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

Prepared by:

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IOWA STATE UNIVERSITY

NASA JPL

MICHIGAN STATE UNIVERSITY

Cummins

TELLUREX CORPORATION

NORTHWESTERN UNIVERSITY

Objectives

- 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 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
- Determine if Phase 2 results make an engine-powertrain system demonstration in Phases 3 and 4 reasonable

Milestones
(2008-2009)

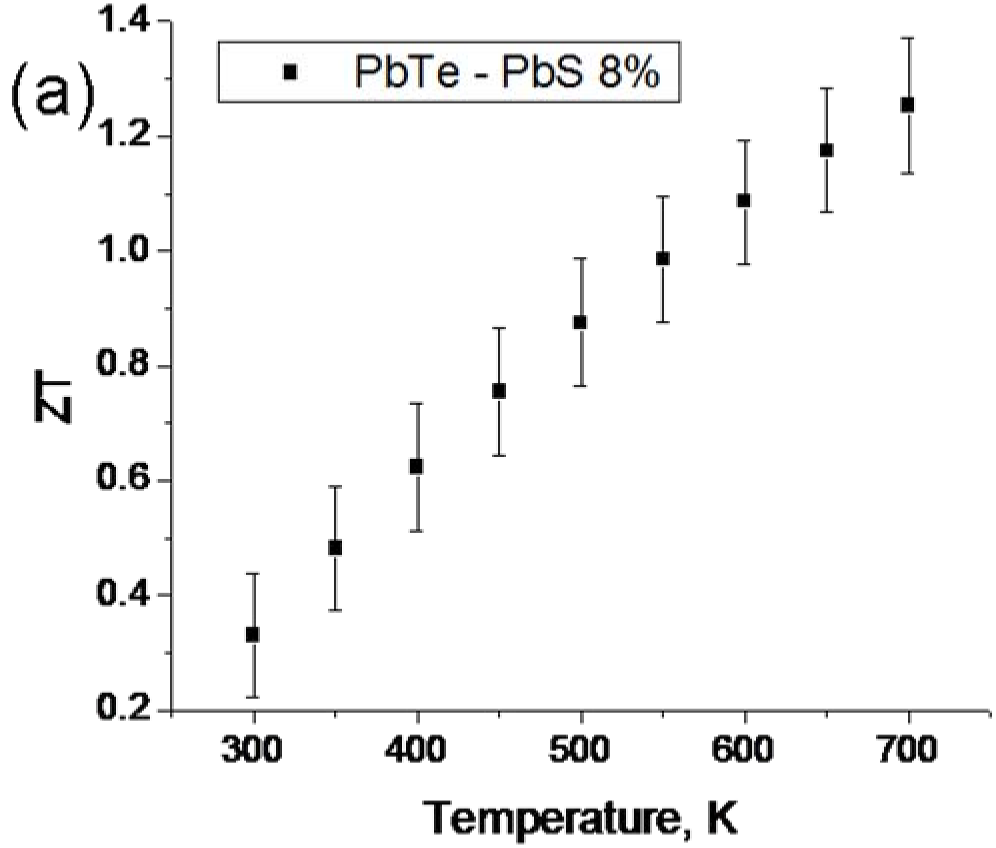
- Identified new thermoelectric systems *that have the potential* for η>14% (hot and cold side of legs with a ΔT of 300-800K)
- Methods for laboratory scale mass production of skutterudite (SKD) unicouples has been demonstrated at MSU (114 couples in four days, maximum theoretical output 296W, couples exhibit uniform performance characteristics)
- 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 (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 1kW ERS-APU
- **A nominal 50 watt, gaseous N_2 heated, Generation-2 TEG has been designed, constructed and tested (ΔT ~ 500C)**

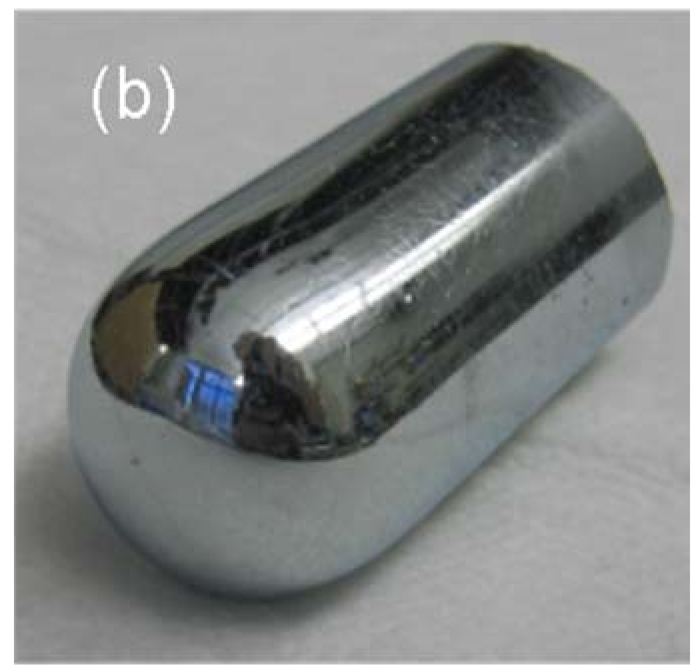
12 Steps to a Prototype TEG

1. **Choose 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)**
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**

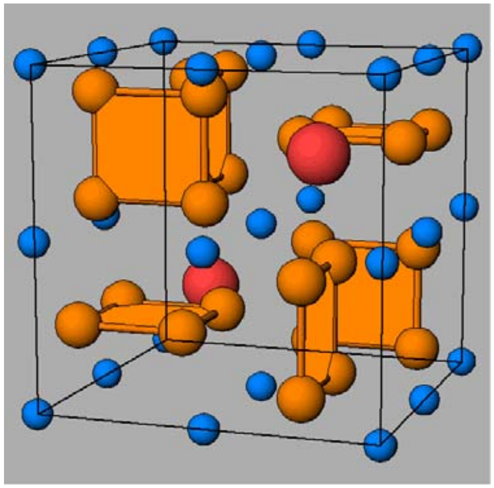
Example Scale-Up of Thermoelectric Material

Work show in this slide supported by: DOE – 80%, ONR – 20%





New Material and System Development: n-Type Skutterudite Material Development



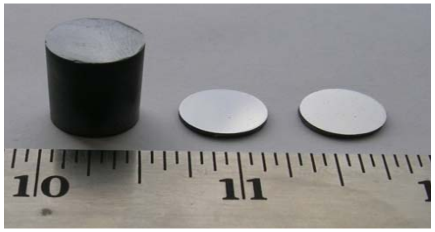
Skutterudite crystal structure

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

- **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

Planetary ball mill

High-energy ball mill

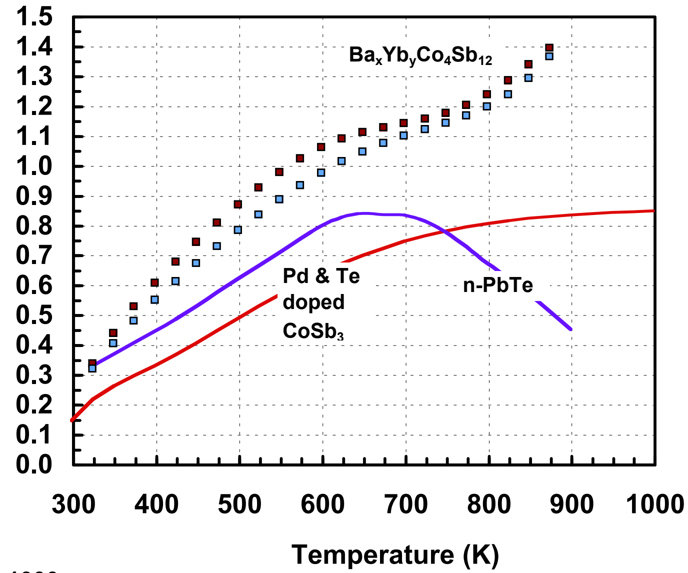


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

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

NMSD: $Ba_xYb_yCo_4Sb_{12}$: Initial Transport Properties Results

- Ball milled $Ba_xYb_yCo_4Sb_{12}$ - initial transport properties
  - ZT ~ 1.3 at 873K (consistent with previous report)
  - ~ 40% improvement 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



