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

Prepared by:

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NASA JPL

MICHIGAN STATE UNIVERSITY

Cummins

TELLUREX CORPORATION

NORTHWESTERN UNIVERSITY

Objectives

- Determine if by using a TEG, a 10% improvement in fuel economy is possible by converting waste heat to electricity for an OTR truck operating at cruise, loaded conditions
- Determine if advanced thermoelectric materials and optimum leg segmentation can provide a cost effective solution for improving fuel economy and idle reduction for an OTR truck
- 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

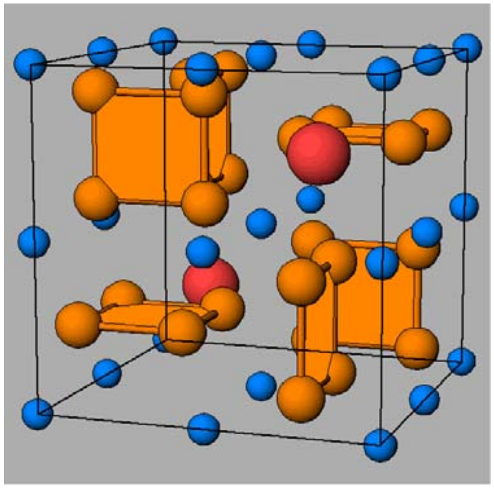
Milestones
(2008-2009)

- Methods for laboratory scale mass production of skutterudite (SKD) unicouples has been demonstrated at MSU (114 couples in four days, maximum theoretical output 296W, couples exhibit uniform performance characteristics …methods being developed will yield 250 couples in four days)
- Fault tolerance and voltage boosting (η>97%) power electronics have been designed and demonstrated
- The hot side thermal stress issue for SKD unicouples has been solved and a patent disclosure issued
- A 500W TEG has been designed and a 100W version tested (est. based tests of MSU fabricated SKD modules, maximum theoretical output 1.3kW at a ΔT = 600C)
- Cost-to-benefit analysis has been completed for 1 and 5 kW ERS-APUs
- **5, 25, 50 and 75 watt, gaseous N_2 heated, TEGs have been designed, constructed and tested (ΔT ~ 500-550C)**

12 Steps to a Prototype TEG

1. **Develop a thermoelectric material system (>90% of thermoelectrics research spending in the past 10 years has been in this step)**
2. **Mix elements in correct proportions and cast the ingot of advanced TE materials (200-500 grams or more at a time)**
3. **Powder process in an inert environment and then hot press the TE materials to improve mechanical strength**
4. **Develop methods to metalize the hot and cold ends of the hot pressed puck which is then cut into legs for module fabrication**
5. **Fabricate the modules so that heat is conducted through the hot side and cold side of the modules while both sides are electrically insulated from the hot and cold plates**
6. **Manage issues related to variable coefficients of thermal expansion while providing the appropriate diffusion barriers for various elements within the thermoelectric material**
7. **Design and construct the power electronics for fault bypass and voltage boosting**
8. **Model, design and construct the heat exchanger system required for this application**
9. **Provide high efficiency insulation to the modules (we use aerogel which is made at MSU, k=0.015W/mK) and suppress element sublimation**
10. **Test the generator performance to measure power output in watts for a give ΔT**
11. **Use numerical simulations to evaluate efficiency gains in a particular application**
12. **Conduct a cost to benefit analysis for the application of interest**

N-type skutterudite material development



Skutterudite crystal structure

Background

- High ZT reported in the 300-800K temperature range for $Ba_xYb_yCo_4Sb_{12}$ skutterudite compositions[1]
- High ZT values mainly attributed to low lattice thermal conductivity due to the broad range of resonant phonon scattering provided by the Ba and Yb fillers
- Samples used for this study were prepared by a multi-step synthesis process, potentially difficult to scale-up

Goal

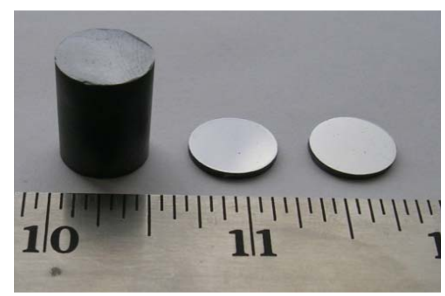
- Develop a scalable synthesis process for $Ba_xYb_yCo_4Sb_{12}$ skutterudite compositions and evaluate TE properties in a first step
- Evaluate applicability for integration into advanced TE couples for waste heat recovery applications

Approach

- **Ball milling**
  - High-energy ball mills: ≤ 15 g loads
  - Planetary ball mill: ≥ 50 g loads
- **Hot-pressing**
  - Graphite dies and plungers

Planetary ball mill

High-energy ball mill

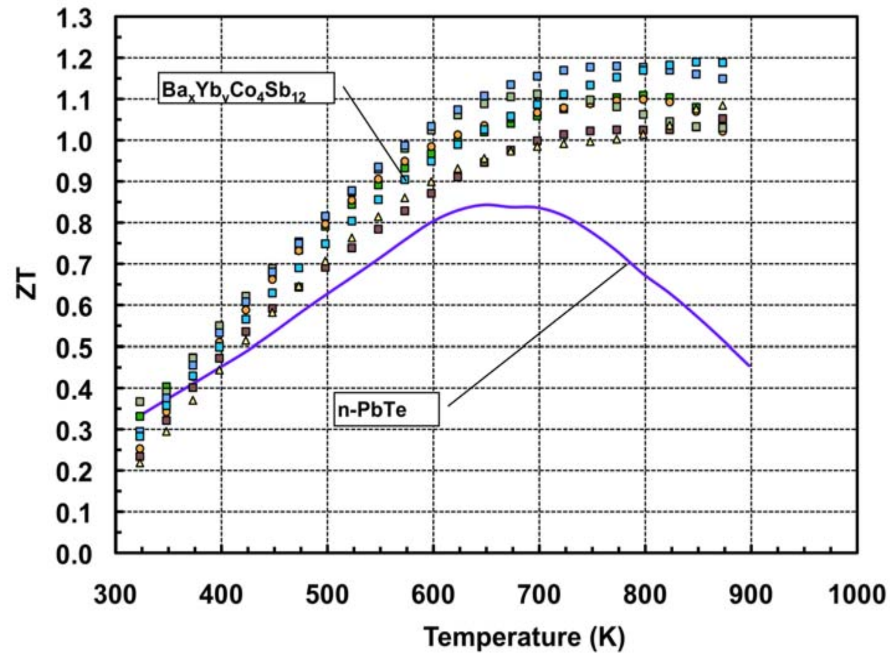


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

[1]X. Shi *et al.* APL 92, 182101 (2008)

$Ba_xYb_yCo_4Sb_{12}$: transport properties results

- **Ball milled $Ba_xYb_yCo_4Sb_{12}$ - initial transport properties**
  - ZT ~ 1.3 at 873K (consistent with previous report)
  - ~ 40% improvement in ZT over n-type PbTe in the 873K-373K temperature range
  - ZT improvement over doped-$CoSb_3$ appears to be due to:
    - Lower thermal conductivity (double rattler)
    - But also higher carrier mobility



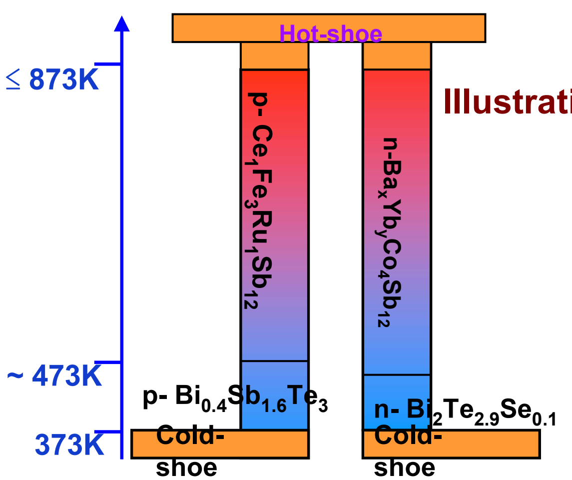
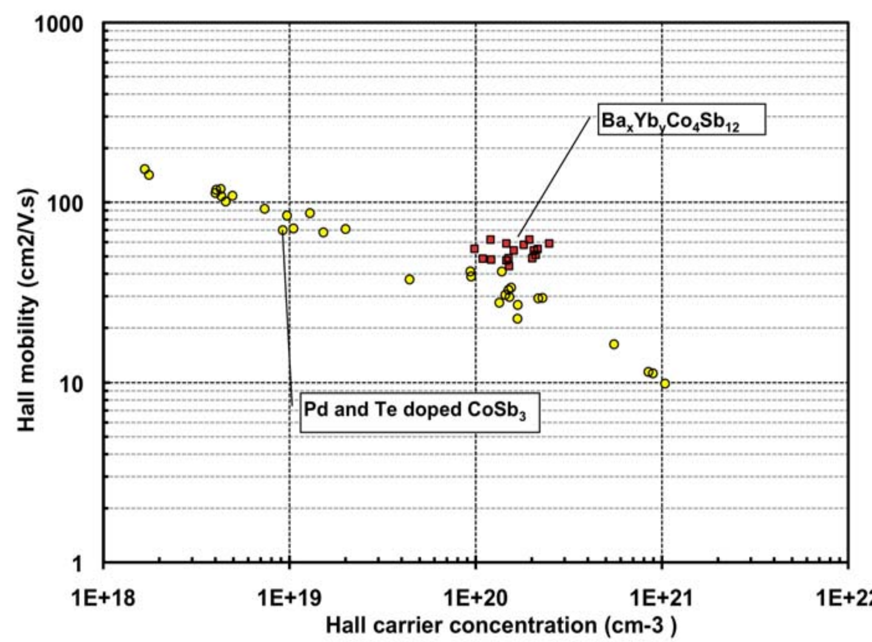


Illustration of skutterudite-Bi_2Te_3 couple

Couple efficiency (%) Calculated

	T_H= 873K - T_C=373K	T_H= 773K - T_C=373K	T_H= 673K - T_C=373K
With Bi_2Te_3 segments	11.8	10.0	7.9
Without Bi_2Te_3 segments	**10.7**	8.8	6.75



