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

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Prepared by:

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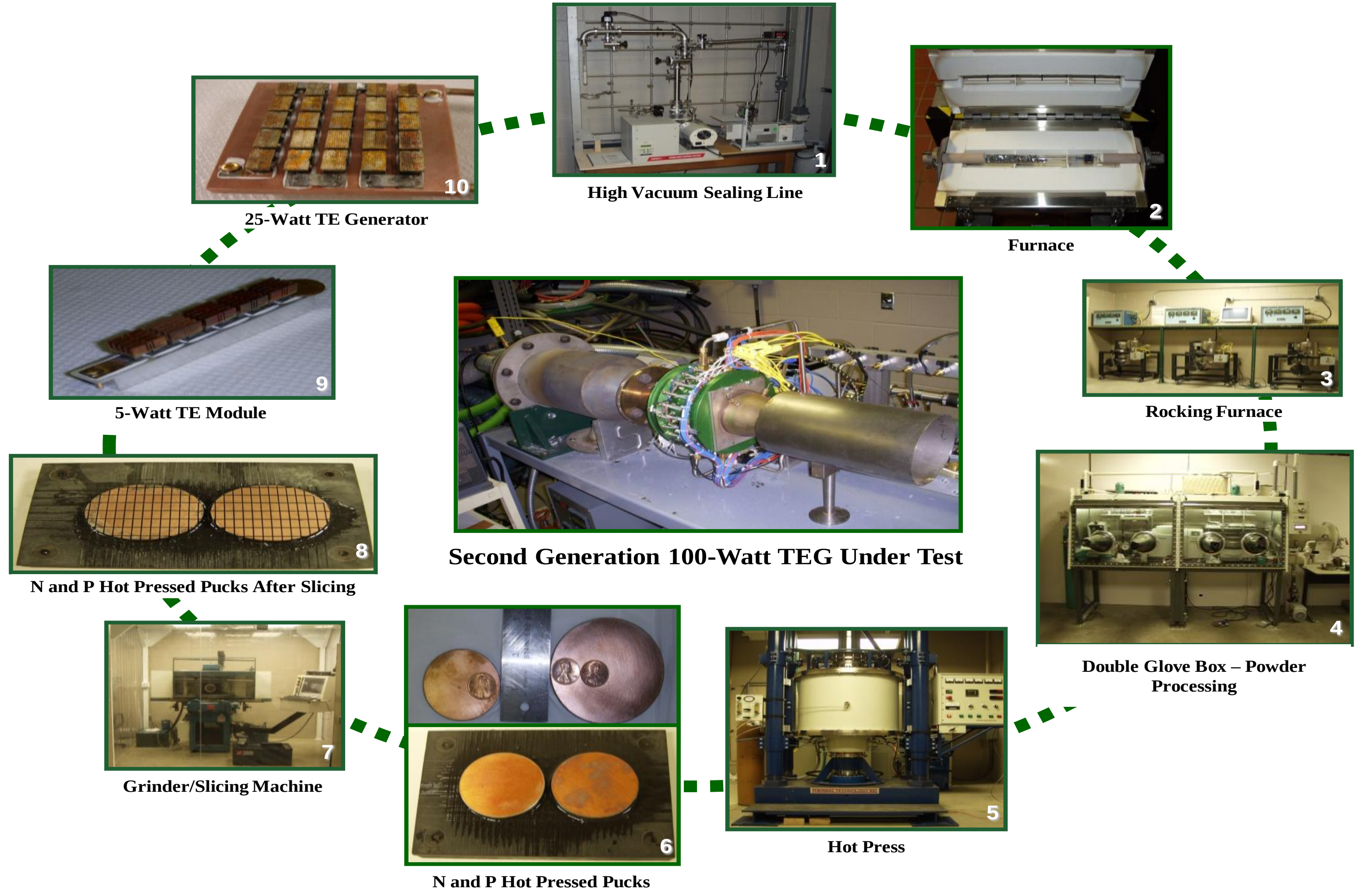
John Fairbanks and Samuel Taylor, Contract Monitors

Objectives and Relevance to DOE Goals

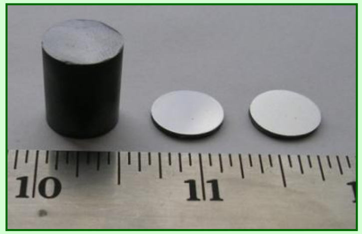
- Using a TEG, provide a 10% improvement in fuel economy by converting waste heat to electricity used by the OTR truck
- Show how advanced thermoelectric materials can provide a cost effective solution for improving fuel economy and idle reduction for an OTR truck
- Determine steps necessary to demonstrate a 1kW TEG
  - ➢ 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

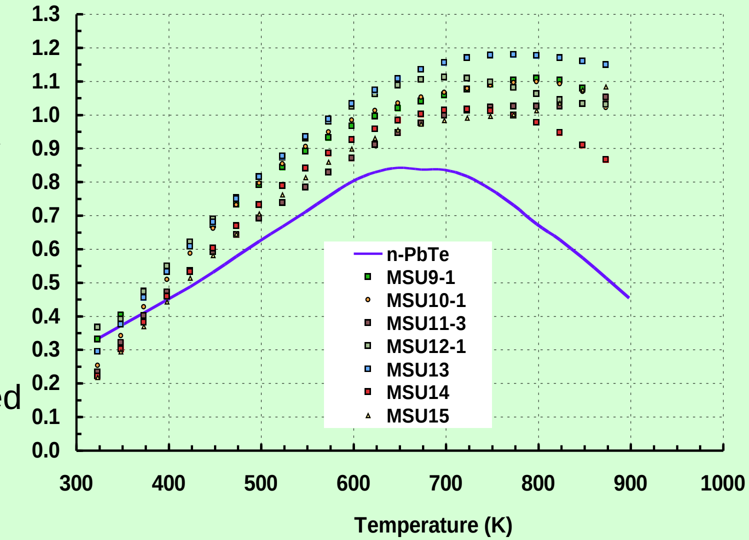


Skutterudite Materials and Metallization at JPL

- 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

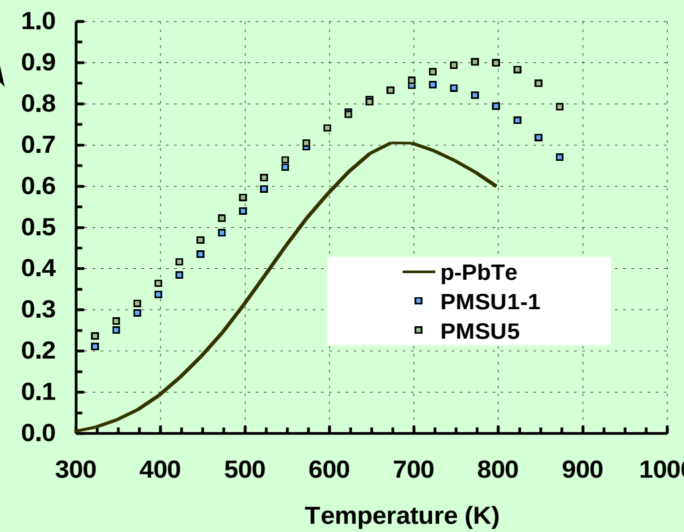


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

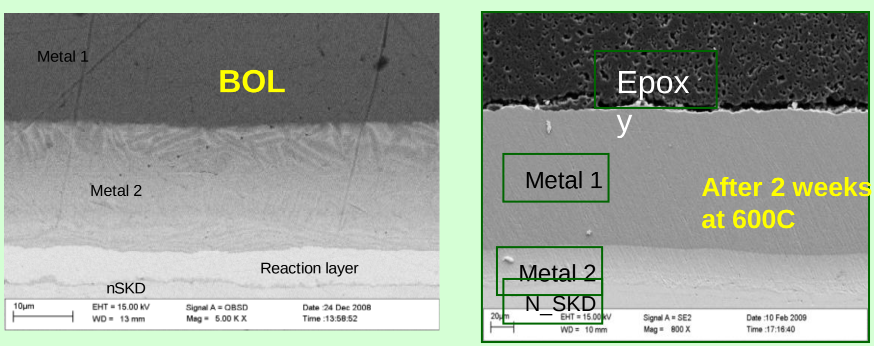


ZT values for n-type $Ba_xYb_yCo_4Sb_{12}$ ball milled materials. Each set of data corresponds to a separate 100 g batch.