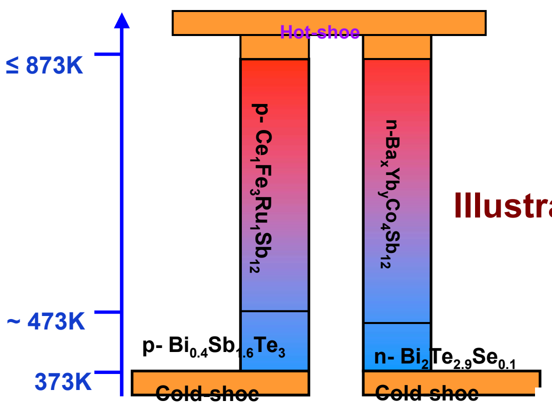
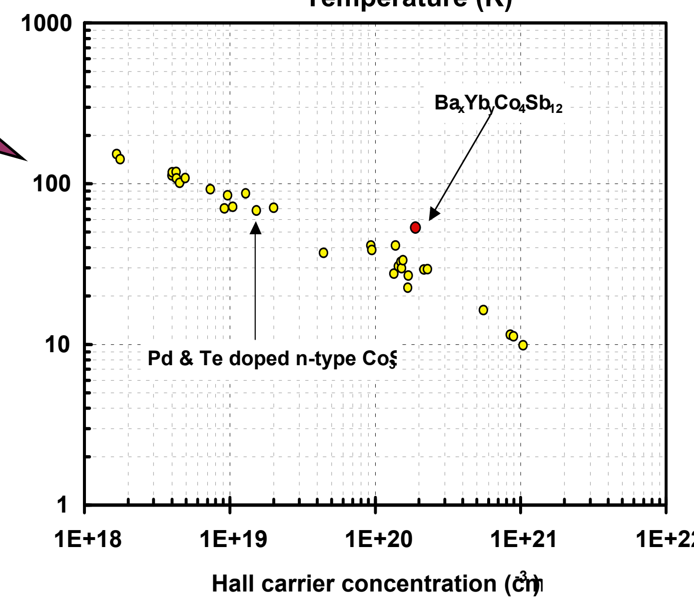


Illustration of skutterudite-Bi_2Te_3 couple

Couple efficiency (%)

	T_H= 873K - T_C=373K	T_H= 773K - T_C=373K	T_H= 773K - 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



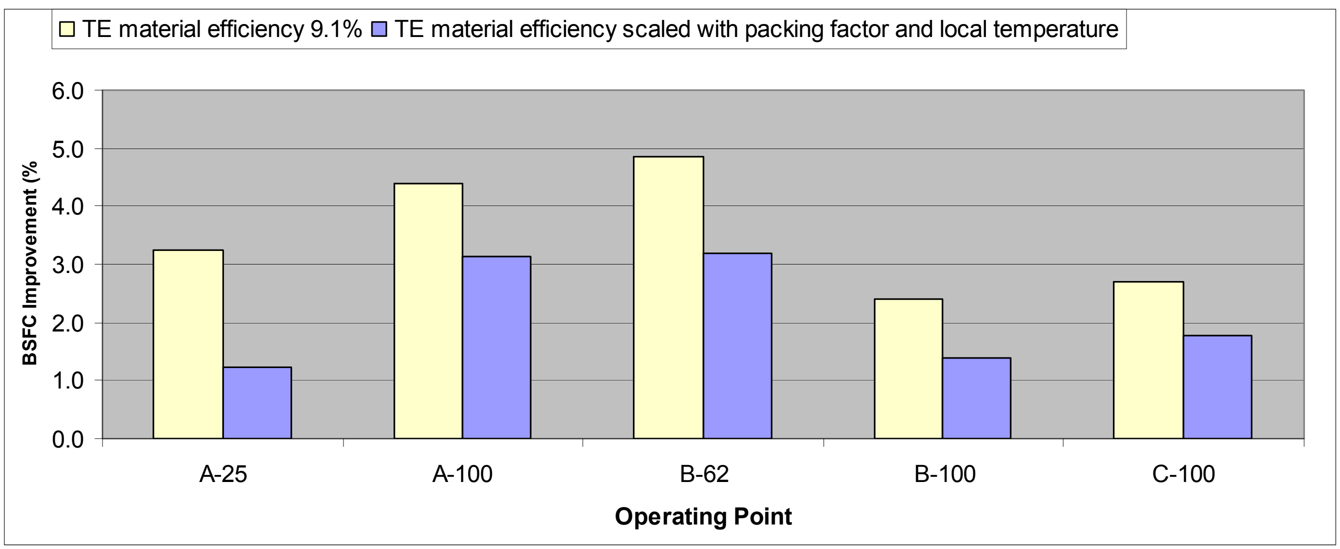
At equivalent carrier concentration, the Hall mobility for $Ba_xYb_yCo_4Sb_{12}$ is higher than that for doped $CoSb_3$

Cummins ISX 6 Cylinder Diesel Engine

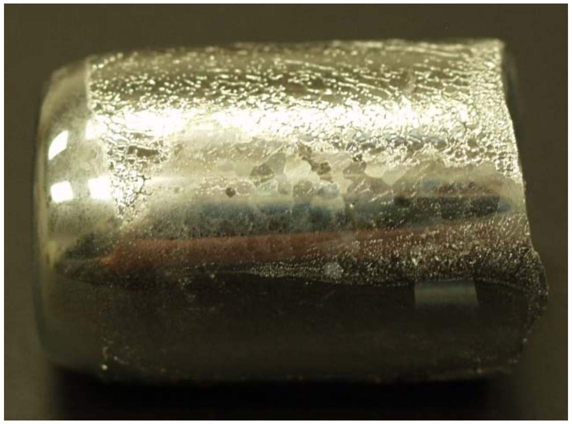
(Image used with permission)

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

Modes		A-25	A-100	B-62	B-100	C-100
	Units					
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

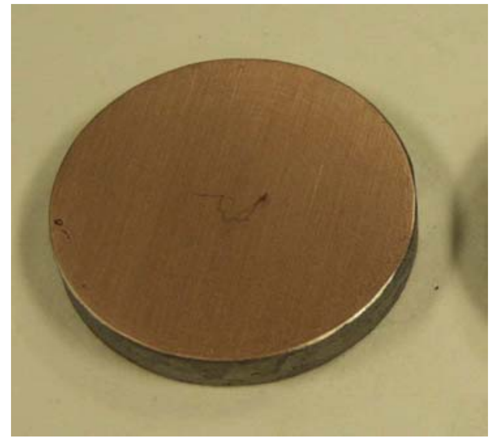


2009 SKD Thermoelectric Unit Production at Michigan State University

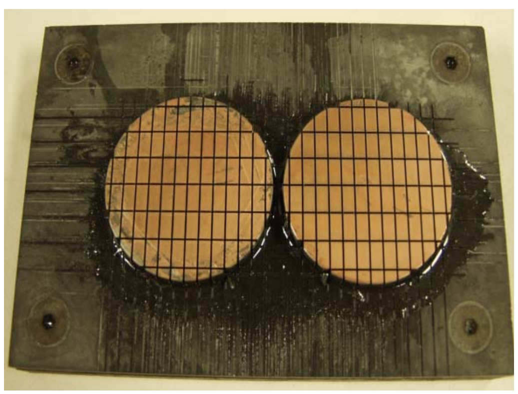


INGOT (29)

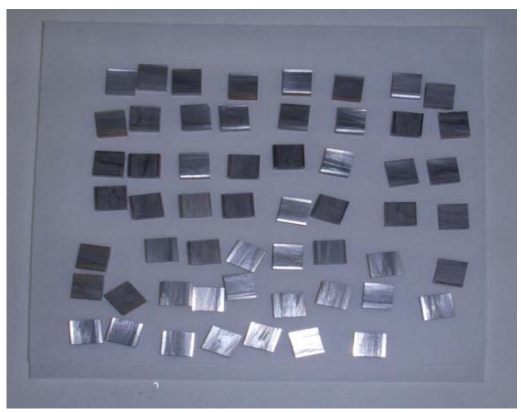
POWDER



HOT PRESSED PUCKS (34)