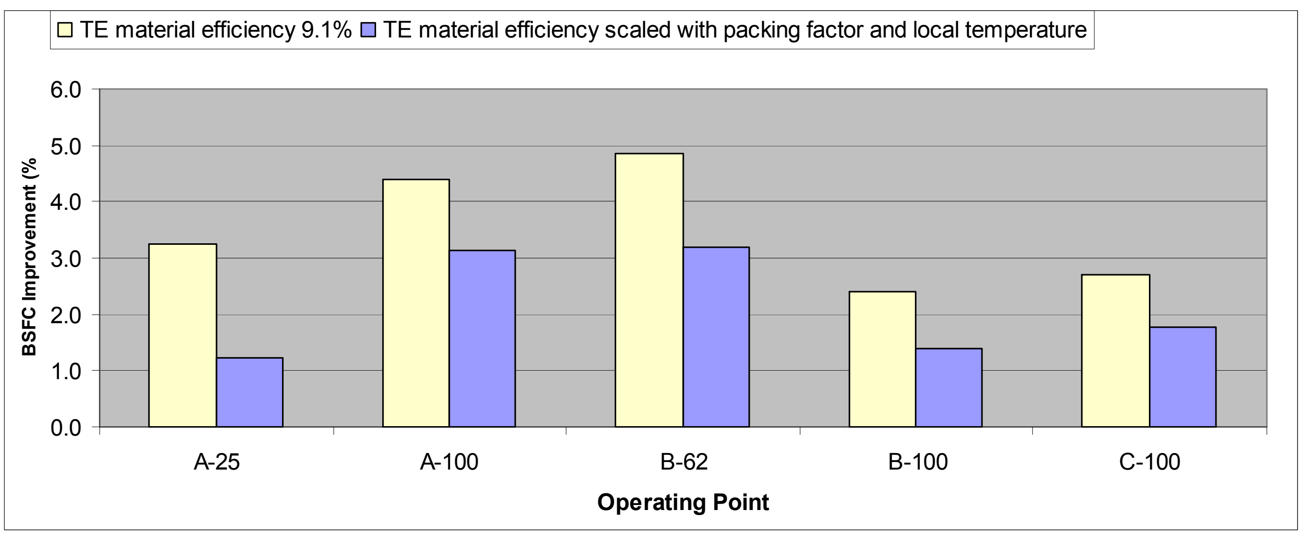
At equivalent carrier concentration, the Hall mobility for $Ba_xYb_yCo_4Sb_{12}$ is higher than that for doped $CoSb_3$

Cummins ISX 6 Cylinder Diesel Engine

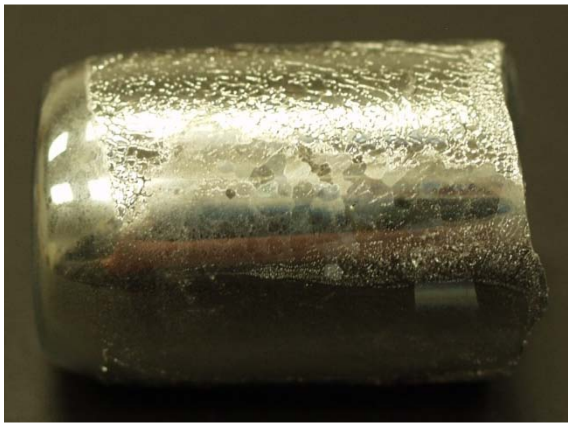
(Image used with permission)

Projected Efficiency Improvement of Option 1: Calculated BSFC Improvement LAST, LASTT-BiTe Materials for ESC Duty Cycle Modes

Modes	Units	A-25	A-100	B-62	B-100	C-100
Engine Crankshaft Speed	rpm	1230.00	1230.00	1500.00	1500.00	1800.00
Torque	ft-lb	472.15	1886.80	1170.20	1887.30	1577.70
BMEP	psi	78.05	311.92	193.45	312.00	260.82
Power	HP	110.58	441.88	334.22	539.02	540.72
	kW	82.46	329.52	249.23	401.96	403.22

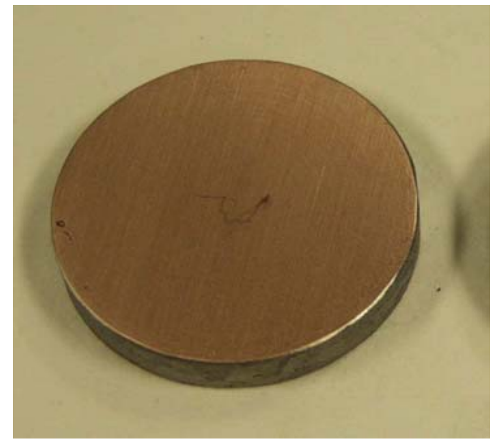


2009 SKD Thermoelectric Unit Production at Michigan State University

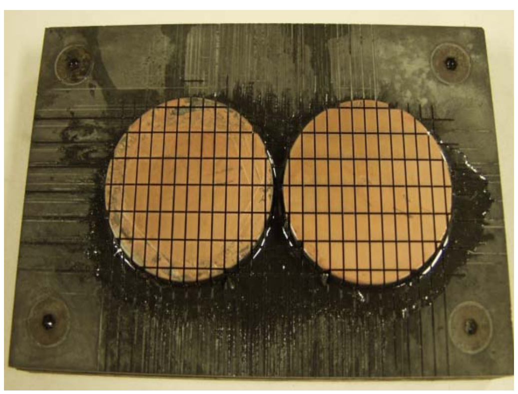


INGOT (29)

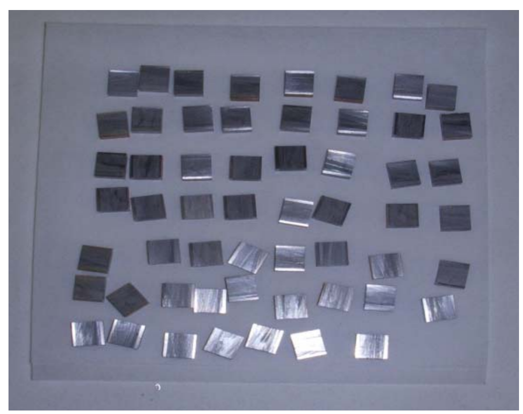
POWDER



HOT PRESSED PUCKS (>90)



