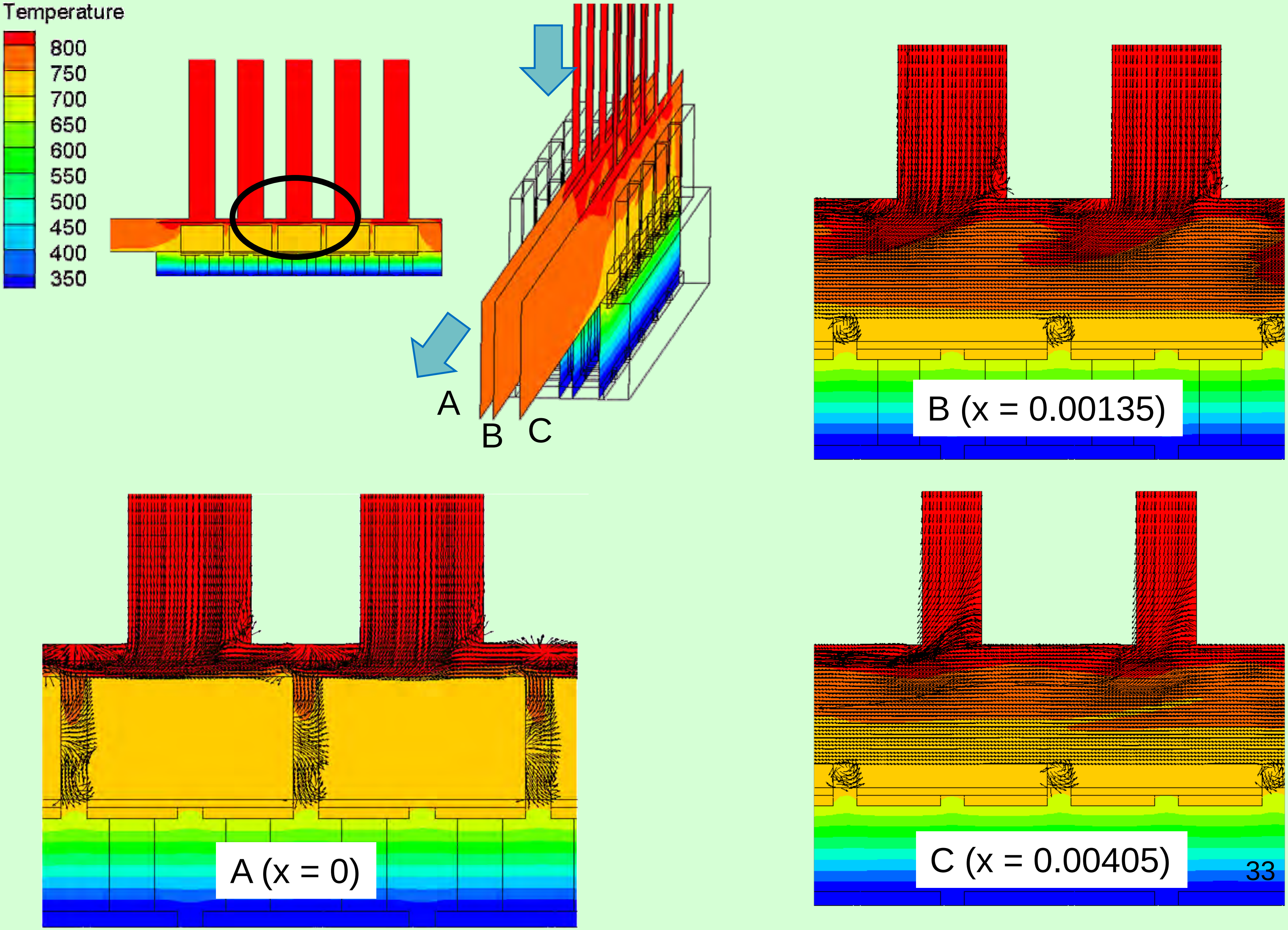


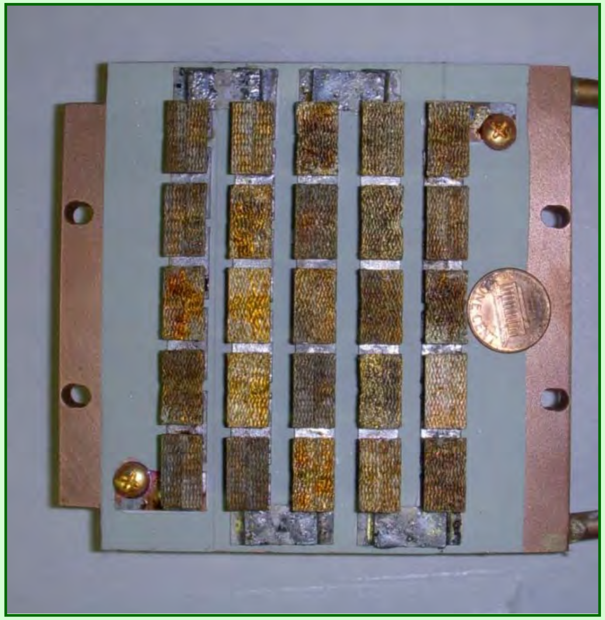
SEM images showing the SKD/metallization interface at beginning of life (BOL) and after 2 weeks aging at 600C. After aging, no degradation of the interface and no significant metal/SKD diffusion is observed.



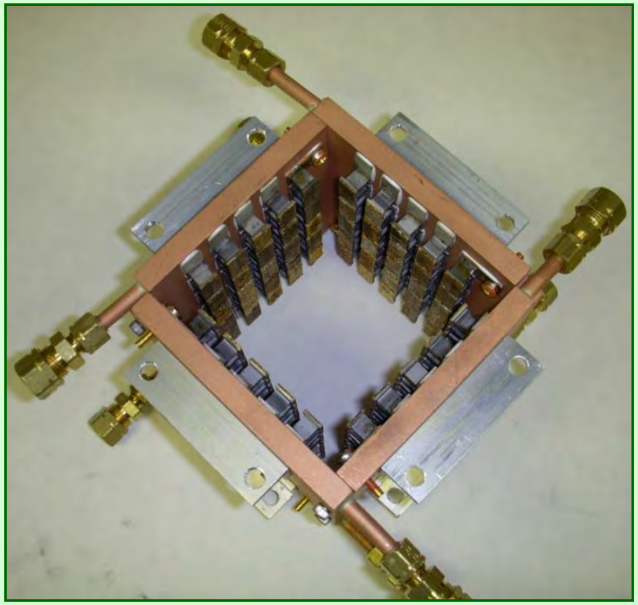
ZT values for p-type $Ce_xFe_{4-y}Co_ySb_{12}$ ball milled materials. Each set of data corresponds to a separate 50 g batch.