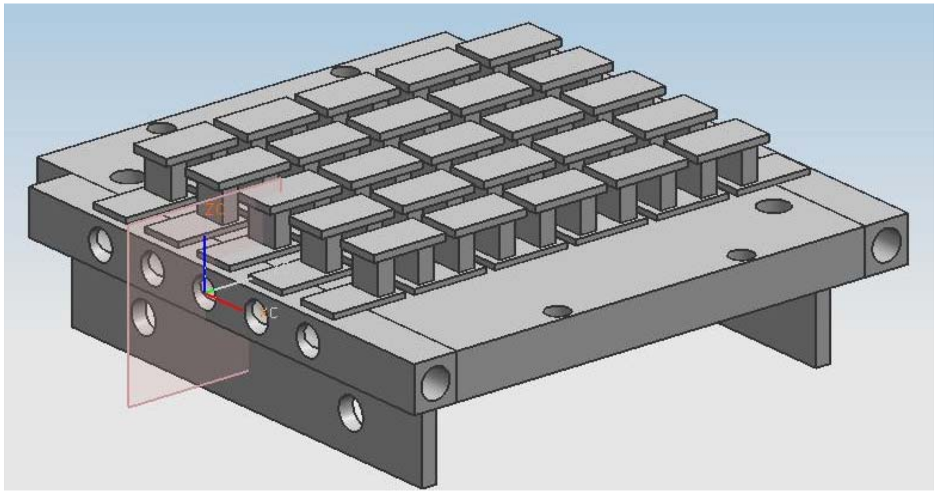
CUT HOT PRESSED PUCK



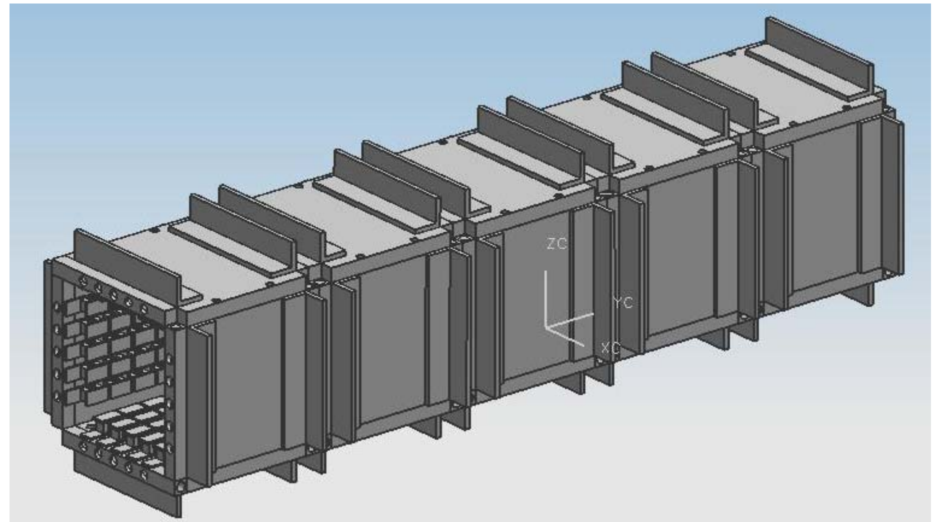
LEGS FROM PUCK > 95% YIELD

5 COUPLE, 13W - THEOR. SKD MODULES (90)

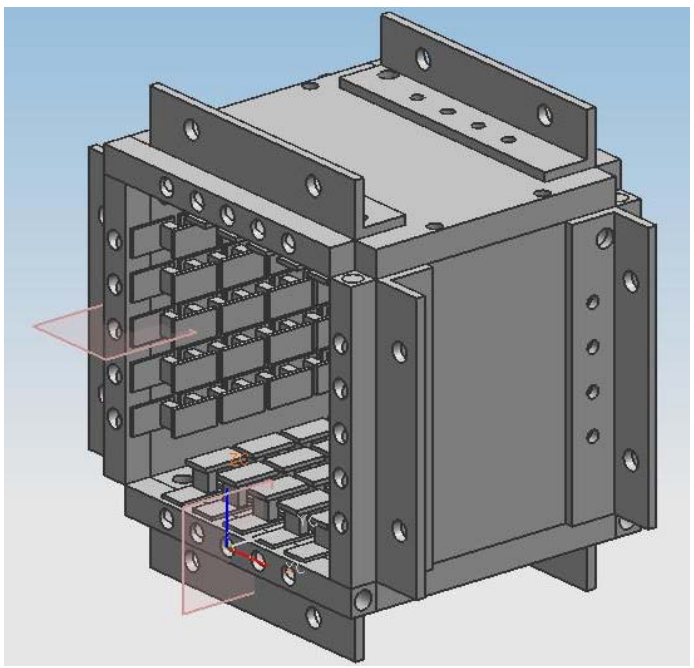
MSU Generation-1 TEG (SKD) Design



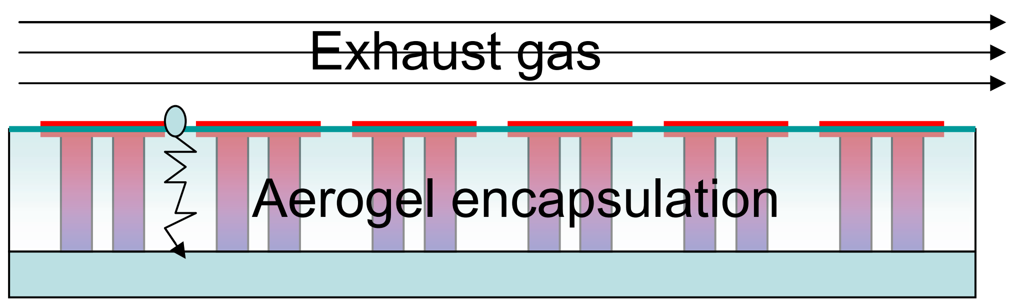
65W (theoretical) section of TEG



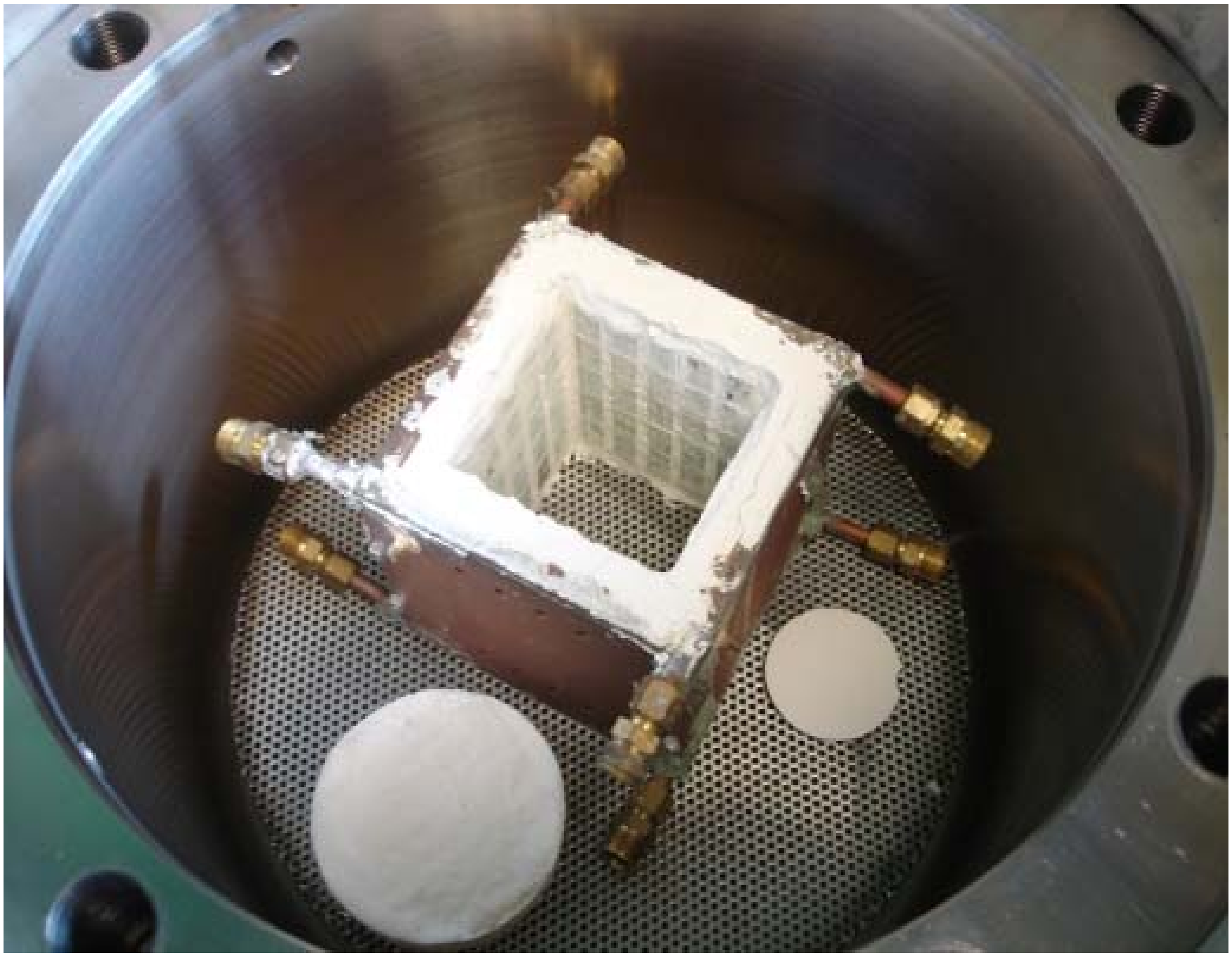
1.3kW (theoretical) 500W (actual est.) TEG
Dimensions 100x100x500 mm