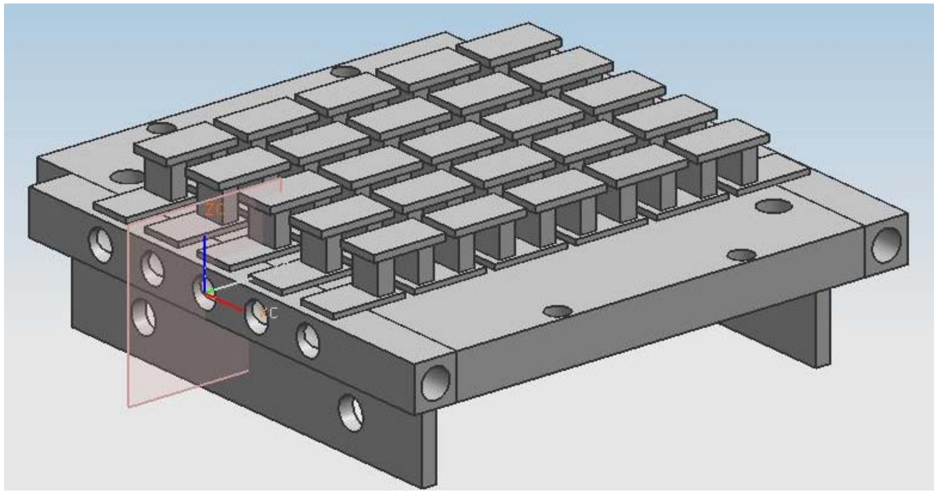
CUT HOT
PRESSED PUCK



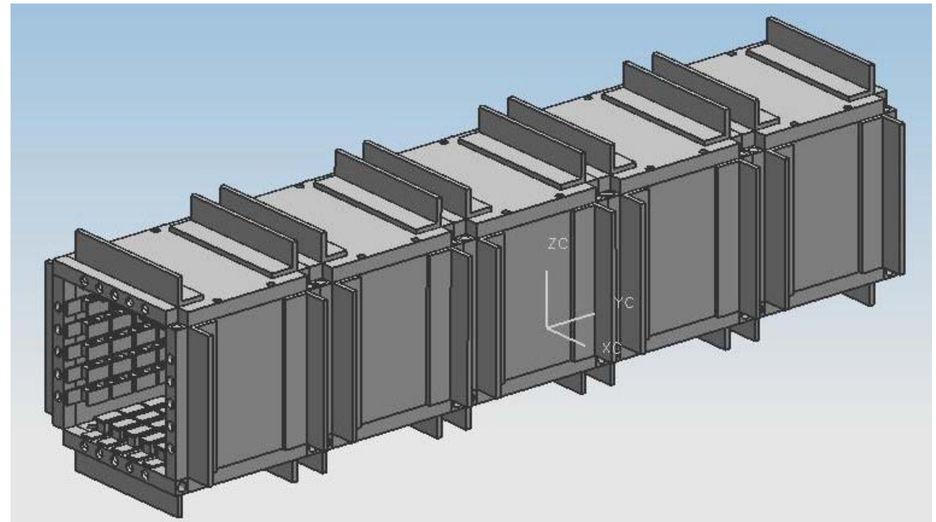
LEGS FROM PUCK
> 95% YIELD

5 COUPLE, 13W -
THEOR. SKD MODULES
(>120)

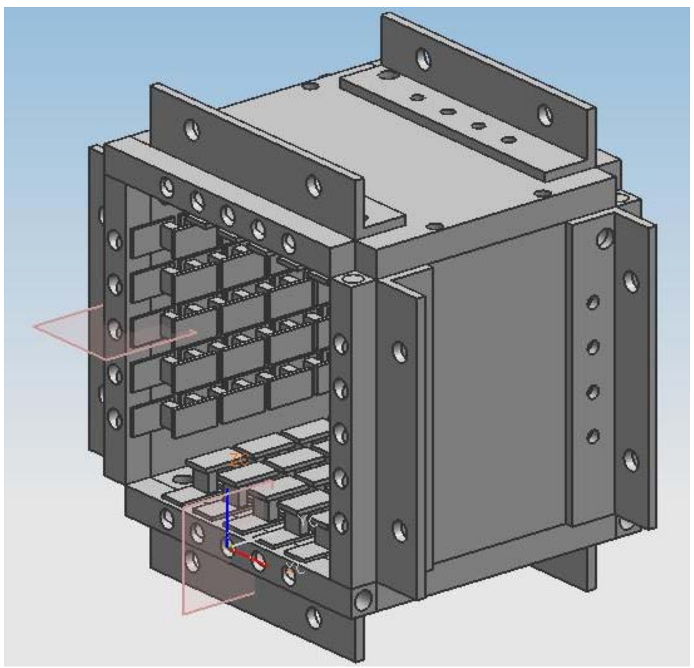
MSU Generation-1 TEG (SKD) Design



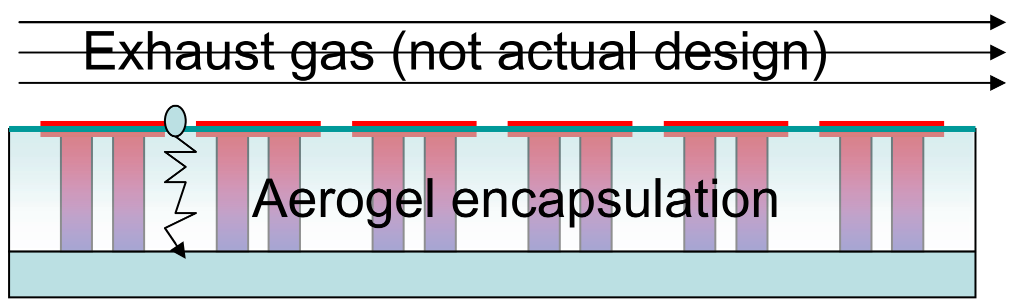
65W (theoretical) section of TEG



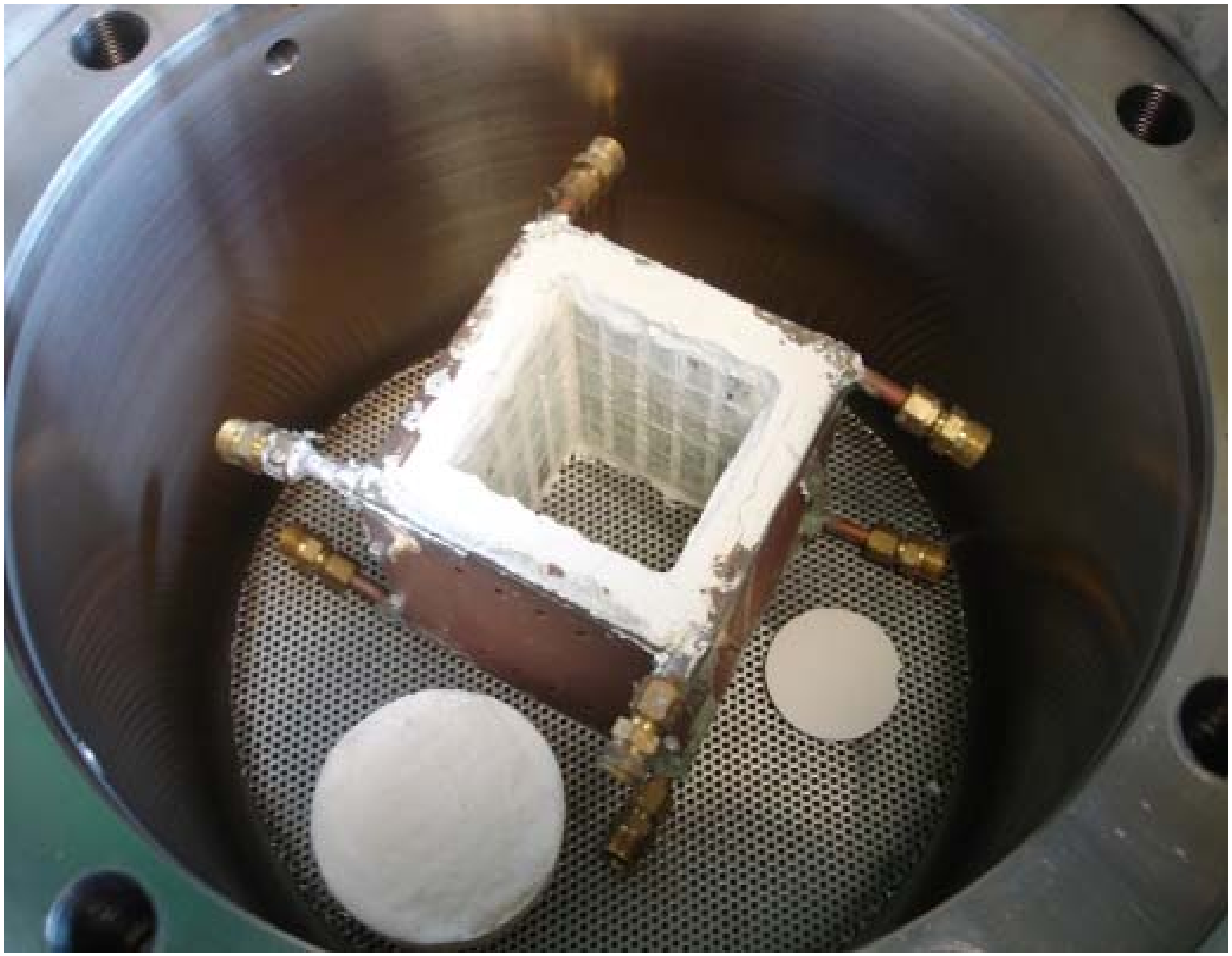
1.3kW (theoretical) 500W (actual est.) TEG
Dimensions 100x100x500 mm