CFD Flow Calculations for Optimum Heat Transfer

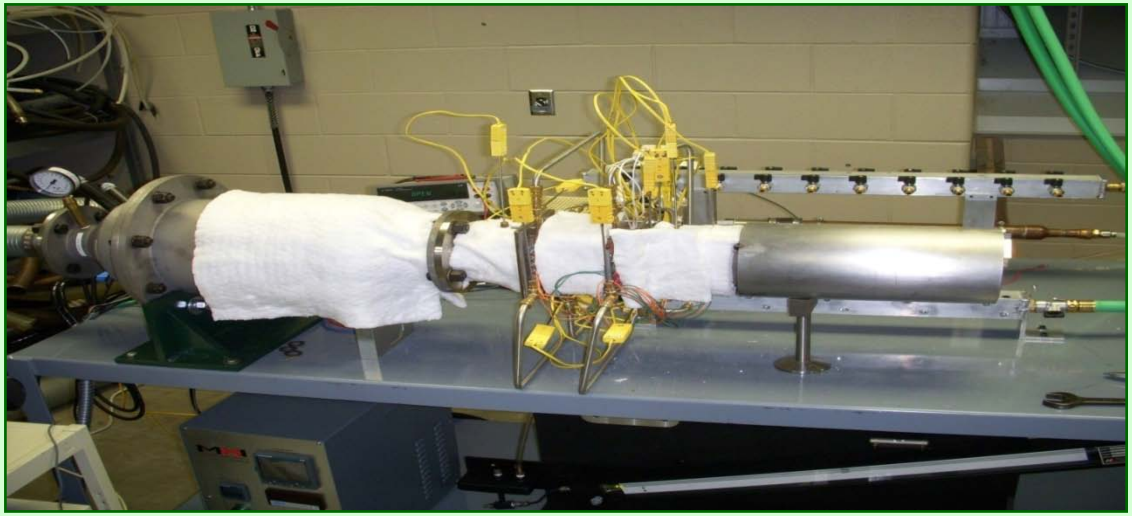




5 - 13W Modules (theoretical @ ΔT=600C) before Insulation



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



Gen 1 TEG Testing Assembly at MSU

Potential for Future Vehicle Experiments at the Energy and MSU Automotive Research Lab – 1MW Dynamic Absorption

Vehicle arrived 21 January 2010 - 1800 hrs

Vehicle departed 2 February 2010 - 1800 hrs