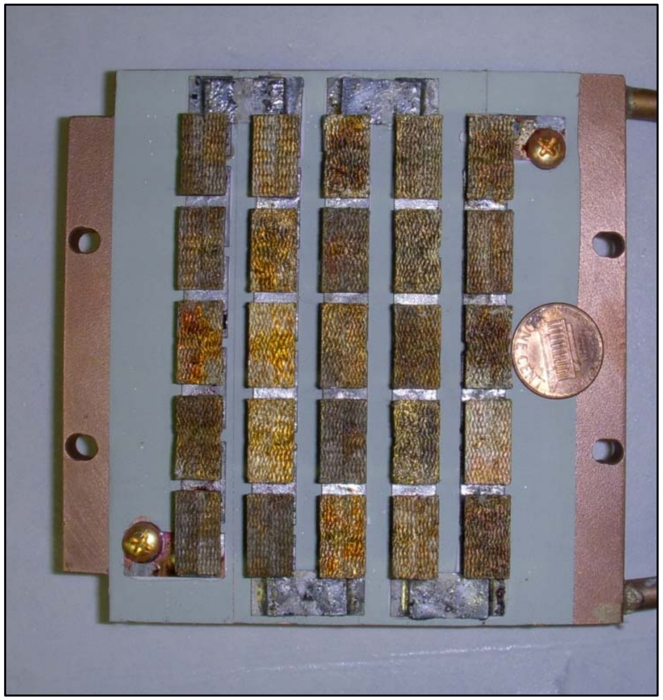


Section of Generator

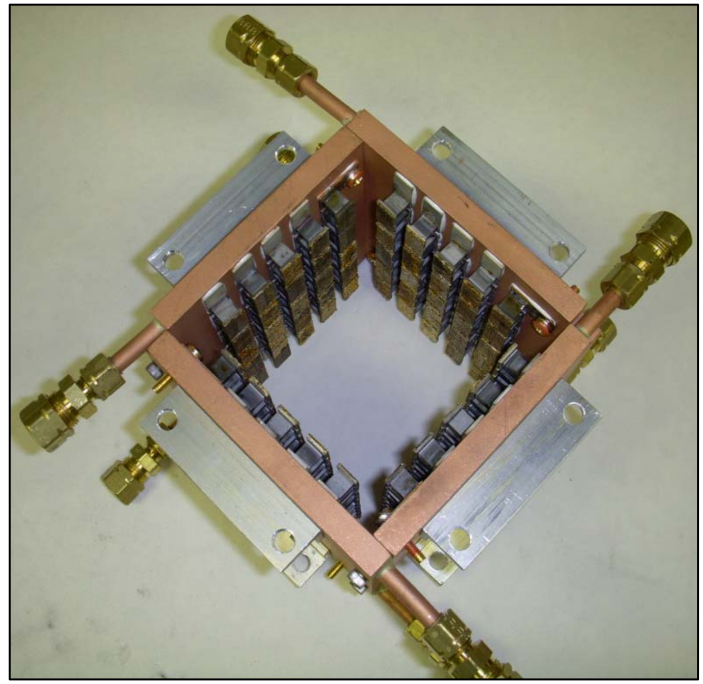


Aerogel Insulated TEG at Michigan State University

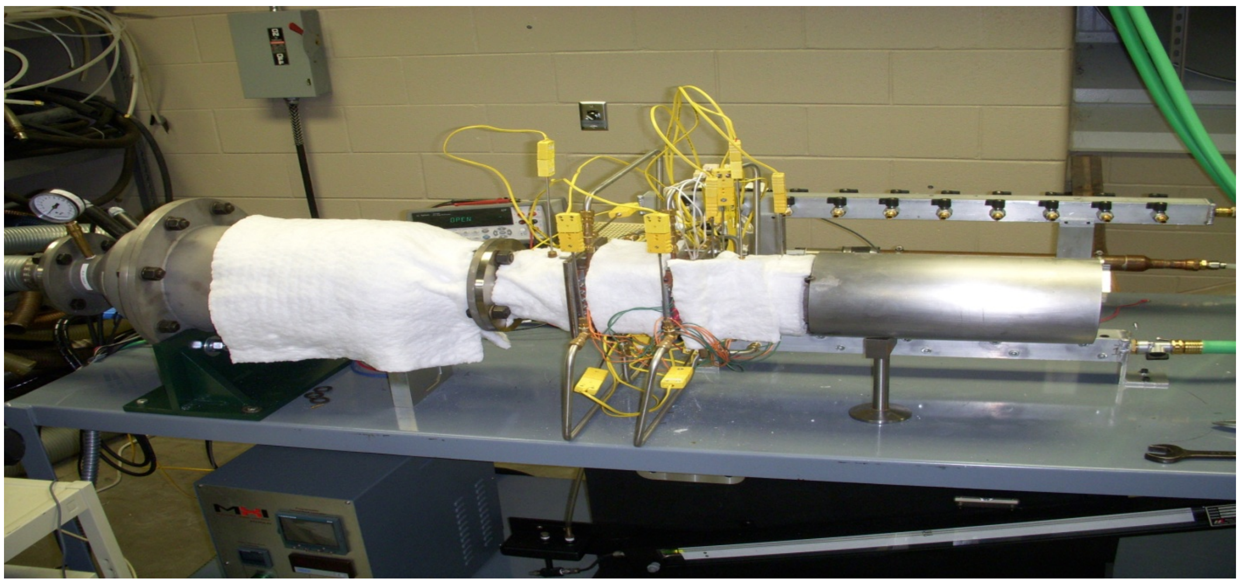




5 - 13W Modules (theoretical @ ΔT=600C) before Insulation

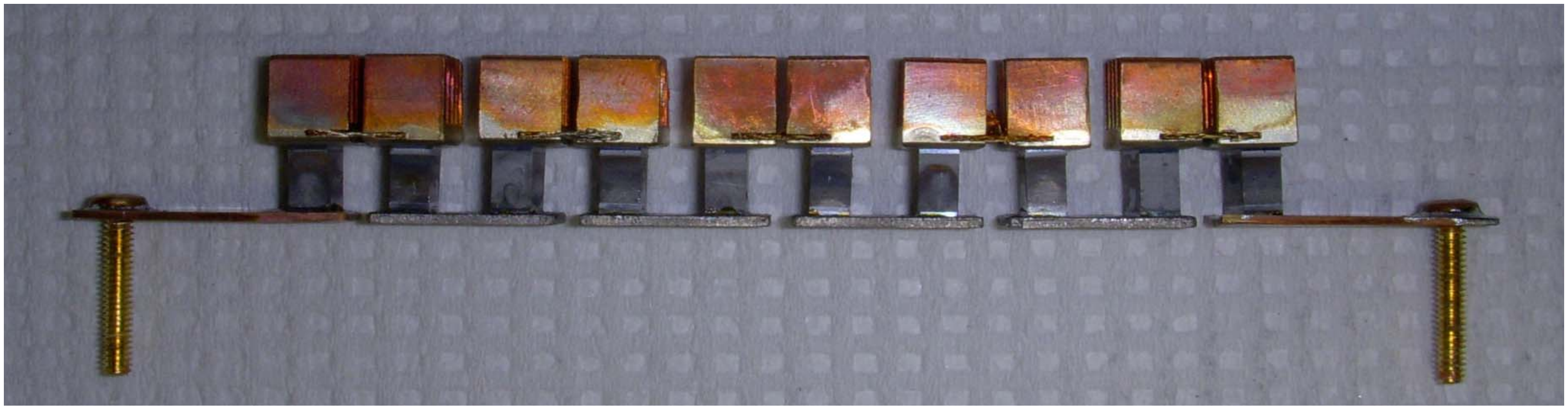


TEG – 260W (theoretical @ ΔT=600C) 20 – 13W Modules



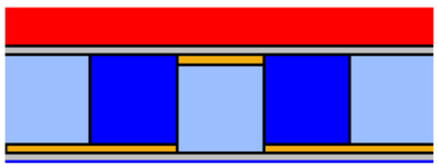
TEG Testing Assembly

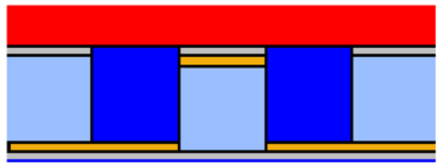