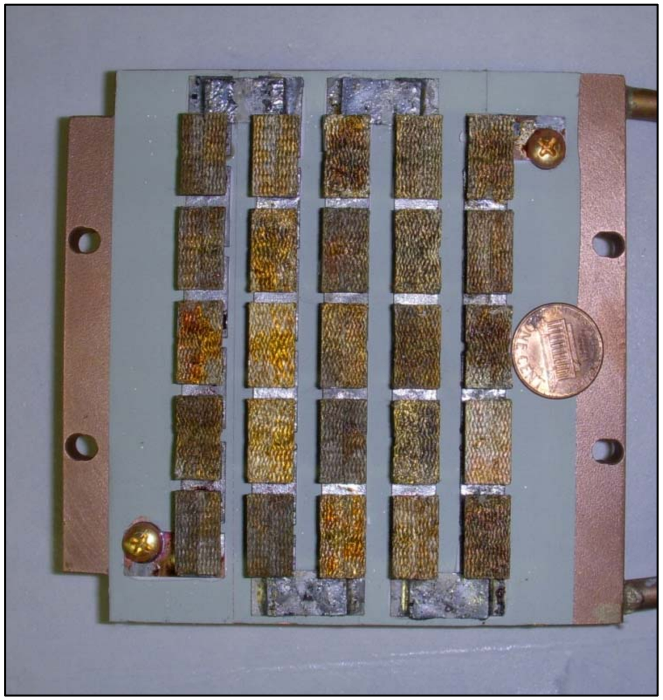


Section of Generator

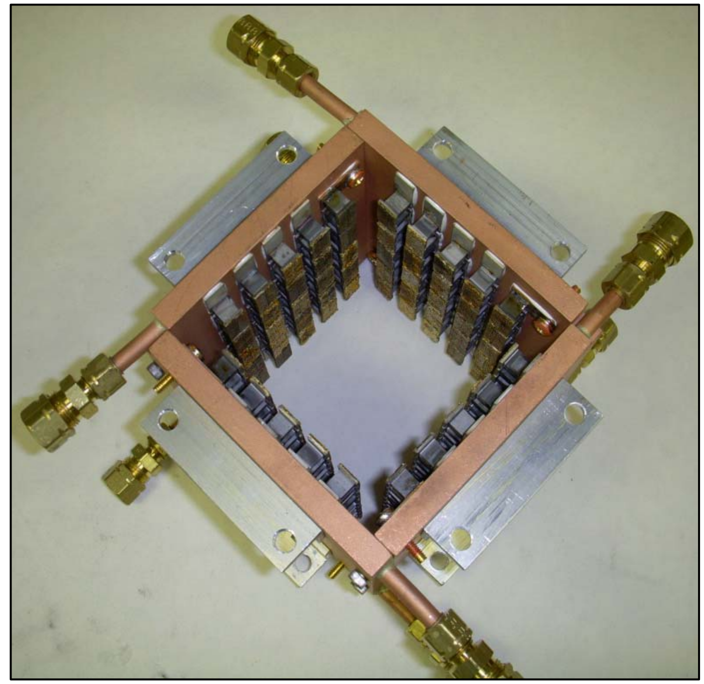


Aerogel Insulated TEG at Michigan State University

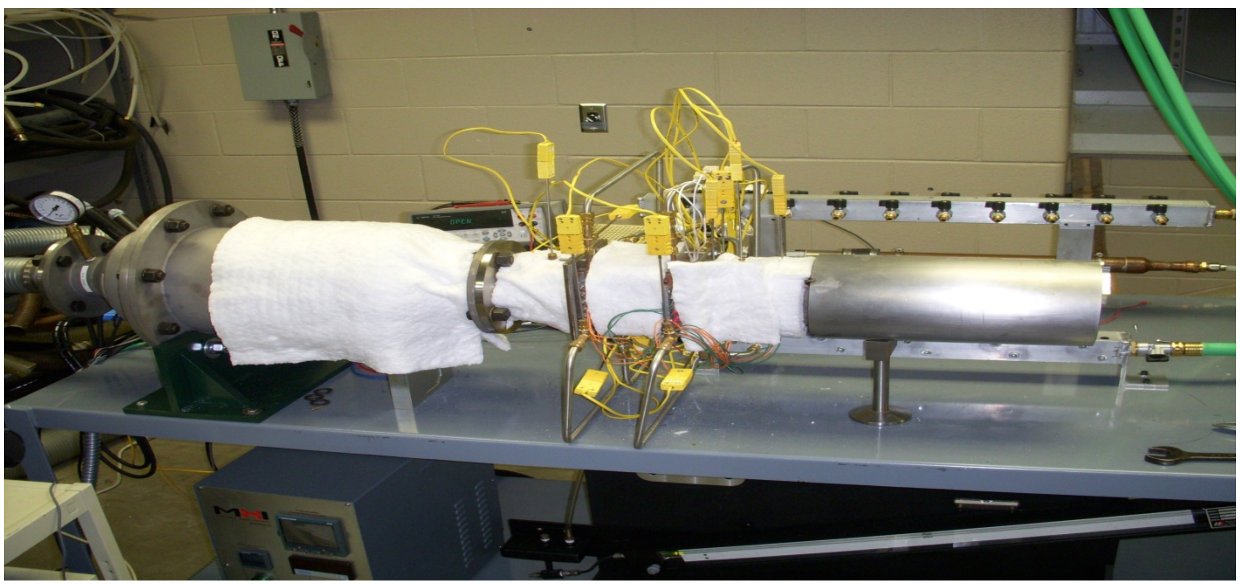




5 - 13W Modules (theoretical @ ΔT=600C) before Insulation

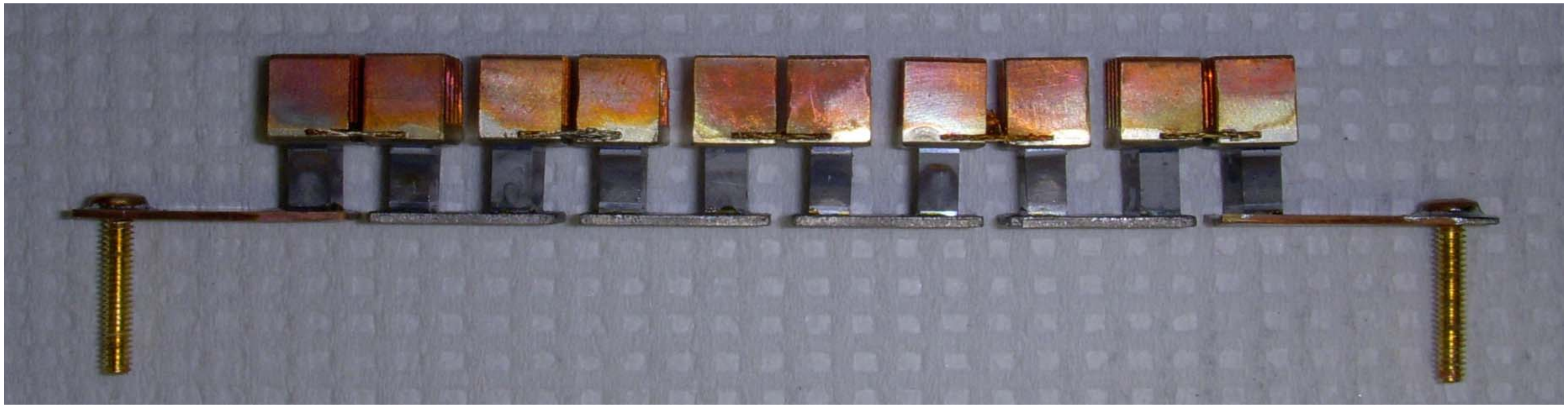


TEG – 260W (theoretical @ ΔT=600C) 20 – 13W Modules

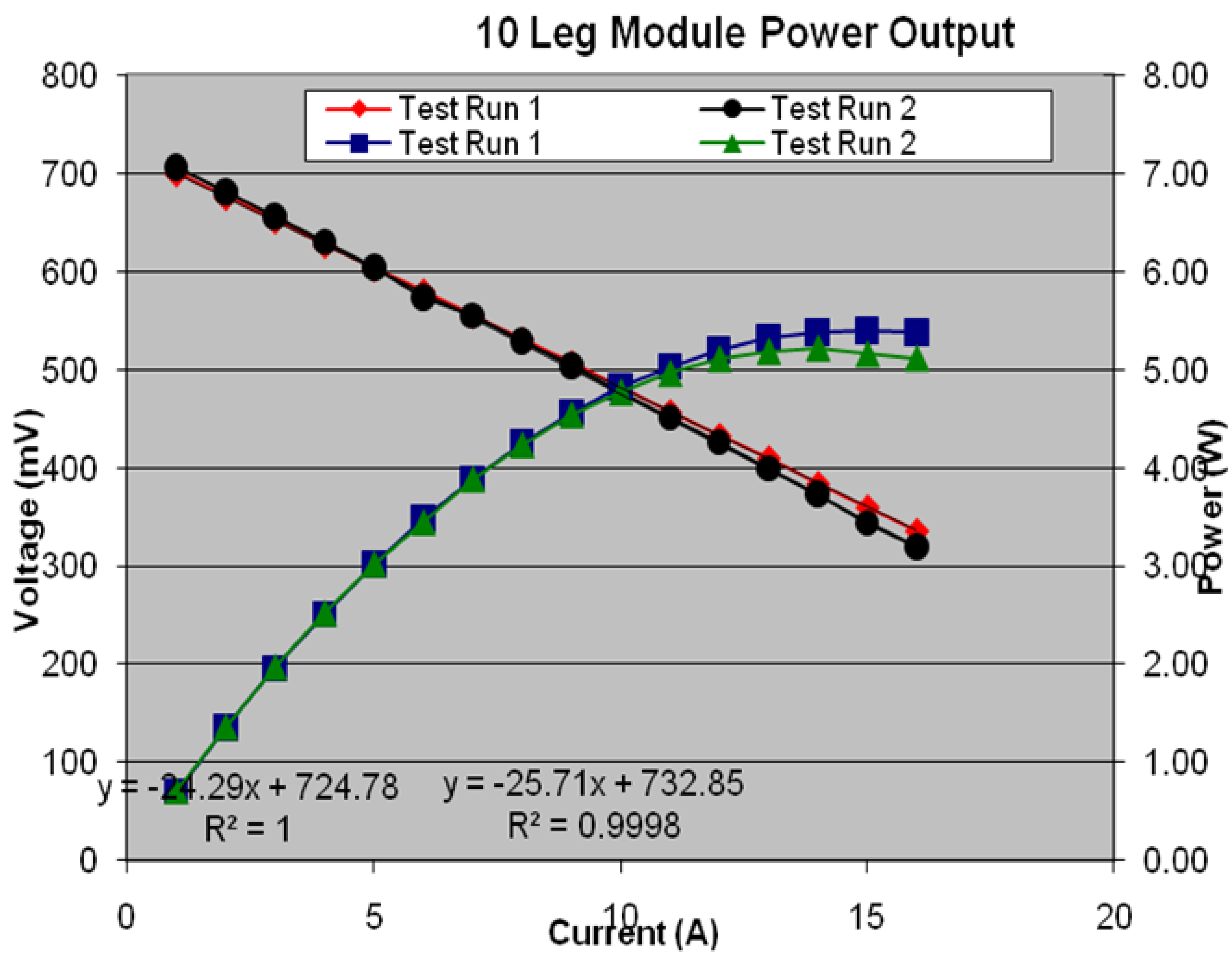


TEG Testing Assembly

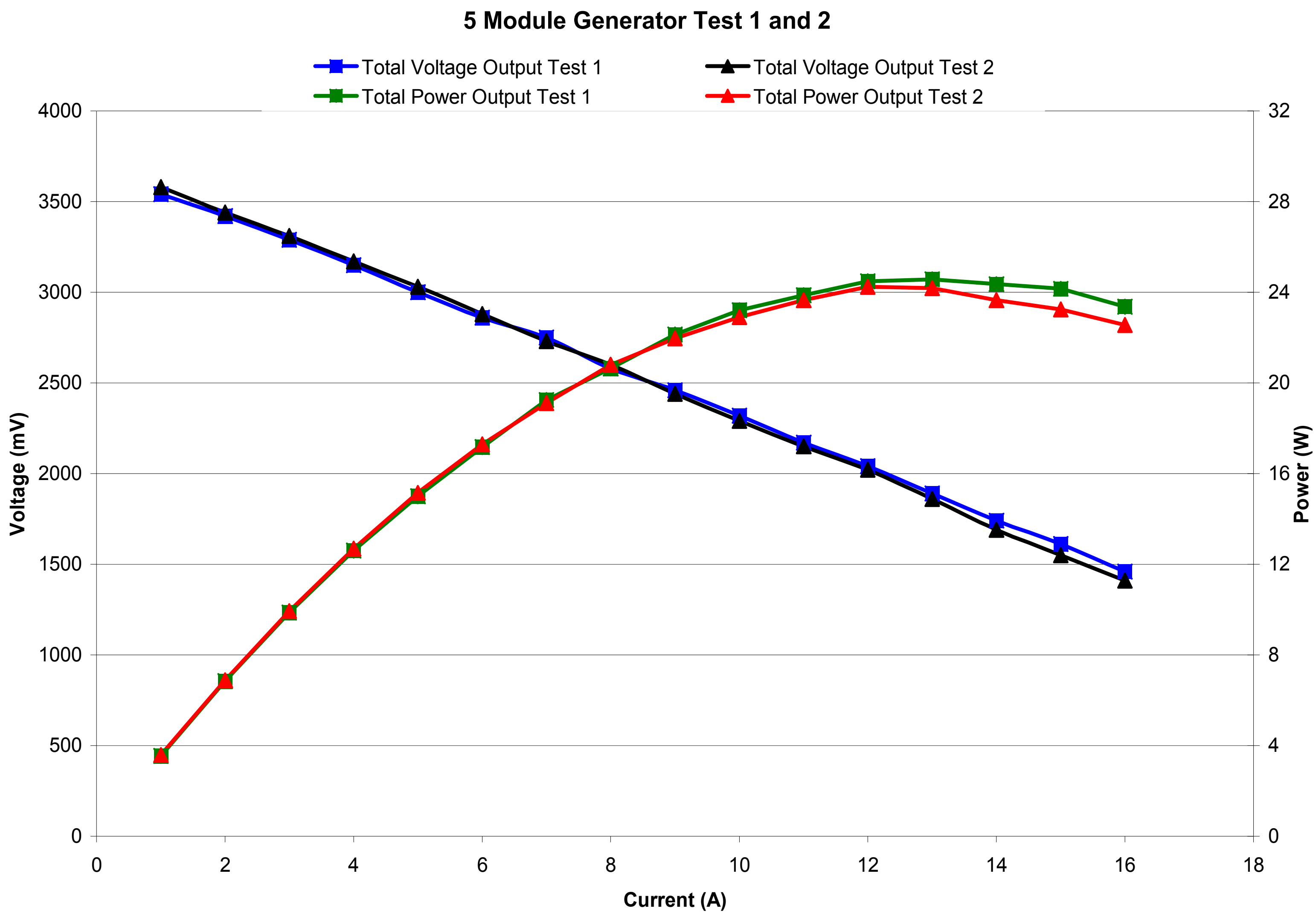
10 Leg Un-insulated Module Fabricated at MSU with Heat Collectors (legs are 3x7x7 mm, area of heat collector is >20x area leg top surface)