- 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



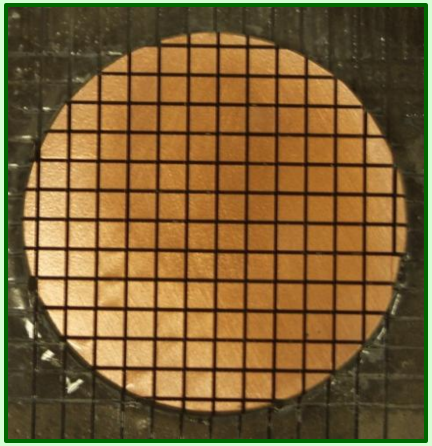
ZT values for p-type $Ce_xFe_{4-y}Co_ySb_{12}$ ball milled materials. Each set of data corresponds to a separate 50 g batch.



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.

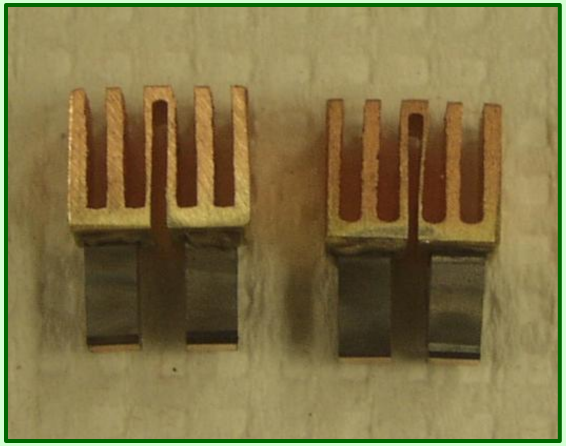
MSU Hot Pressing and Unicouple Fabricating Capabilities

Hot Pressing
2” or 3”
~ 7 hours/puck
8 pucks/week



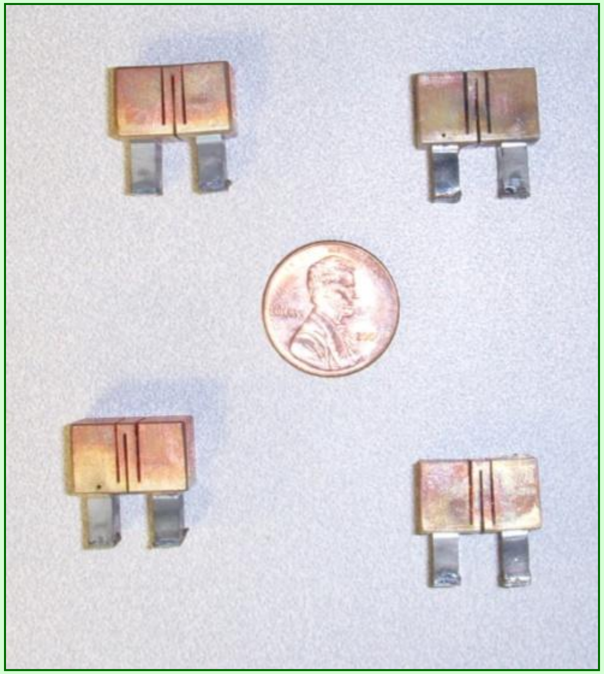
Dicing 2” puck
Yields 112 legs
3.5 mm x 3.5 mm