10 Leg Un-insulated Module Fabricated at MSU with Heat Collectors (legs are 3x7x7 mm, area of heat collector is >20x area leg top surface)



Heat Transfer Studies: Accomplishments in 2008-09

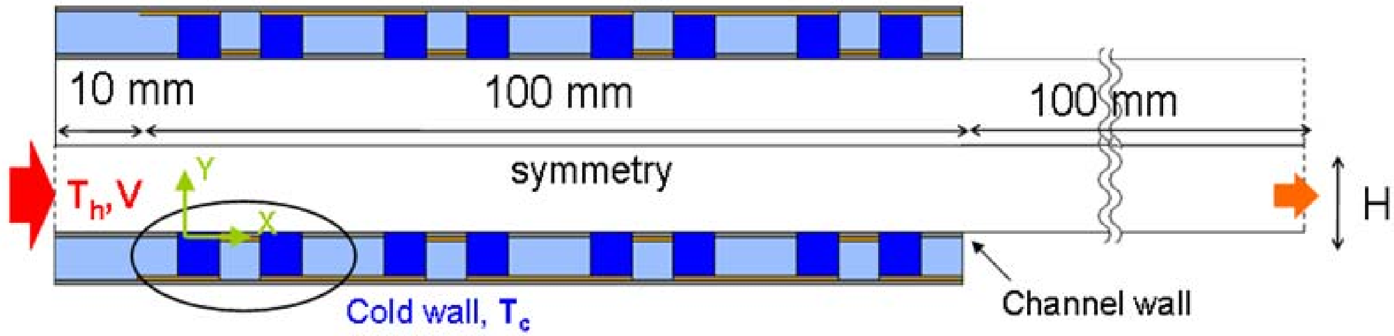
Developed and computationally evaluated a design concept to overcome thermal stress problems that can occur at high ΔT.

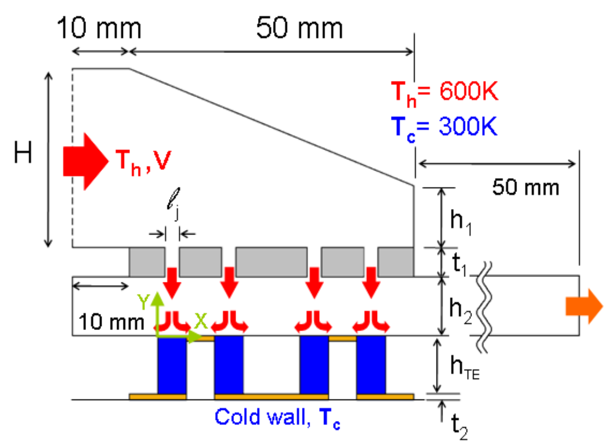


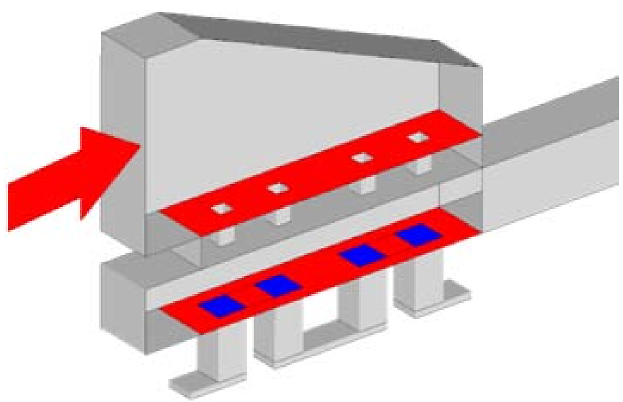


Developed and evaluated two HX concepts:

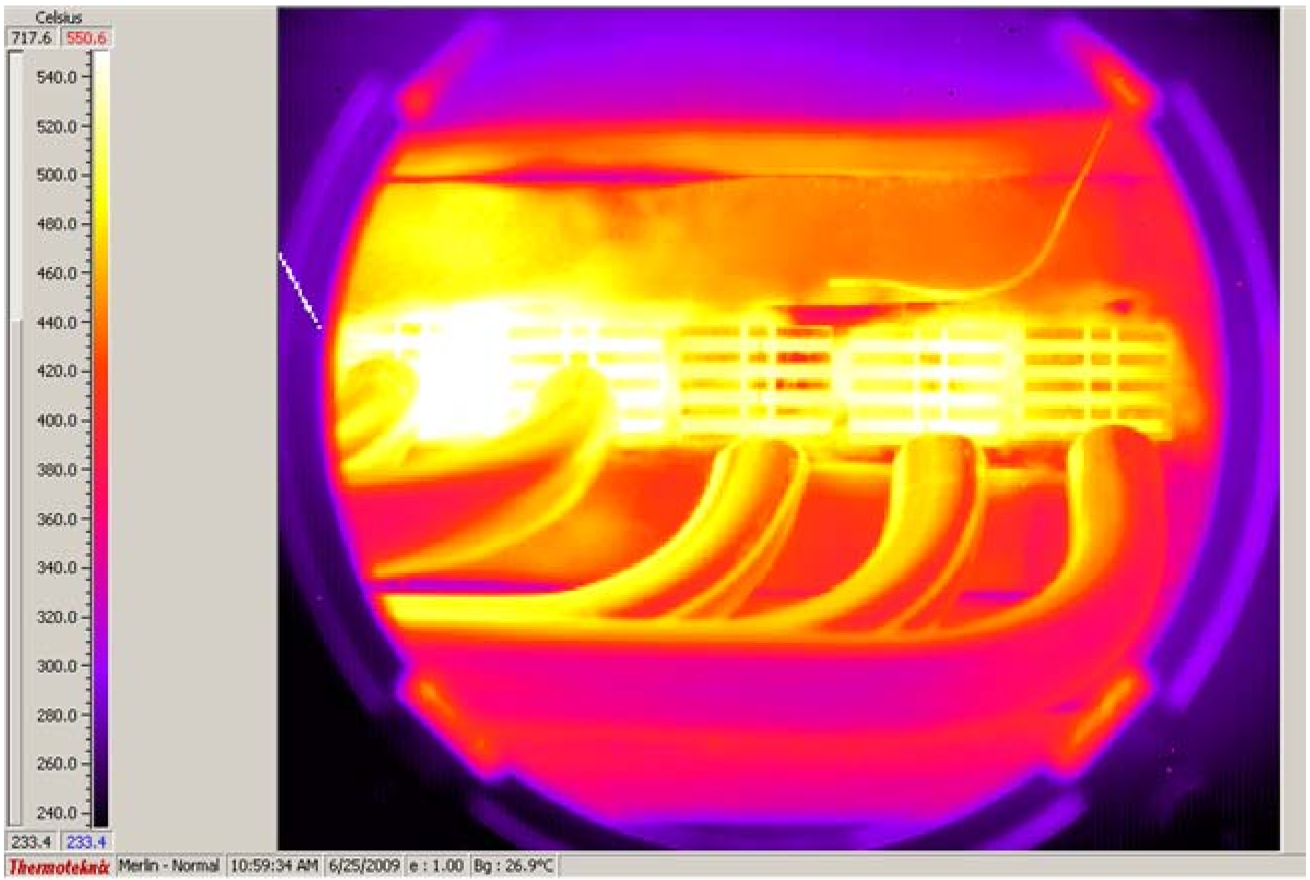
- starting boundary layer
- jet impingement