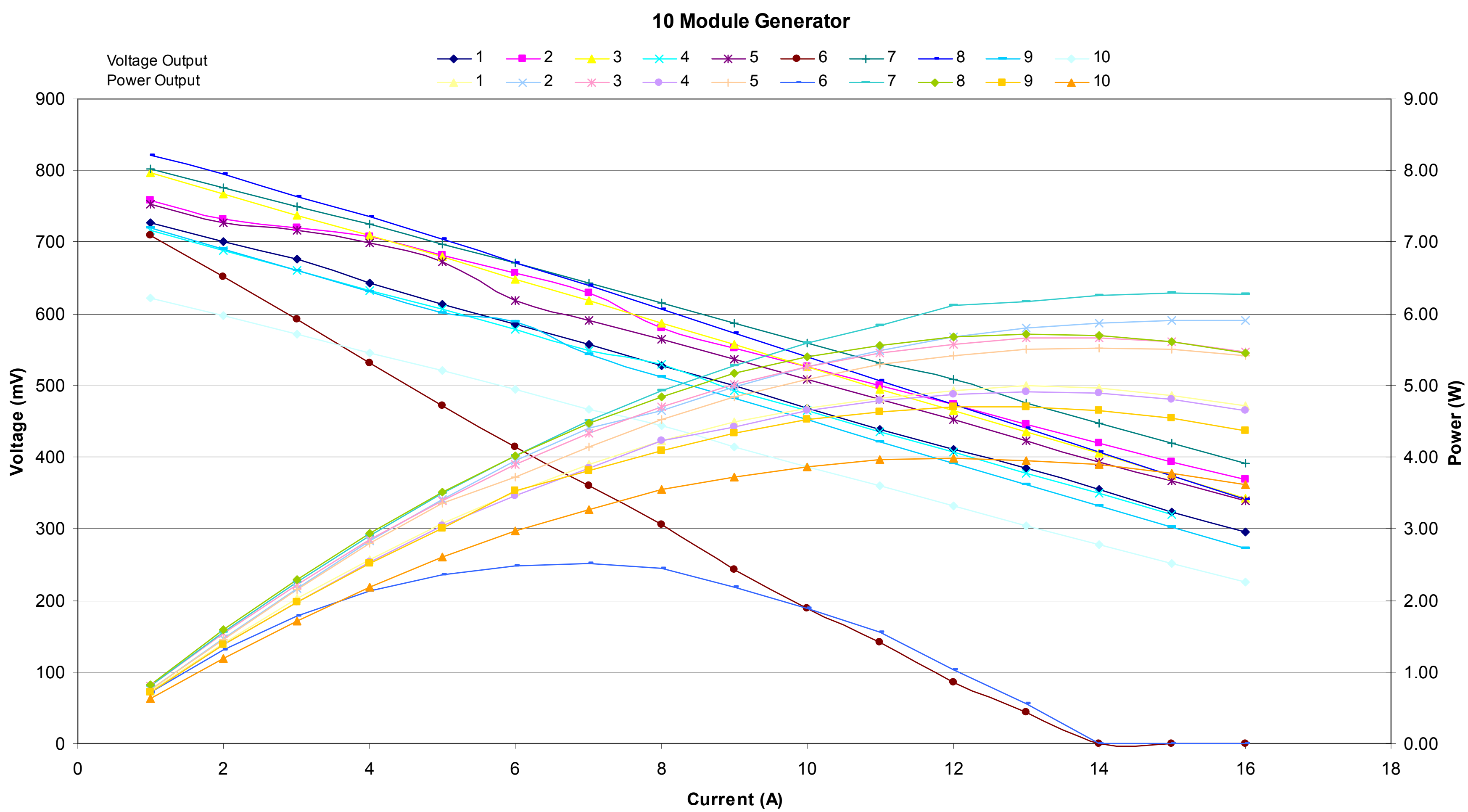
Voltage and power curves for a single 10 leg module for 2 different test runs. The module produced 5.4 Watts



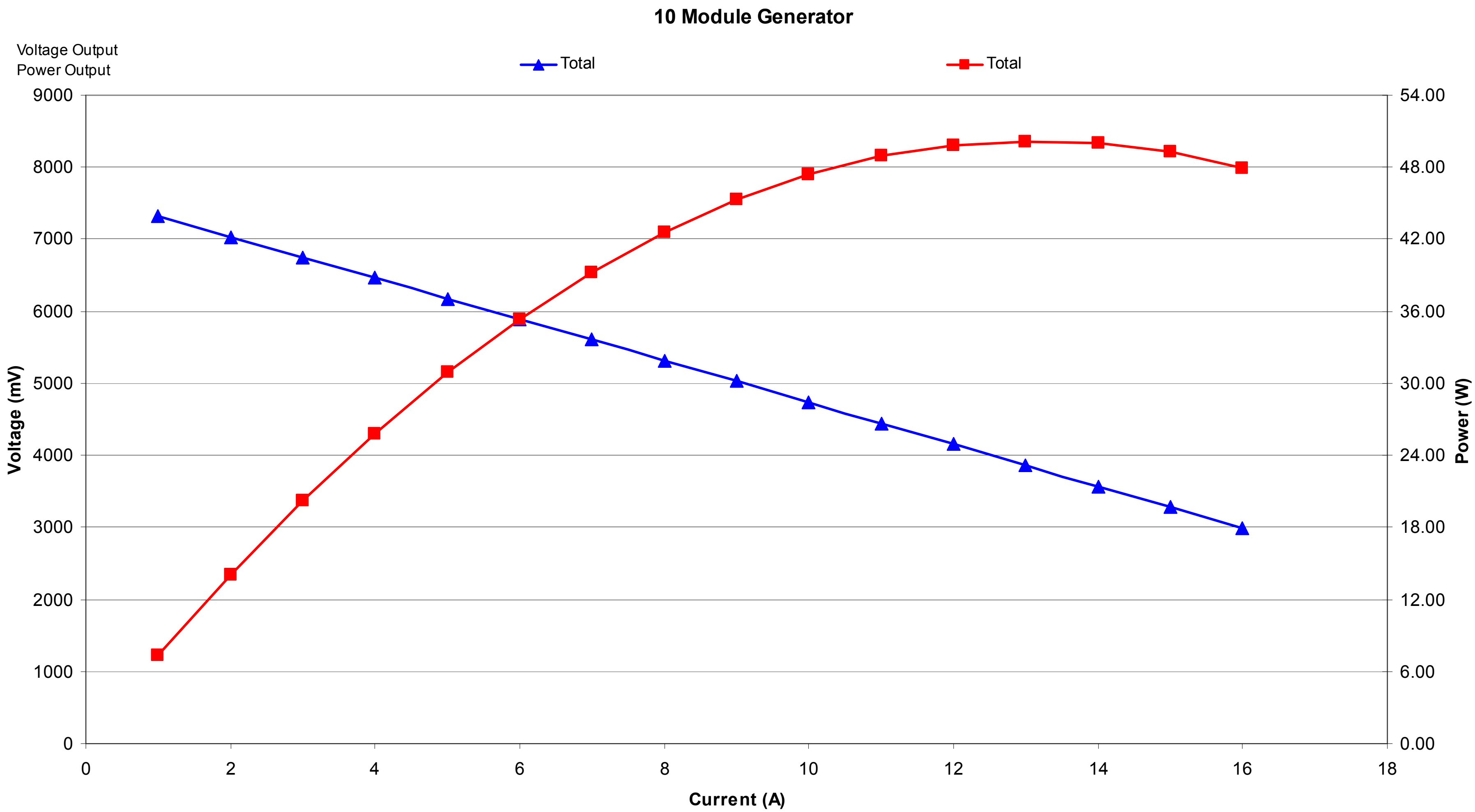
Voltage and power curves for a five 10 leg module for 2 different test runs. The TEG produced 24.6 Watts



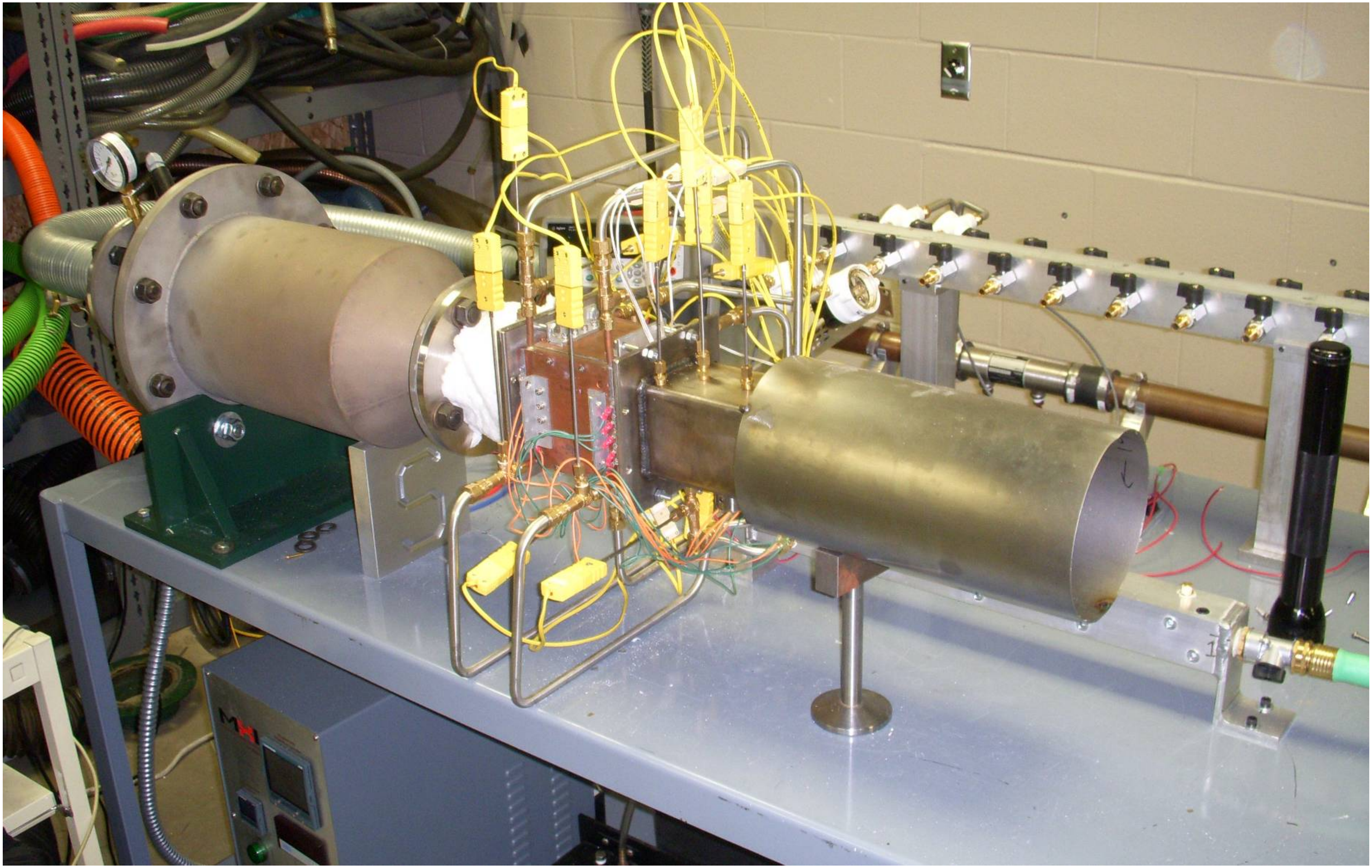
Output of 10 Module TEG (8/4/09)