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

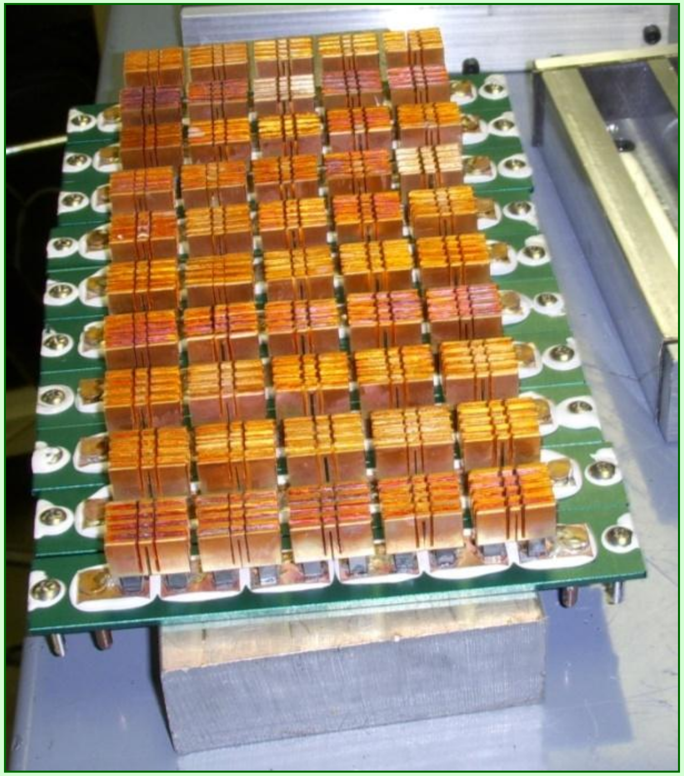


Unicouple fabrication 20 per batch run, ~80 per 8 hr day, 200-360 Watts per week

MSU Fabricated Unicouples and Modules

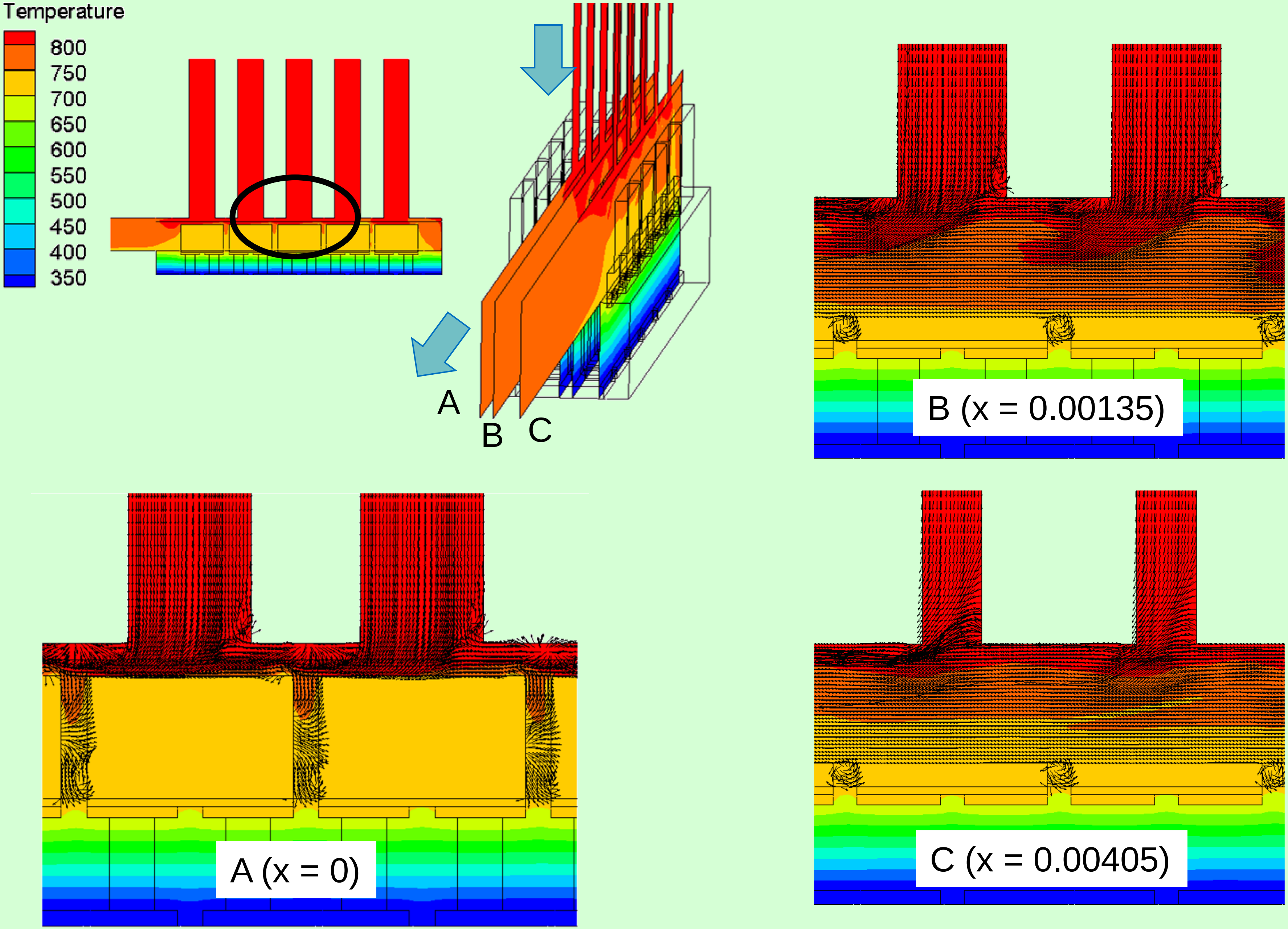


Unicouples ready to be made into modules with MSU expansion joint design

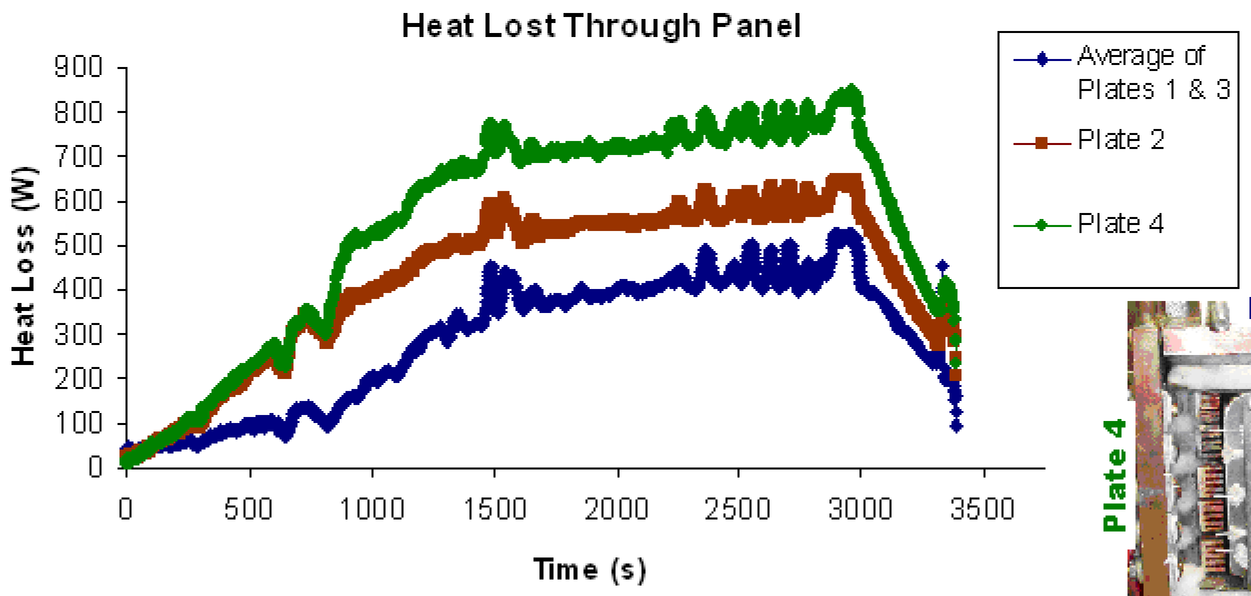


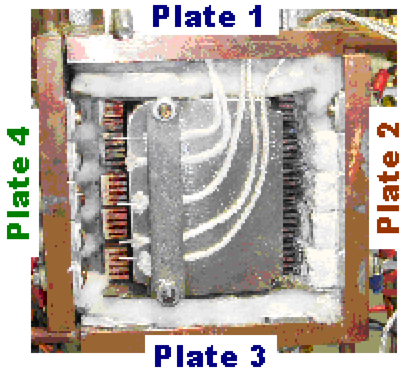
Multiple 5-Couple modules assembled and ready for aerogel insulation

CFD Flow Calculations for Optimum Heat Transfer



Aerogel vs High Temp Wool Insulation

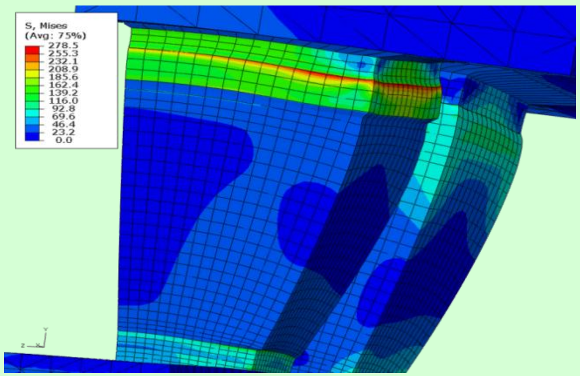




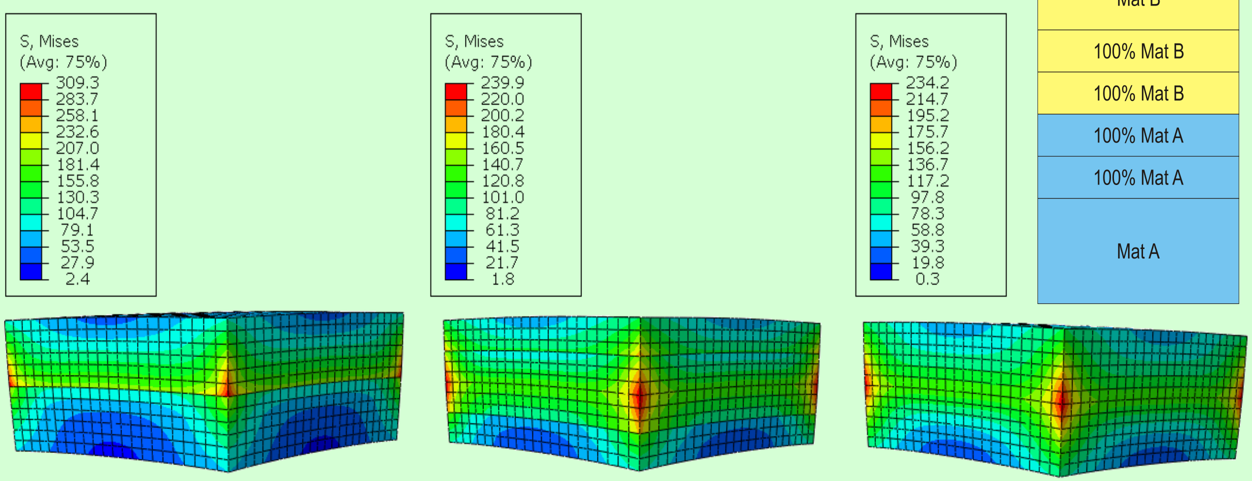
- **Average of Plates 1 & 3: high-temp wool with mica sheet, no modules**
- **Plate 2: Modules, aerogel insulation**
- **Plate 4: Modules, high-temp wool**

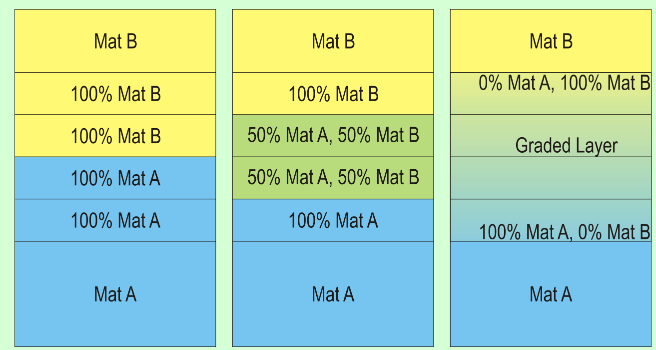
Stress Distribution in Couples and Methods of Stress Reduction