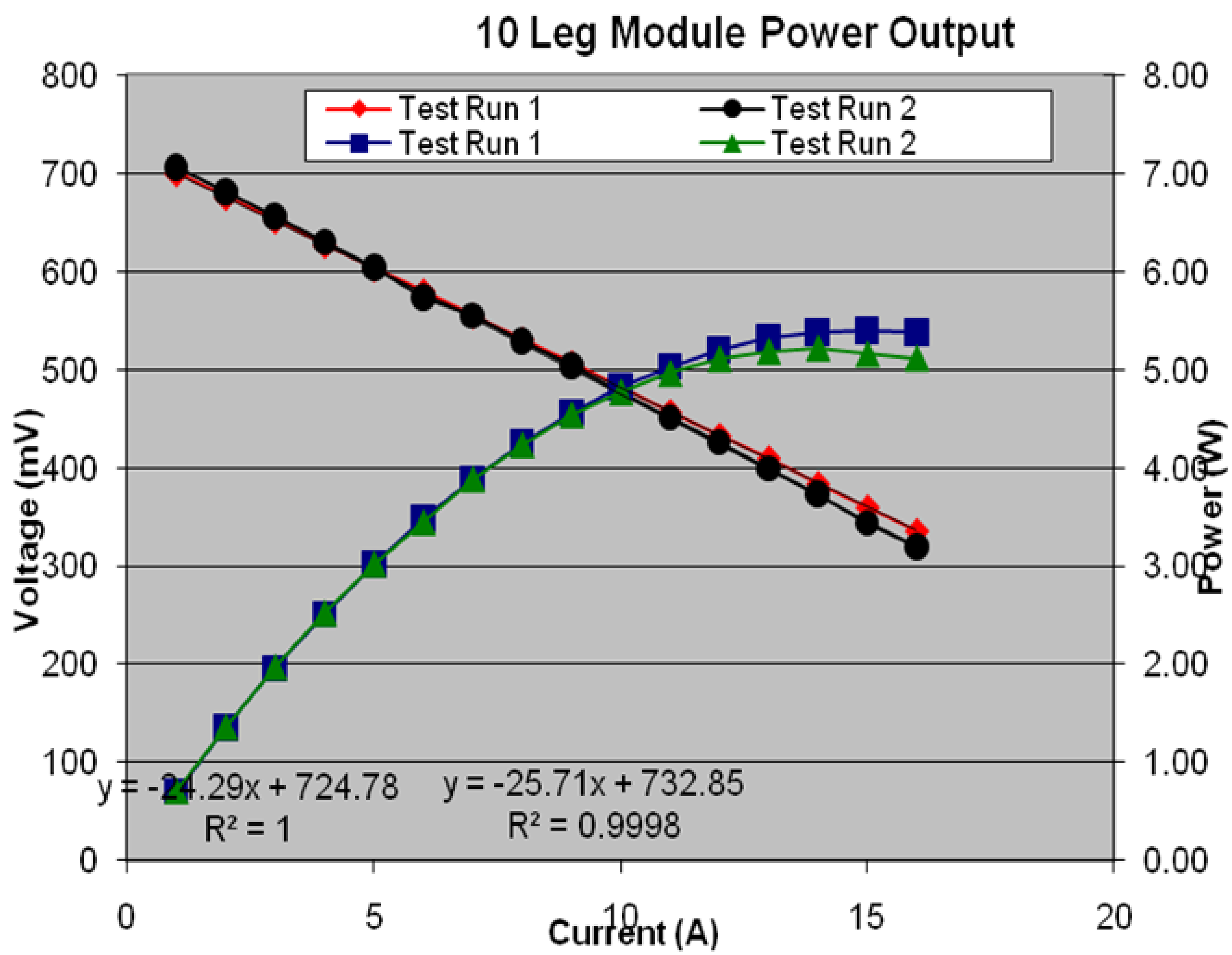




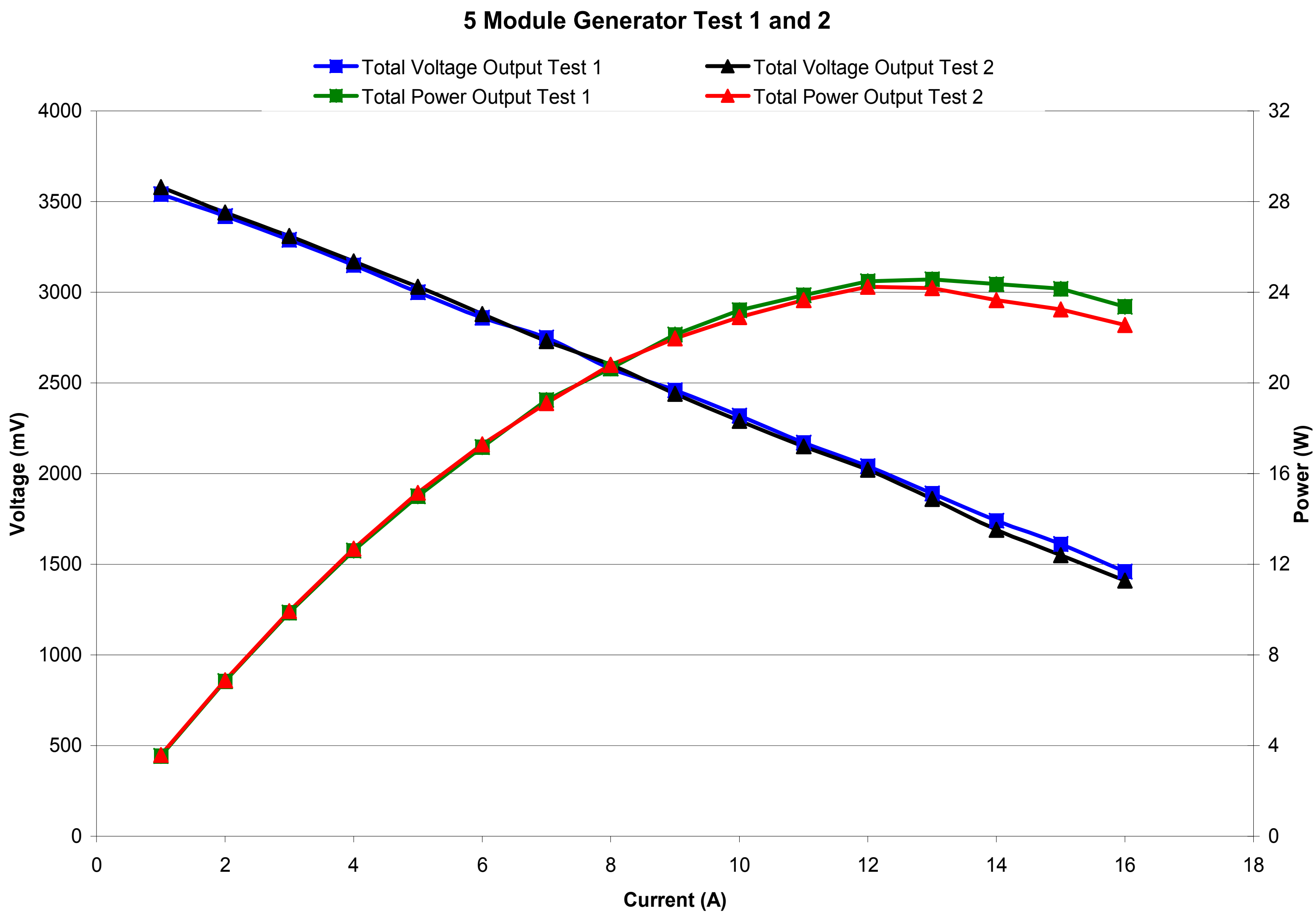
Infrared picture of a 10 leg module within the generator with tubes to create direct impingement of the hot gas onto the heat exchanger fins