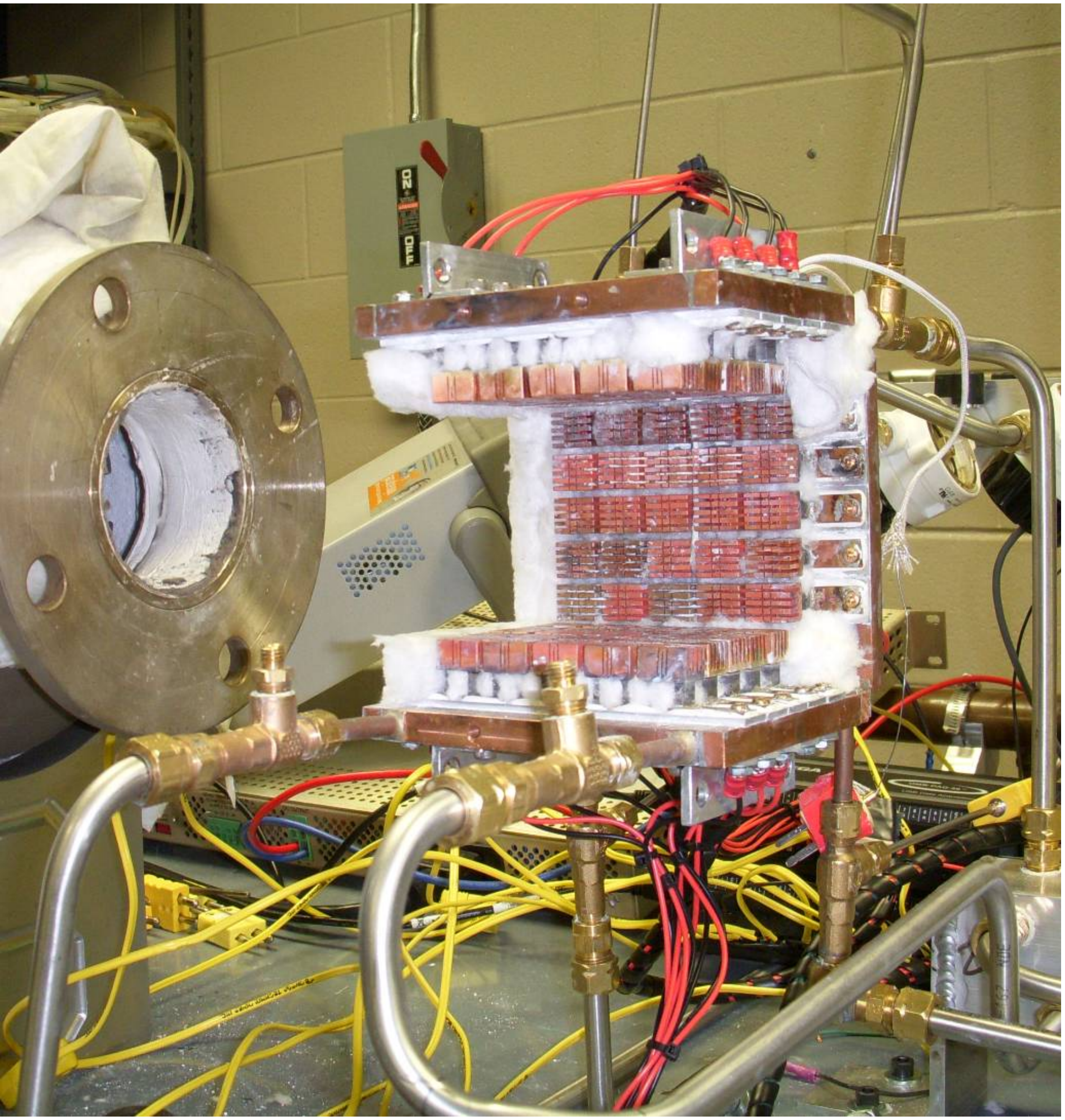
10-Module TEG output ~50.12W, ΔT~550^oC



50/100W Generator Shown Without External Insulation

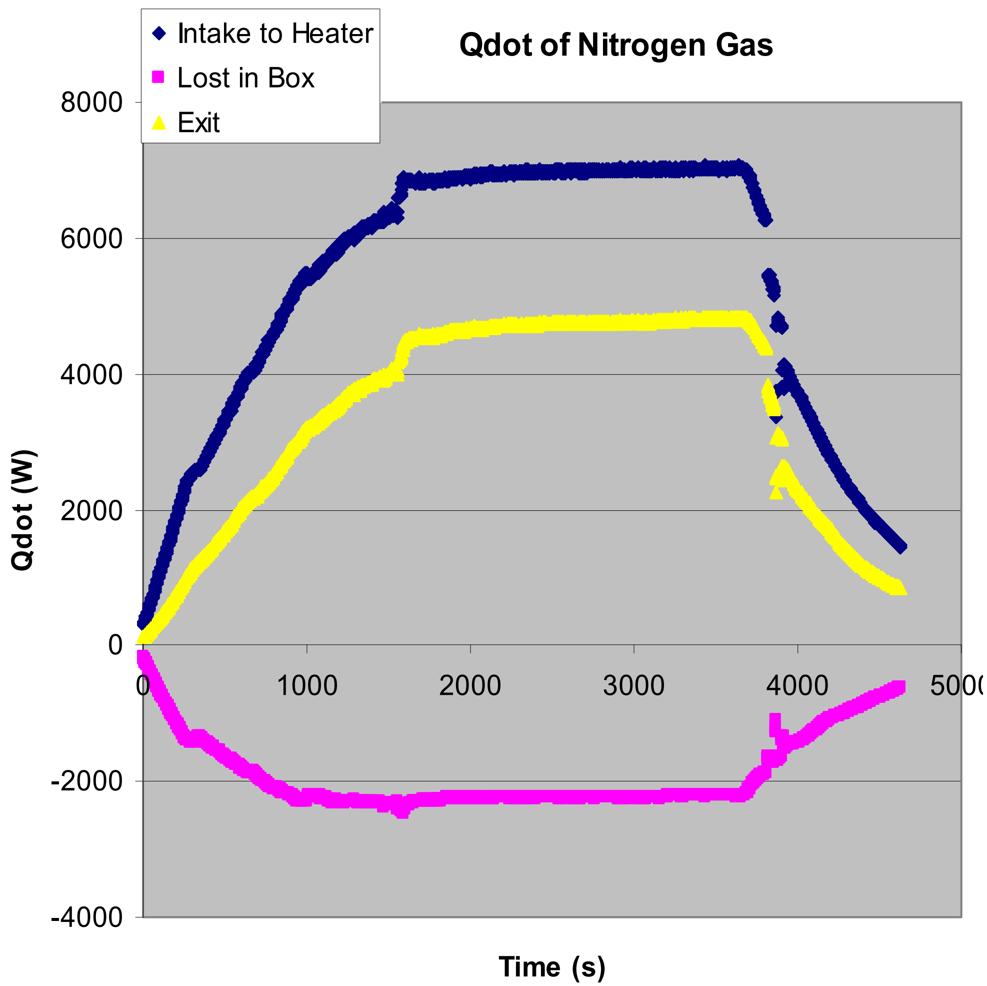


50/100W Generator Geometry

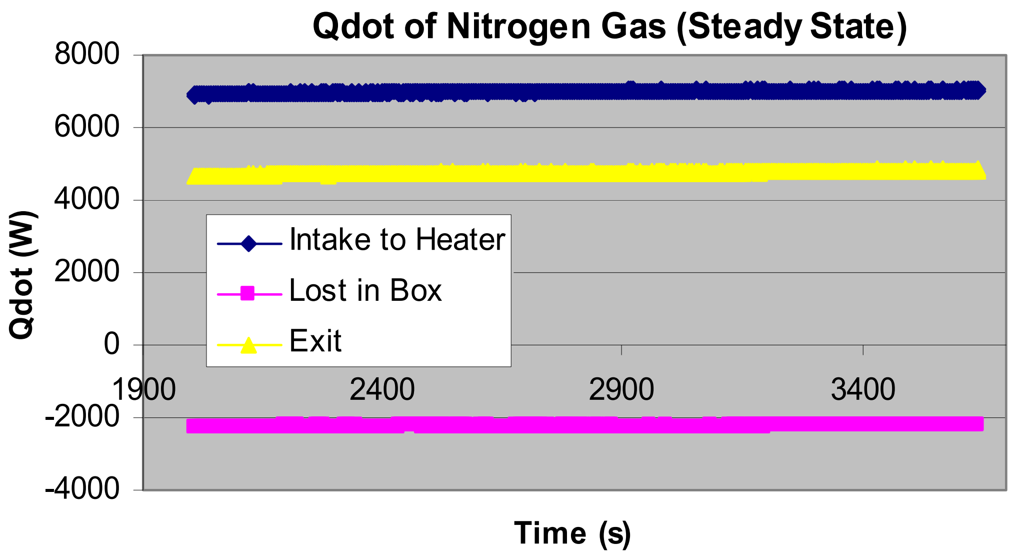


- ¾ of Generator is Shown
- Water lines to cool copper plates
- Electric lines to measure voltages
- Thermocouples to measure temperatures