High stresses high at hot side interfaces

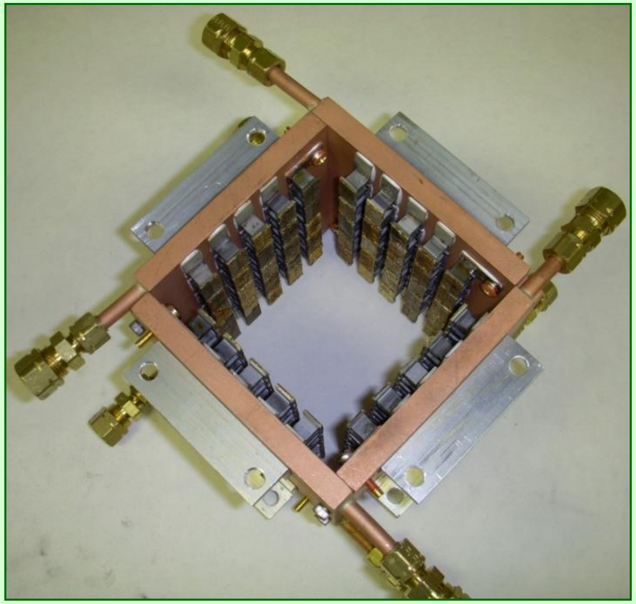


Stress distributions at Layers 1 through 4, pure layers at the left, 50-50 layer in the middle, and graded layer at the right. … (25% stress reduction)

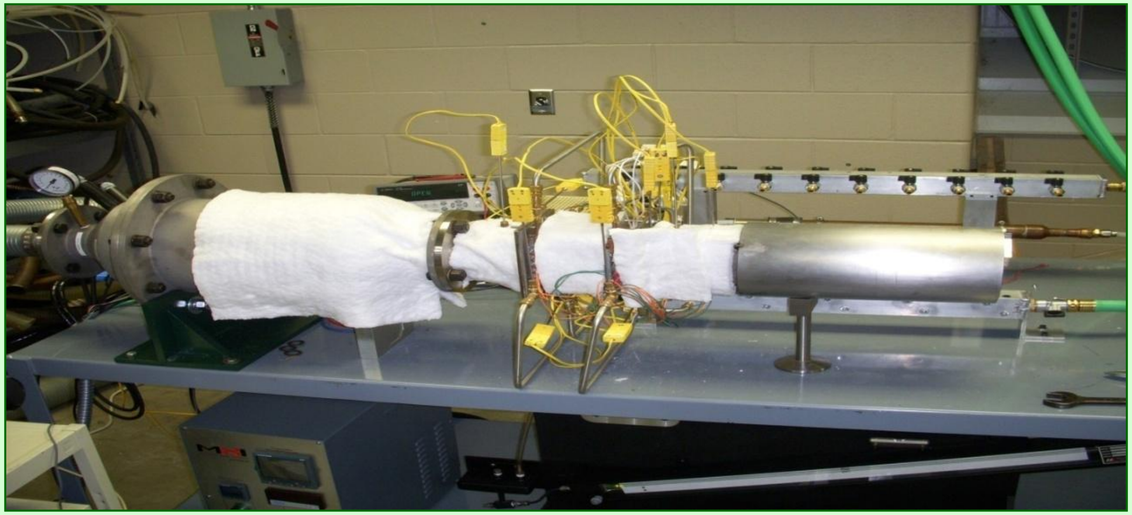




5 - 13W Modules (theoretical @ ΔT=600C) before Insulation

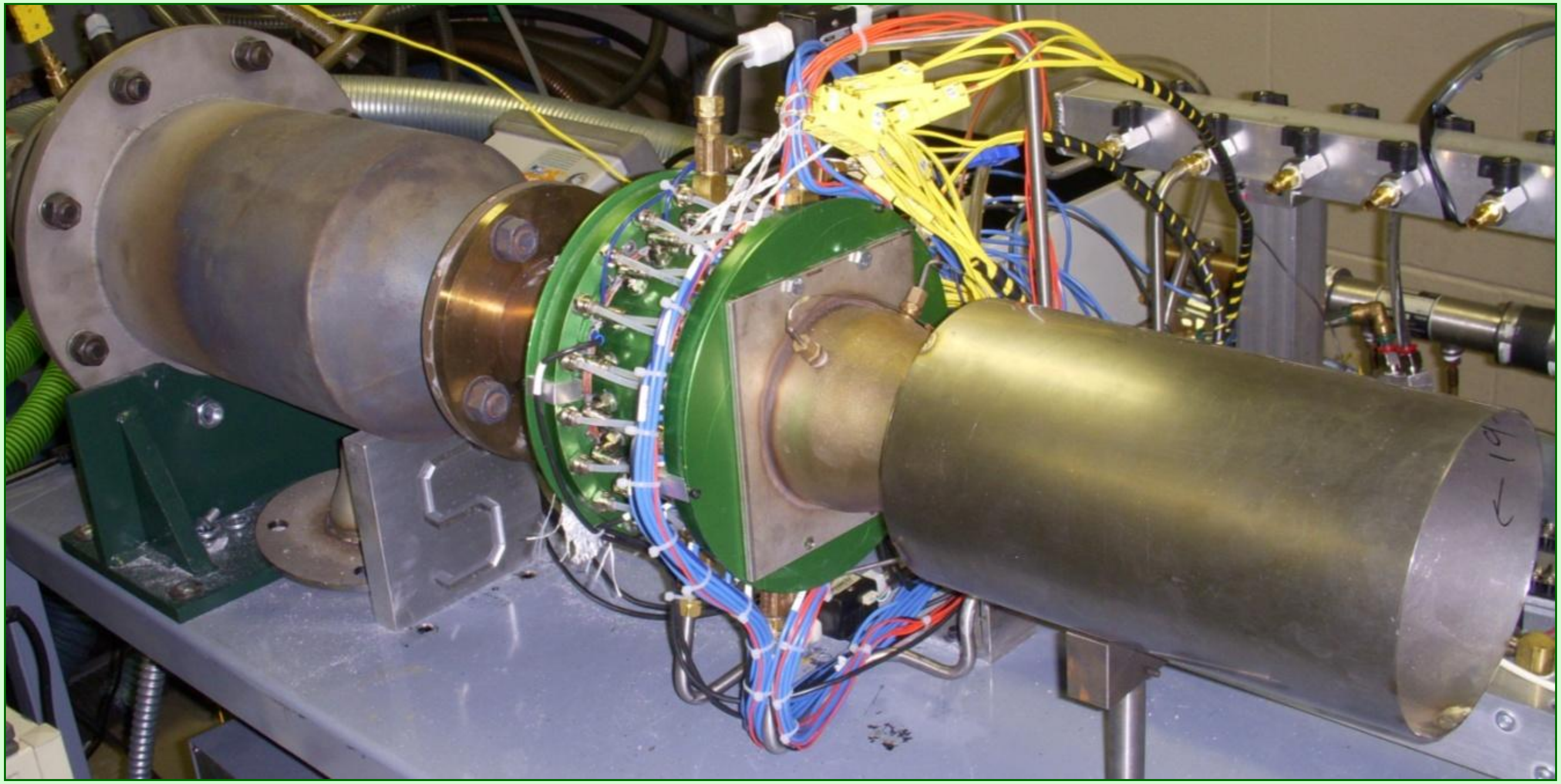


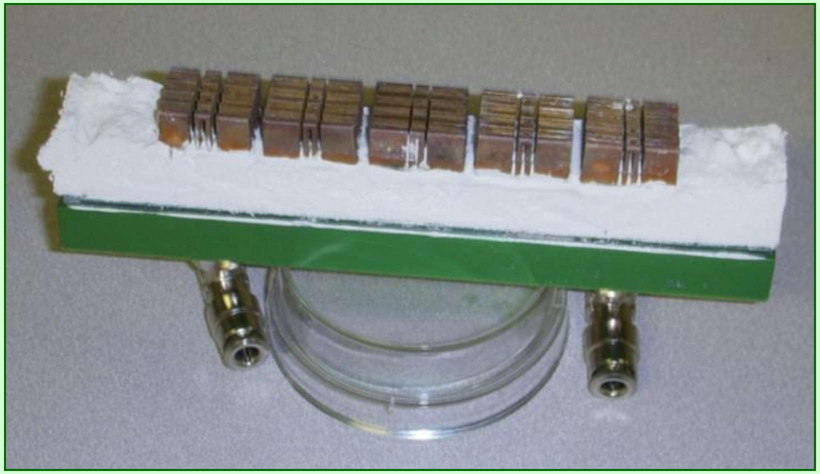
TEG – 260W (theoretical @ ΔT=600C) 20 – 13W Modules