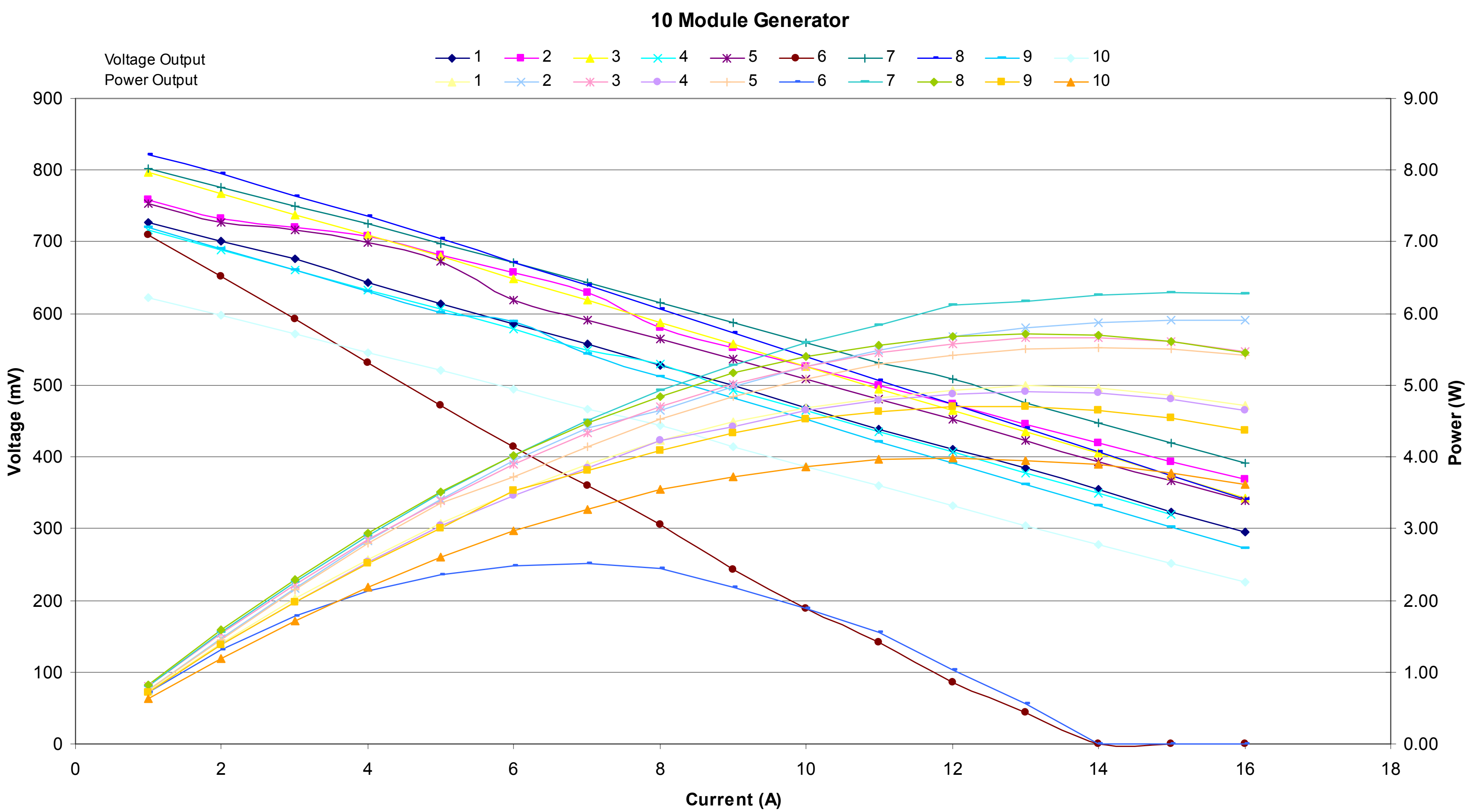
Voltage and power curves for a single 10 leg module for 2 different test runs. The module produced 5.4 Watts



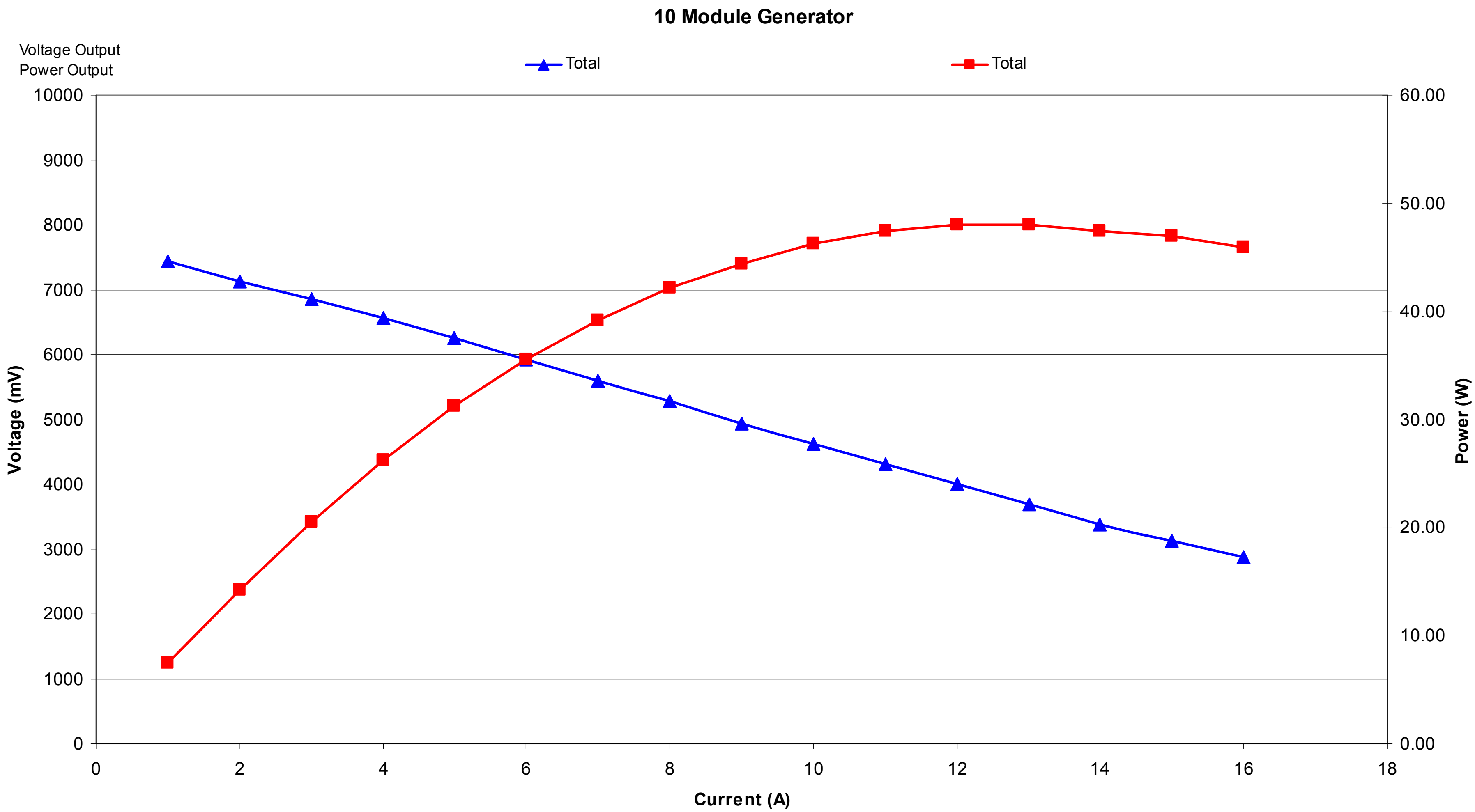
Voltage and power curves for a five 10 leg module for 2 different test runs. The module produced 24.6 Watts