Nitrogen Heat Transfer

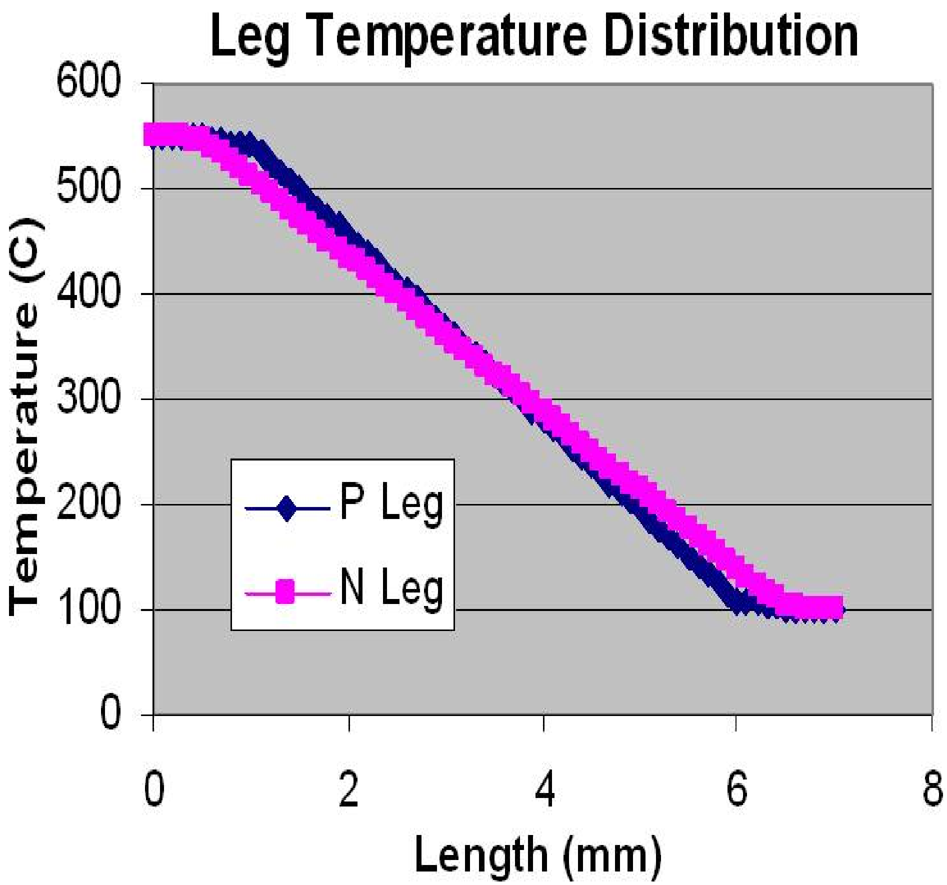


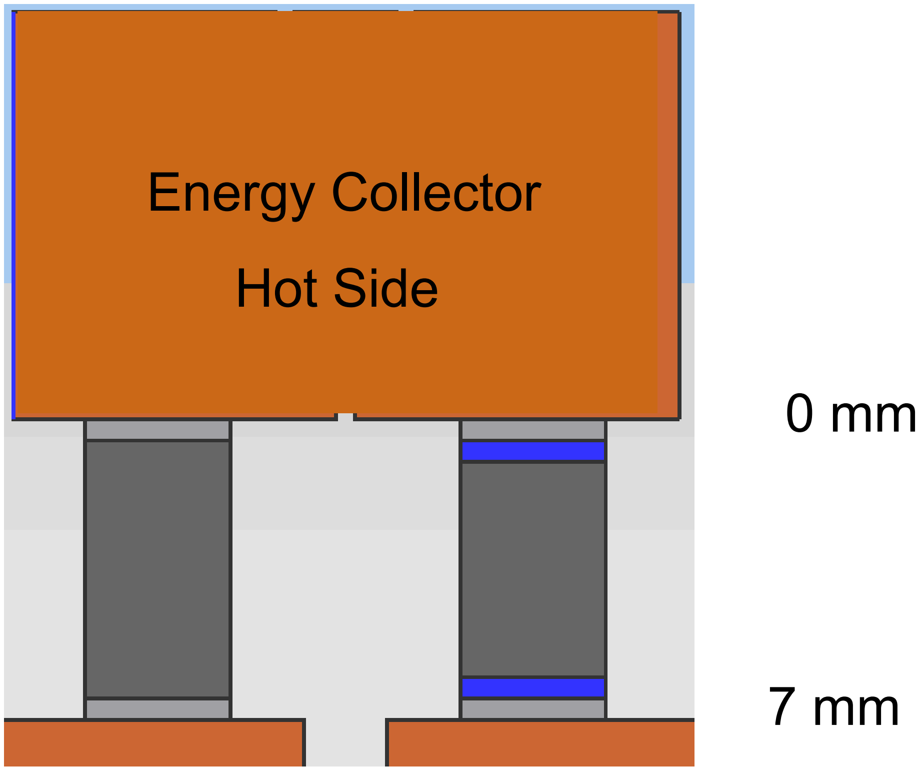
Entire Test



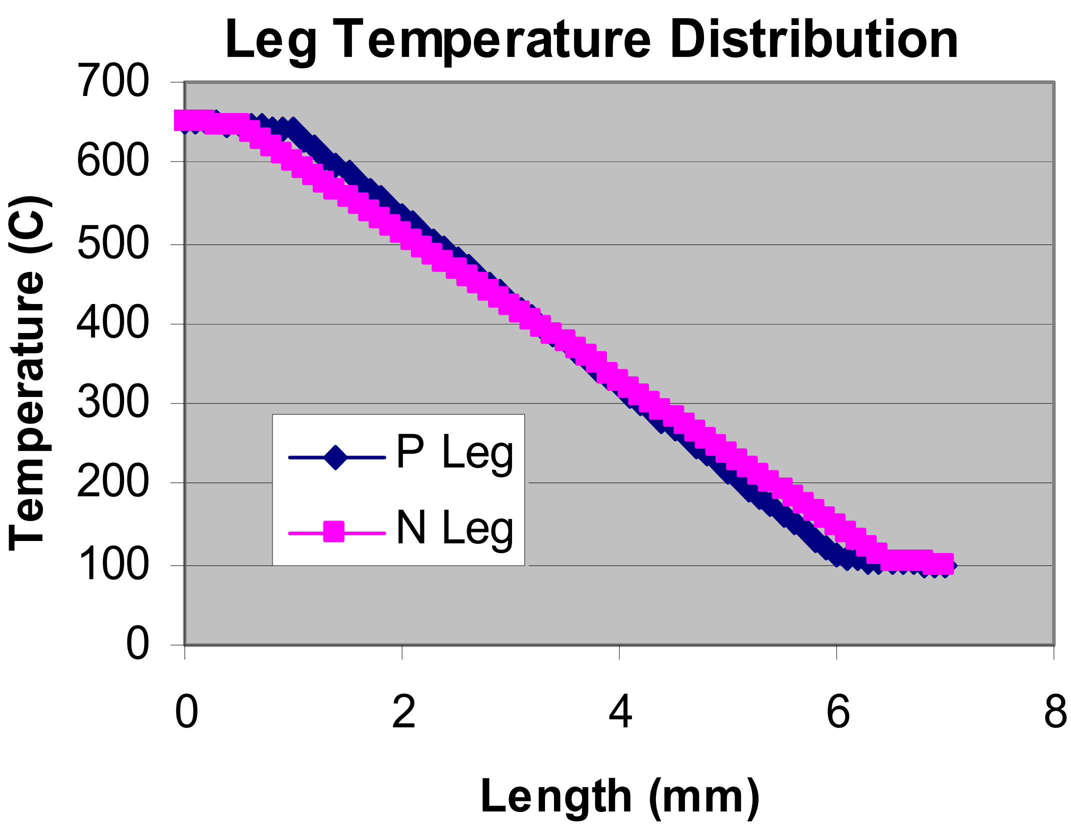
Steady State

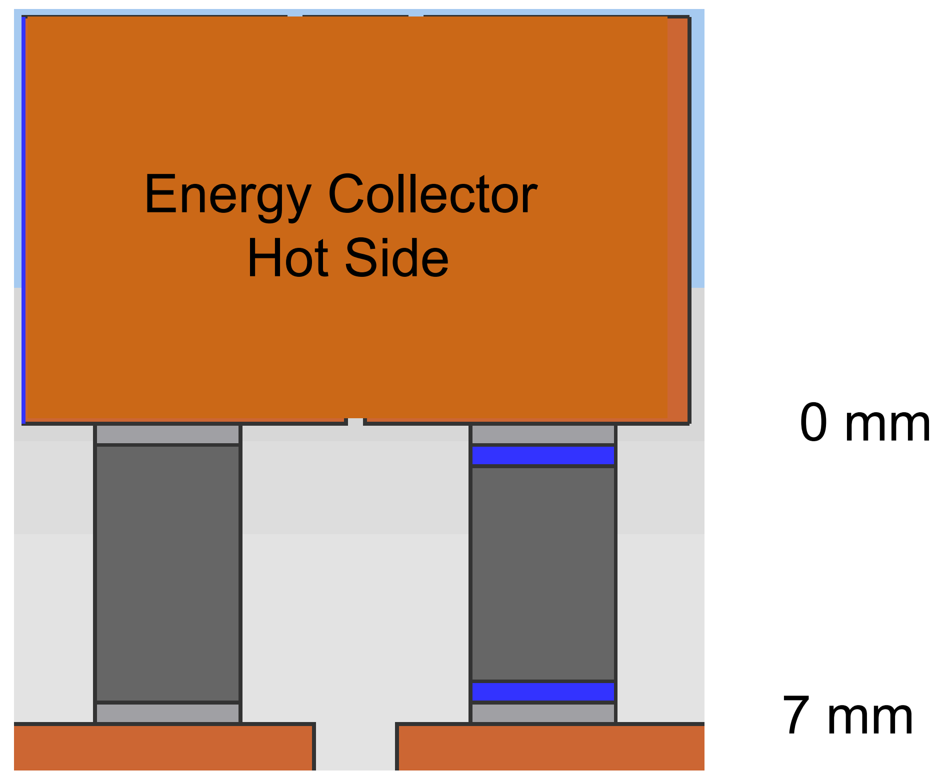
Leg Temperature Distribution – 100W





Leg Temperature Distribution – 50W





Summary of Proof of Concept 50W TEG Test
(10 – 5 Watt Modules, 1:<3W, 1:>3W<4W, 3:>4W<5W, 5:>5W)

- **Material of TE elements: Skutterudite, hot pressed**
- **Skutterudite theoretical effective/maximum ZT (100-650C) 0.69/0.85**
- **Maximum Generator Power: 50.12W**
- **Theoretical leg efficiency with no internal resistance or heat transfer losses (effective ZT=0.69 for n & p type, 2.2W/couple max. meas.) ~8.5%**
- **Measured Module Efficiency (1+ W/couple, Incl. insulation losses and only counting energy through the TE module, not counting cooling water pumping losses) 4%**
- **Overall TEG Efficiency of 50 watt unit tested (one half 100W unit) 0.7%**
- **Estimated Efficiency based on 100W TEG (performance of 50W TEG) 1.4%**
- **Estimated Efficiency of Gen2 TEG (300W) we could build using this energy source 4.2%**