Gen 1 TEG Testing Assembly at MSU

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

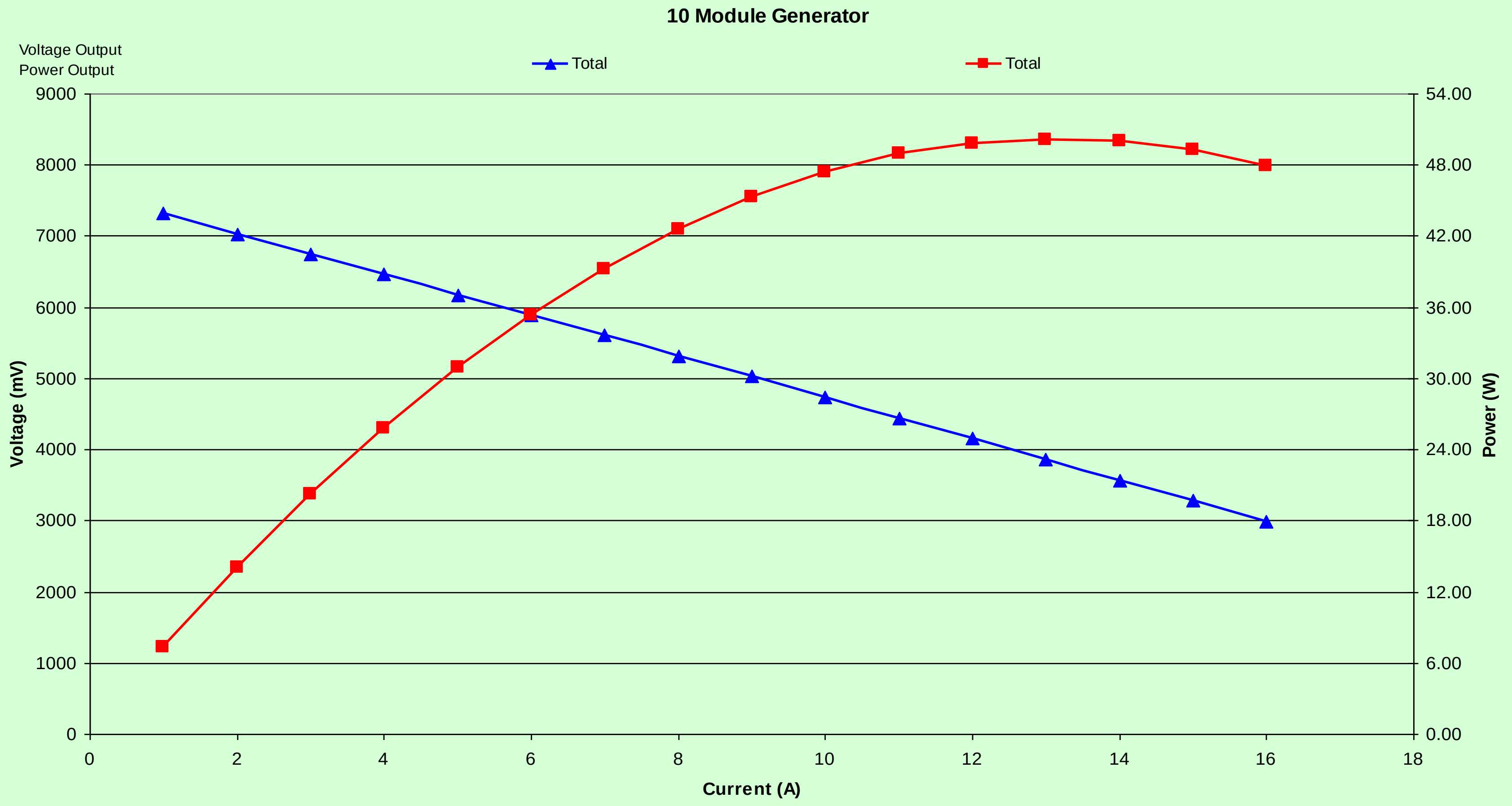




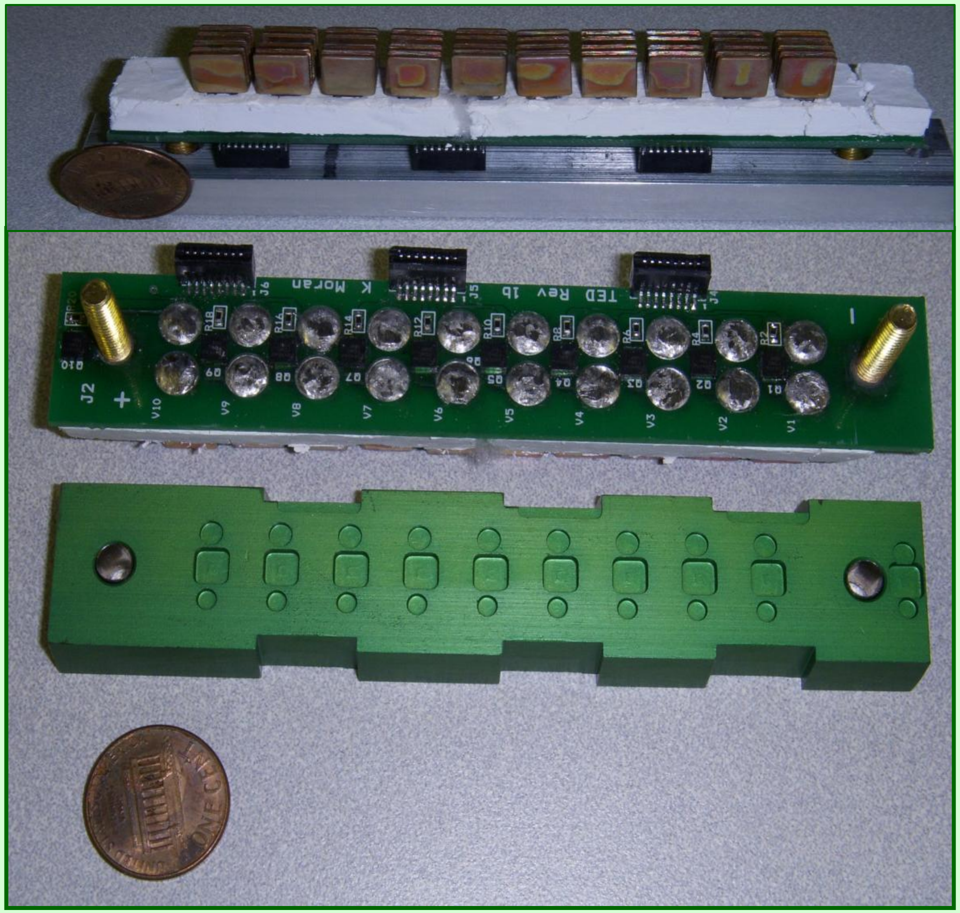
Module with aerogel insulation mounted to cooling plate