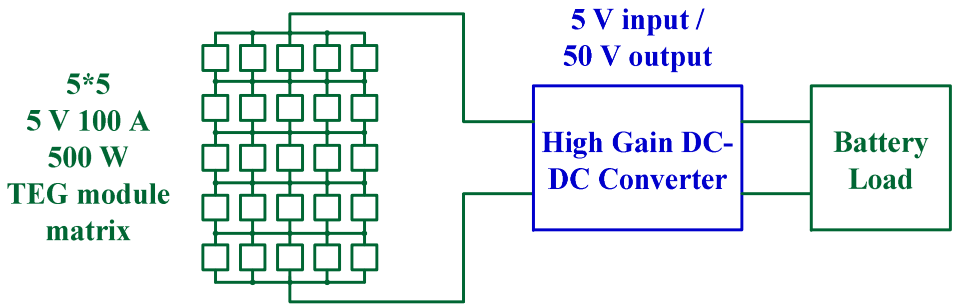
Output of 10 Module TEG (8/4/09)



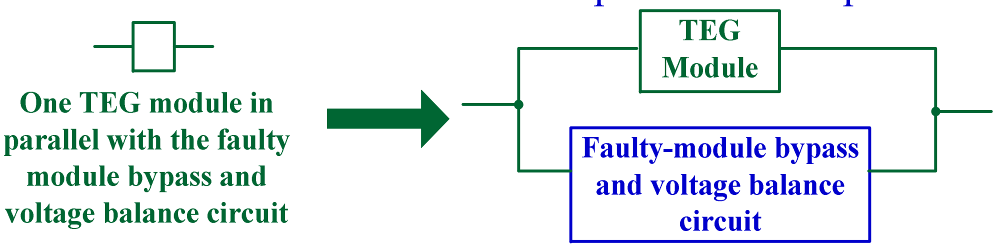
Sum of 10-Module TEG output, ΔT=500°C (sum of individual peaks 50.2W)



Power Electronics: Fault Tolerance and Voltage Boosting of TEG and Future Plans

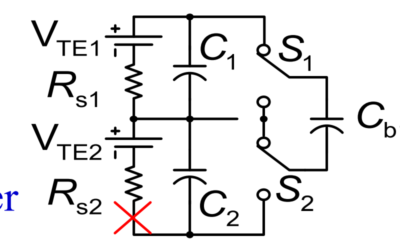


➢ A high efficiency low voltage input high gain dc-dc converter is needed for TEG module matrix to output maximum power.

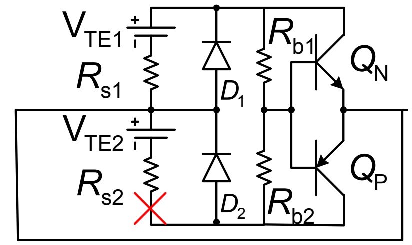


➢ A low cost faulty-module bypass and voltage balance circuit is needed for each TEG module to increase the reliability of TEG module matrix.

Faulty-module bypass and voltage balance circuits



Switched capacitor faulty –module bypass circuit



Class B amplifier faulty – module bypass circuit

Features:

➢ **Faulty-module bypassing with maximum power output of the rest modules.**

➢ **Terminal voltage auto balance with sensorless implementation.**

Challenges:

➢ **Finding a simple and low-cost implementation.**

Future Plan:

➢ **Full power (1 kW) operation of proposed dc-dc converter prototype will be tested.**

➢ **Low cost faulty-module bypass and voltage balance circuit will be proposed and proved of concept.**

➢ **Power electronics circuits will be built and tested for the integration and demonstration in the 500W TEG beign constructed at MSU.**

Analysis of Implementing an 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)=$5568 per year or $37120 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

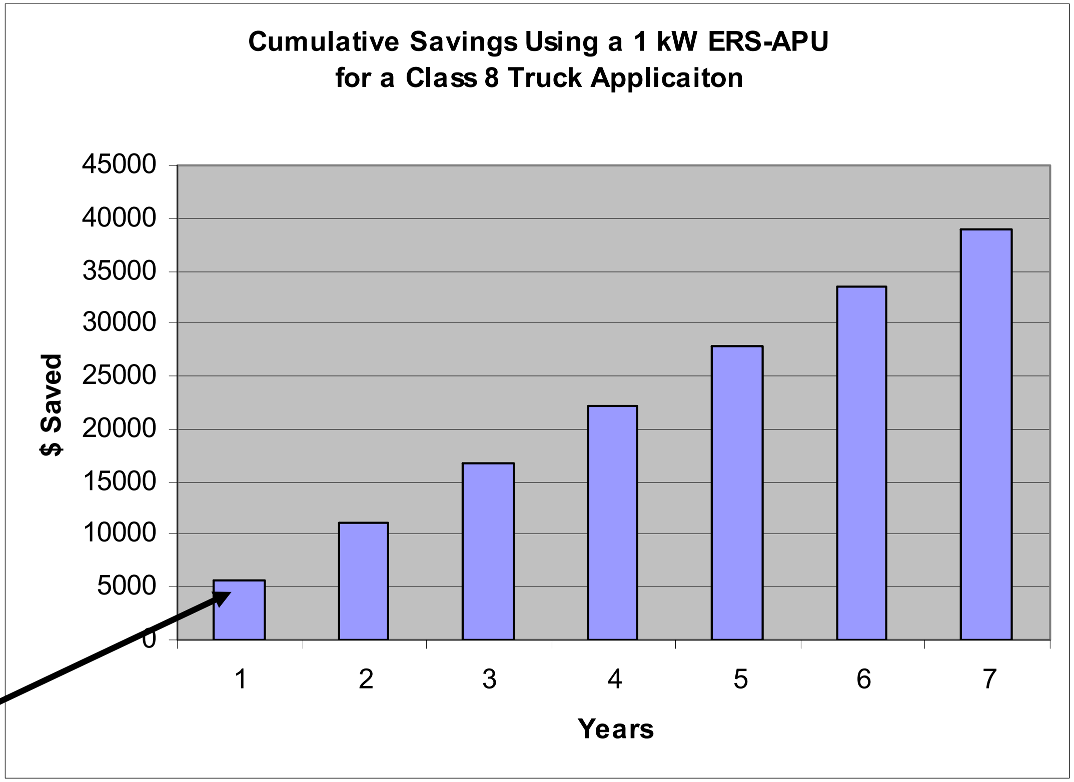
[2] Roadmap and Technical White Papers, USDOE-EERE, 21CTP-0003, Dec. 06

TEG Cost Estimates vs. Savings for a 1kW ERS-APU
(Assumptions shown in previous slide)

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

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 developed and demonstrated a 5-couple module which produced 5.4 watts at an average ΔT estimated to be ~500 ^{o}C hot side energy supplied with gaseous N_2 (2.6 W / couple when heated directly)**
- **MSU has demonstrated 1, 5 and 10 module TEGs to produce 5, 25 and 48 watts (50.2 W peak), respectively at a ΔT ~ 500C, heat supplied with gaseous N_2**
- Power conditioning electronics were designed and tested for the Gen-1 TEG demonstration. A Gen-2 system is being tested
- High heat flux head exchanger designs critical to success of practical TE waste heat recovery systems are being designed and testing
- Using TEG technology, a 5% improvement in bsfc for an OTR truck is a reasonable 5 year goal…a cost effective application may be as an ERS-APU for trucks and buses (ERS-APU = Energy Recovery System-Auxiliary Power Unit)
- Plans for a proof-of-prototype ERS-APU testing on a diesel powertrain will be finalized in late August