Sidebar: Energy supplied ~16 SCFM @ 700^{o}C, approx. exhaust output of a 2.4L SI, 4-cylinder PFI engine operating at road load (2000RPM, 2 bar BMEP, T exh. port = 804^{o}C, T exh. manifold exit = 591^{o}C, 18.25 SCFM)

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, 10% electrical energy conversion efficiency when operating as an APU (high temp, 0.249 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(.004))mi per gal))=120 gal/yr fuel savings
  - From Idle Reduction: (0.829[1] gal per hr engine – 0.249 gal per hr for TE APU)(8hrs. Idle per day)(300 days per year)=1392 gallons per year fuel savings
- **Total Savings**
  - (120 + 1392 gal/year) ($4/gal)=$6048 per year or **$42336** over 1 M mile 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

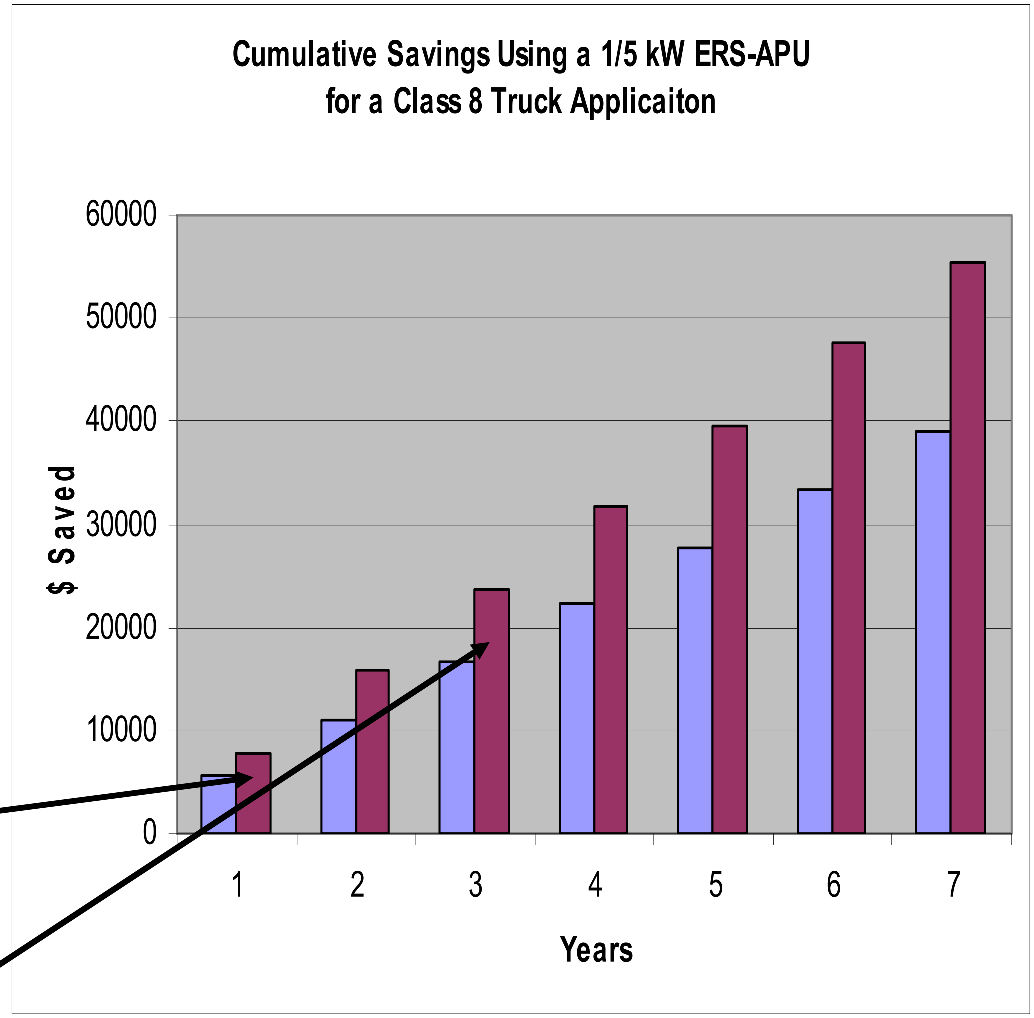
TEG Cost to Benefit for a 1/5kW ERS-APU

Total 1 kW System Price Based on Four Subsystems

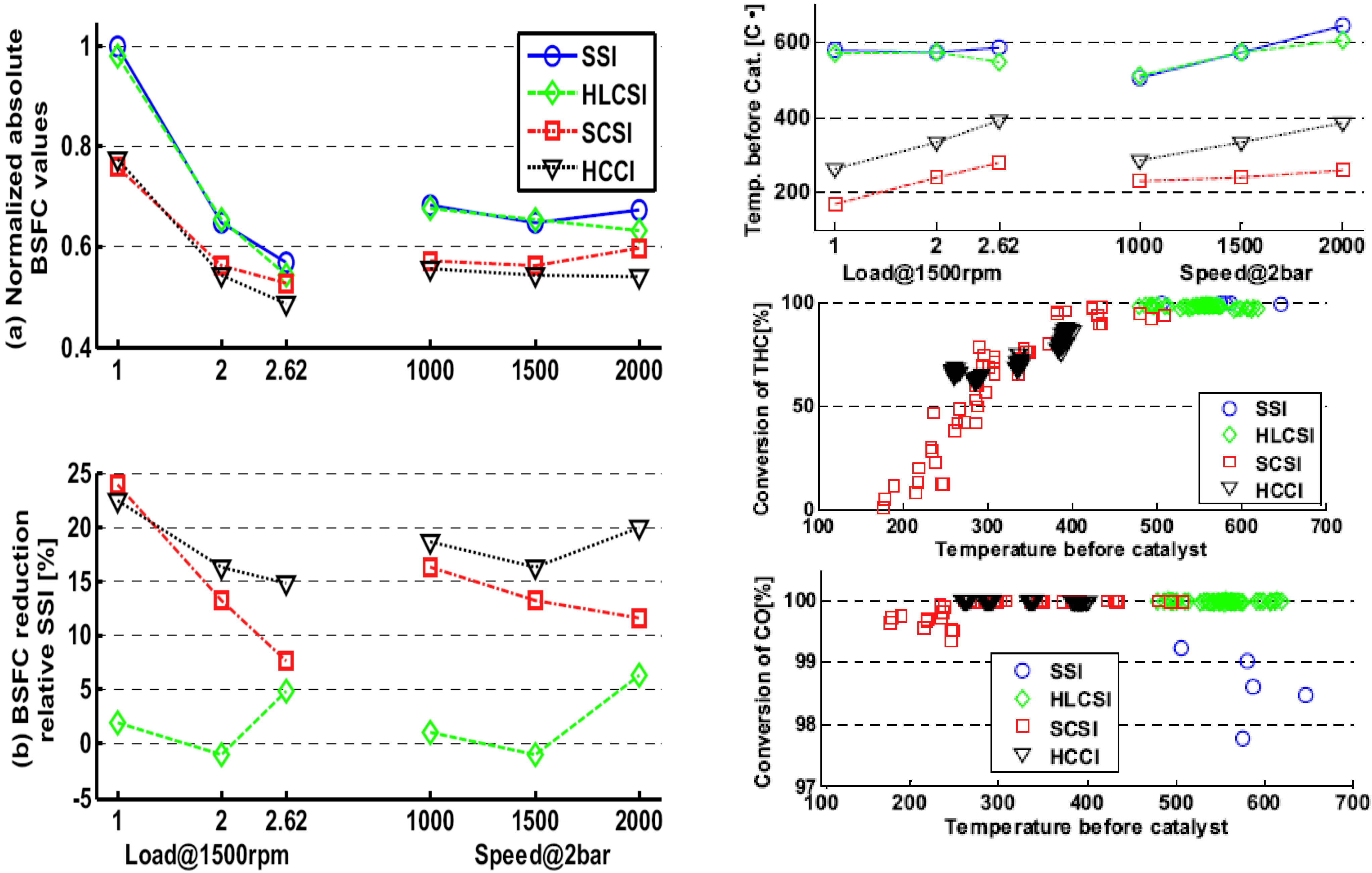
- Electrical/Electronics $943.28
- TEG Subsystem
  - TE Materials $1200.00
  - Module Assembly $1124.85
  - Housing $400.00
- Burner $717.00
- Cooling Subsystem $388.64

Total Price $4773.77

Total 5 kW System Price $19276.13



Other Aspects to Consider for Gasoline and Diesel Powered Vehicles. How Much Will HCCI/PCCI Combustion Reduce Effectiveness of TEG?



Left- (a) Final BSFC values normalized to the value for SSI at point 1. (b) BSFC reductions for HLCSI, SCSI and HCCI in percentages compared to SSI values at the respective operating points. Right- Temperature measured before the catalyst and conversion of THC and CO vs the temperature measured before the catalyst. SAE 2008-01-0426

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)

- MSU has demonstrated 1, 5, 10 and 20 module (each 5-couple) TEGs which produced 5, 25 and 50.2 W and 75W, respectively at a $\Delta T \sim 550\ ^oC$, heat supplied with gaseous N_2 (2.2 W / couple when heated directly at $\Delta T \sim 700\ ^oC$)

- Using the performance of the Gen 1, 100 Watt generator demonstrated, we estimate that we would recover about 2.99 kW from the exhaust of an OTR truck at cruise conditions ….**suggest we are five years from a viable 1/5kW systems with reliable performance provided one has adequate support!**

- A 10% improvement in fuel economy would require a ~1000% improvement in system performance over the Gen 1 system demonstrated in this work. We understand the path to a 300% improvement. A 10% bsfc improvement using TEGs for passenger car energy recovery applications with **advanced engines** will be very challenging.

- Substantial engineering and scientific developments required for practical application of TEGs for energy recovery in transportation: **Reduce** system degradation, couple resistance and heat transfer losses; **Improve:** module reliability, thermoelectric material properties, insulation and fabrication methods and heat exchanger designs are **critical** for this application.

Thanks to Our Sponsors, DOE for Supporting this Work!

John Fairbanks – DOE HQ

Sam Taylor – EERE