Five insulated modules and cooling plates assembled into circular generator

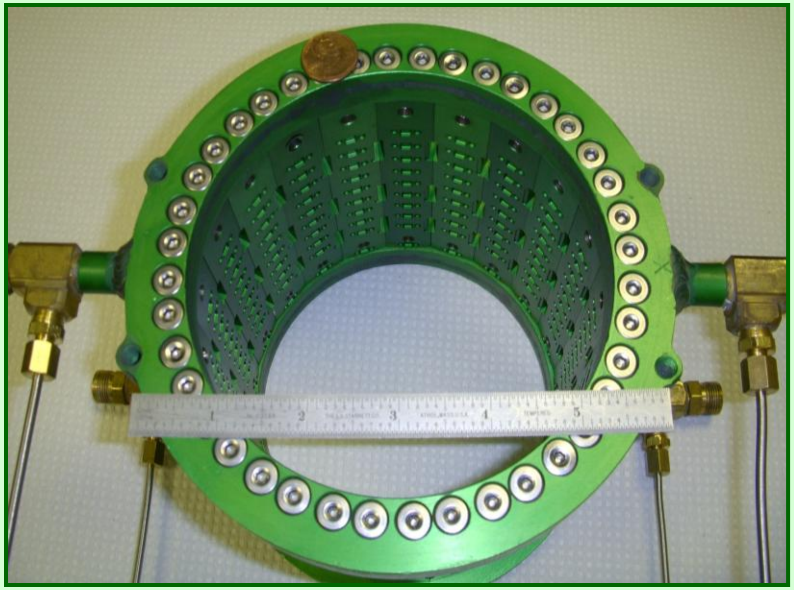
10-Module TEG output ~50.12W, ΔT~550ºC (8/4/09)
Best Result at MSU to Date from 50/100W Generators
(50W nominal produced 50.12W, Gen 1 100W nom. – 73W, Gen 2 100W nom. – 70W)

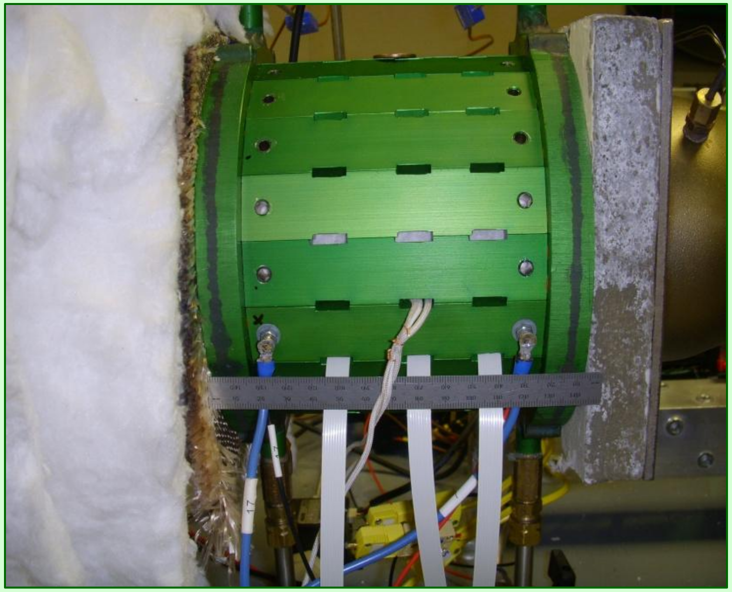


Module with Couple Bypass Technology (CBT)

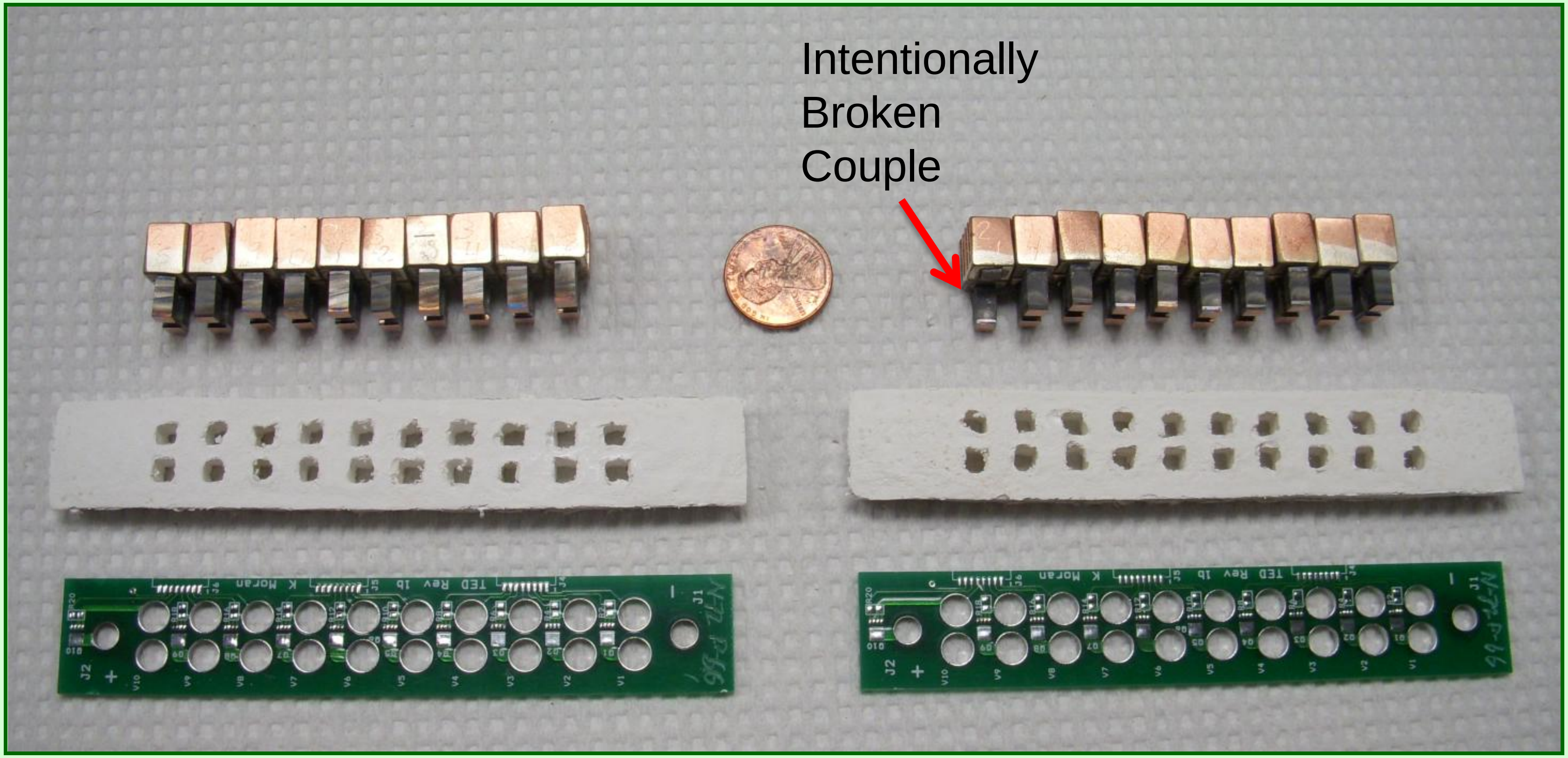


Gen 3 - 20 Module TEG Housing with CBT





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



CBT Module Experimental Results and Projections

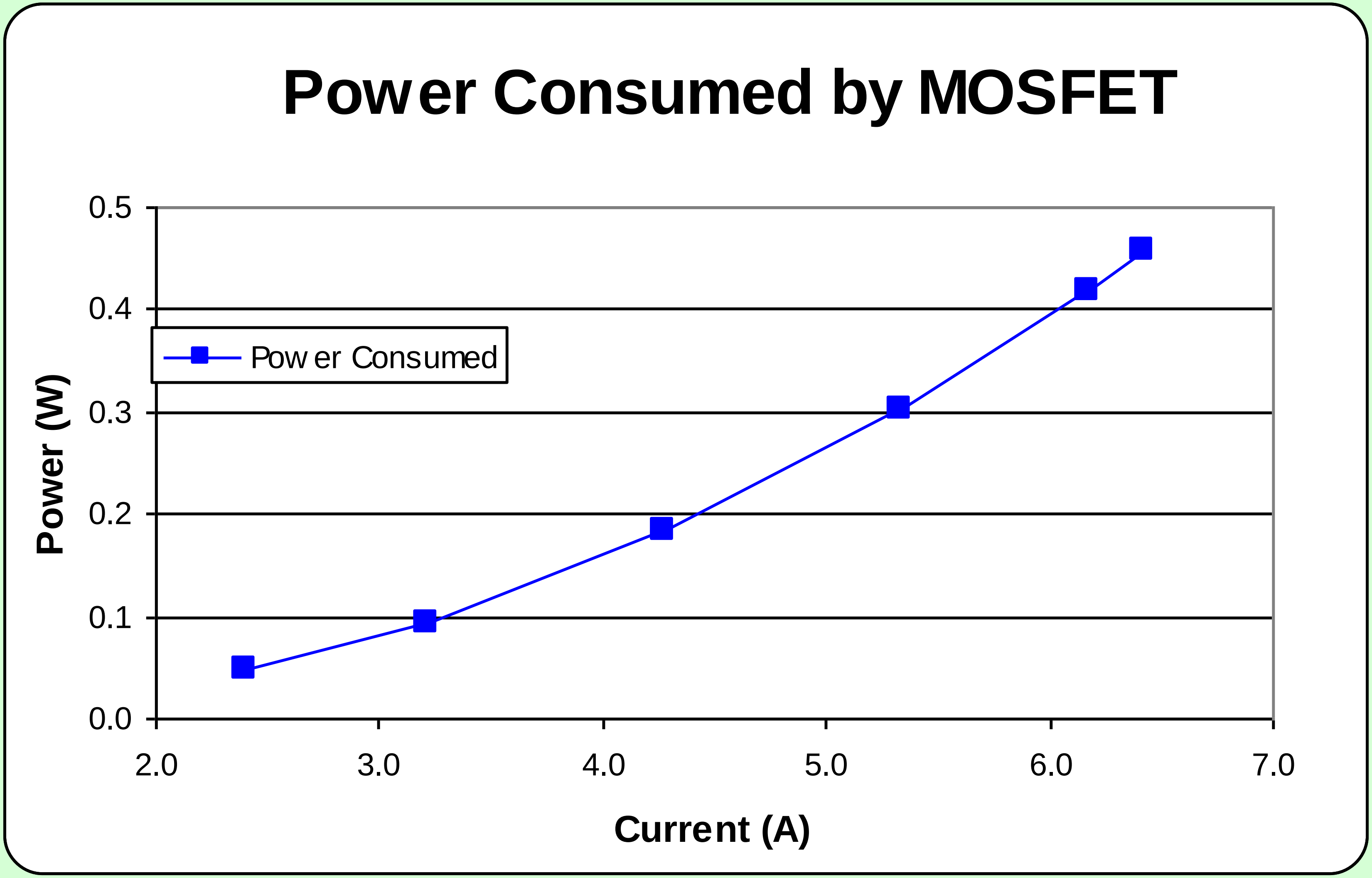
Module Power Measurements (modules shown on previous slide)

- 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)

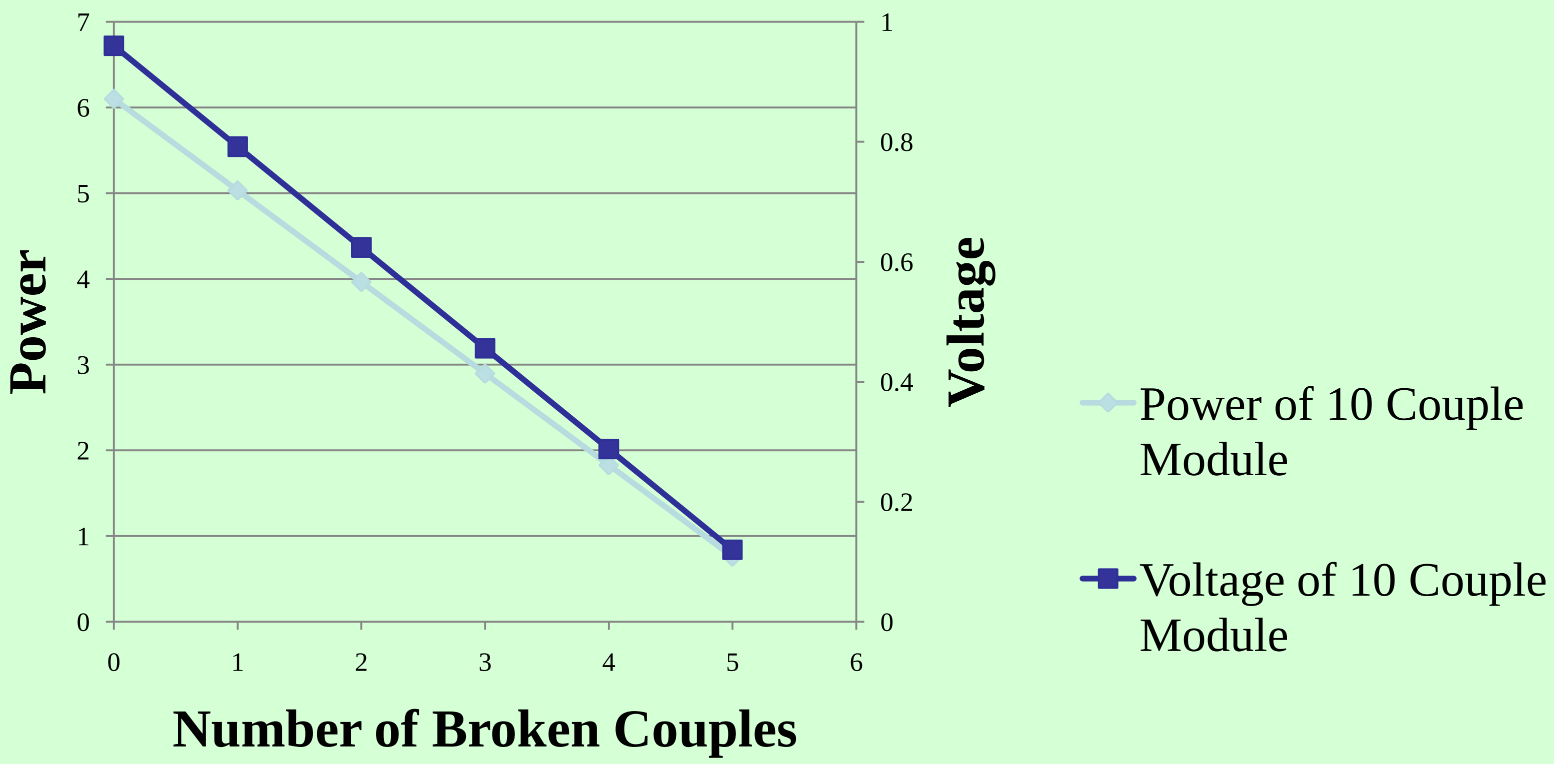
Module Power ***Estimates*** based on Single Couple Measurements

- 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
- Estimate of Module Performance Based on Worst Couple in above module: Module Power (550C ΔT) 3.2 Watts at .503 Volts and 6.35 Amps

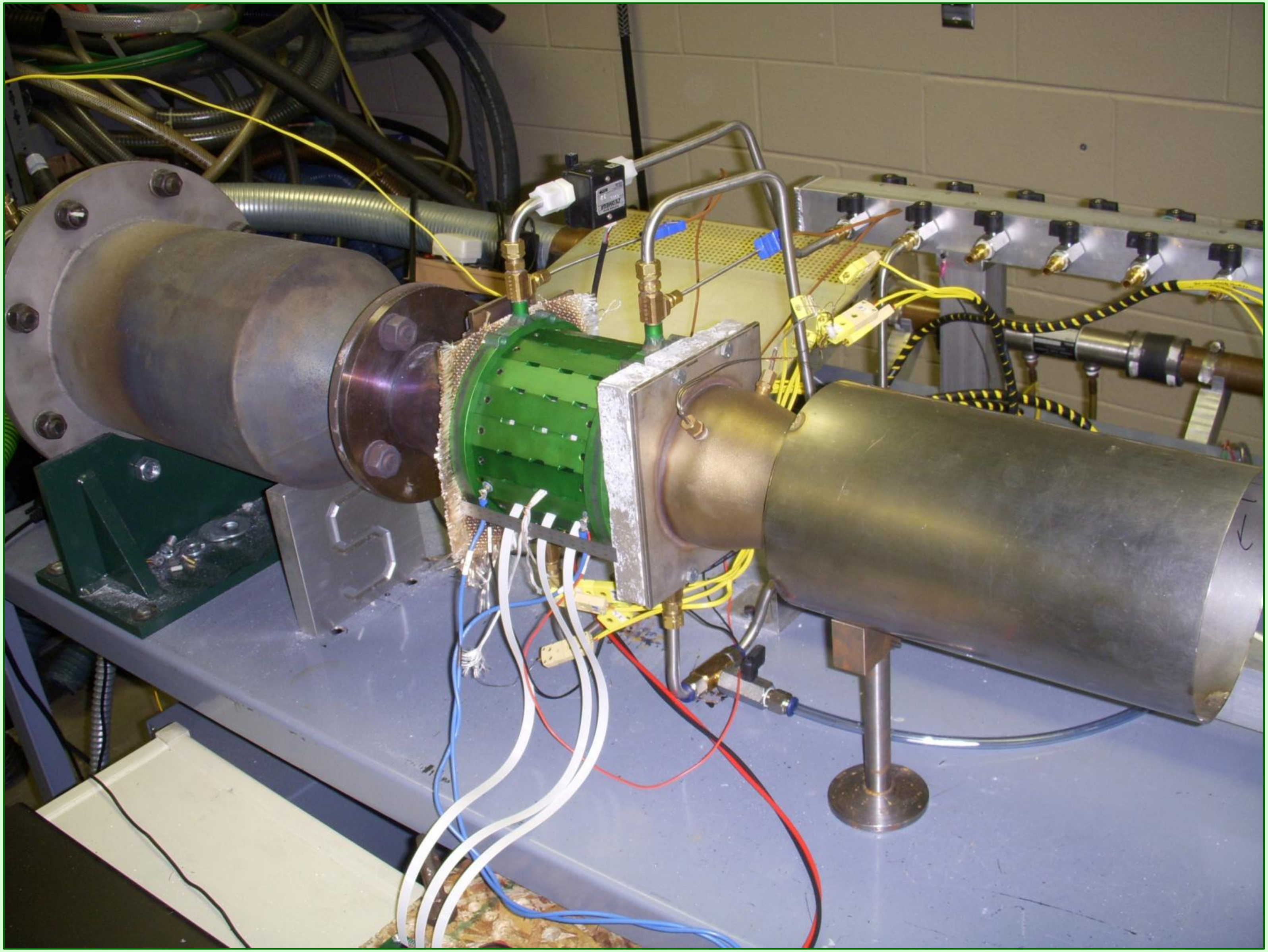
Power Consumed by MOSFET



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**

Analysis of Implementing a 1kW ERS-APU for Waste Heat Recovery and Idle Reduction for a Class 8 OTR Truck

- **Assumptions**
  - 1kWe ERS-APU operating on diesel fuel $4/gal (38.6MJ/liter), 5MPG base fuel economy, 1kW energy recovery engine exhaust energy recovery with belt integrated motor-generator, **7%** electrical energy conversion efficiency when operating as an APU (high temp, 0.35 gal/hr.), operates 300 days per year (8.3 hours on road and 8 hours with APU in operation (1kWe), 150K miles per year)
- **Savings Calculation**
  - From Waste Exhaust Heat: (150000 mi. per yr./5 mi per gal)-(150000mi./(5 + 5(0.004))mi per gal))= 120 gal/yr fuel savings (0.004 is 1/250kw for a 1kW ERS-APU)
  - From Idle Reduction: (0.829[1] gal per hr engine – 0.35 gal per hr for TE APU)(8hrs. Idle per day)(300 days per year)=1149 gallons per year fuel savings
- **Total Savings**
  - (120 + 1149 gal/year) ($4/gal)=$5076 per year or **$35532** over 1 M mile (7 year) life of engine
- **Other Potential Benefits**
  - Fuel savings due to an efficient motor-generator replacing an inefficient alternator, near silent operation, engine wear reduction due to reduced idling, emission reduction benefits. Fuel efficiency of heavy duty trucks could be improved by 8-12% by systematic electrification of accessories in a systematic fashion.[2] Implementation of a ERS-APU would hasten this electrification.

[1] Estimate of Fuel Use by Idling Commercial Trucks, Paper No. 06-2567, 85th Annual Meeting of the Transportation Research Board, Washington D.C. Jan.22-26, 2006

[2] Roadmap and Technical White Papers, USDOE-EERE, 21CTP-0003, Dec. 06

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

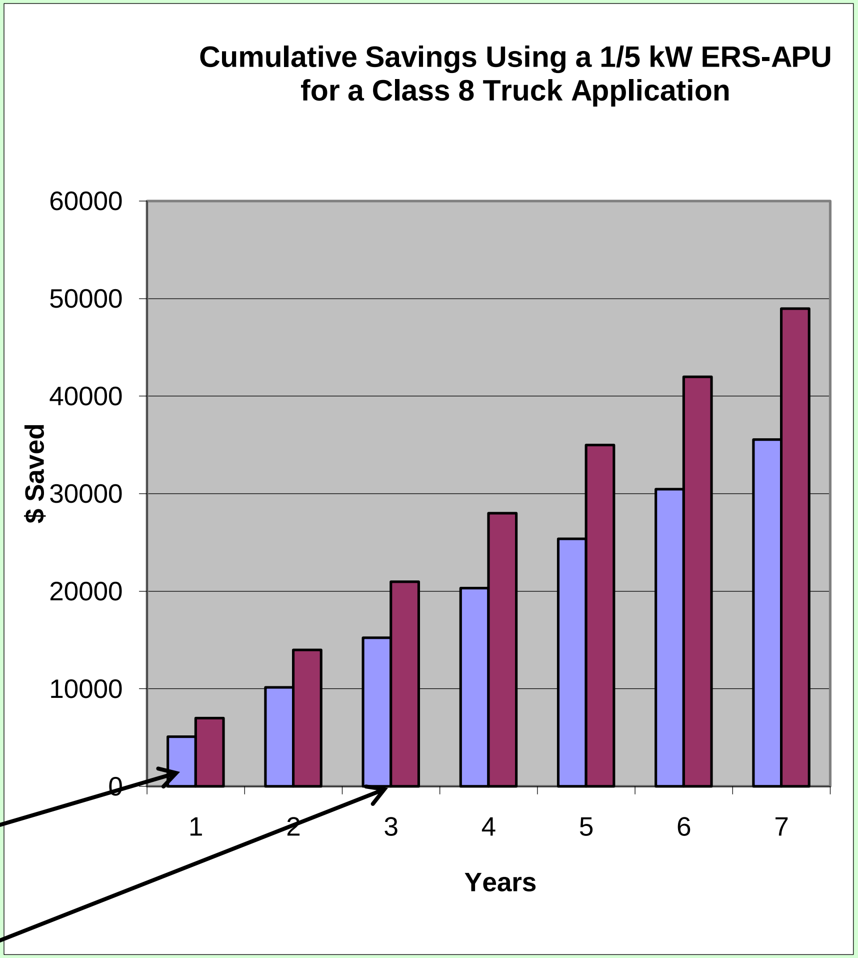
Total 1 kW System Price Based on Four Subsystems

- 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~~* **$16698.56**

(* Arrows point to payback date)



2010 Milestones and Important Issues

M1: Couple bypass circuit designed, validated and demonstrated (patent appl. filed). Technology termed **C**ouple **B**ypass **T**echnology (CBT)

M2: Better material reliability and longevity enabled by functionally graded material at hot side interfaces (patent appl. filed)

I 1: Hot side interfaces which are system material system dependent are not well established and still need development

I 2: Couple level performance needs to be translated to module level performance by reducing electrical and thermal resistive losses

I 3: Reproducibility and uniformity of fabricated legs needs improvement

Summary

- Systems for material synthesis, powder processing, hot pressing, leg and SKD module fabrication are operational at MSU (ingot to couple 95% utilization of material)
- Major Issues that Impede Advanced TEG Implementation Identified
- Couple Bypass Technology developed and demonstrated...permits electrical series configuration for numerous modules
- Using available TEG technology, a 3-5% improvement in bsfc for an OTR truck is a reasonable 5 year goal…first viable application may be as an ERS-APU for trucks and buses (1 and 3 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

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