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

Prepared by:

Harold Schock, Thierry Caillet, Eldon Case, Charles Cauchy, Jonathan D'Angelo, Jean-Pierre Fleurial, Tim Hogan, Mercouri Kanatzidis, Matt Lyle, Ryan Maloney, Christopher Nelson, Jennifer Ni, James Novak, Fang Peng, Trevor Ruckle, Jeff Sakamoto, Robert Schmidt, Tom Shih, Ed Timm

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Project ID# ace049

Outline of Presentation

- **Overview**
- Objectives and Relevance
- Milestones
- Approach
  - New Material and System Development (NMSD)
  - Mechanical Property Characterization and Powder Processing (MPCPP)
  - Power Electronics
  - Heat Transfer Studies
  - Efficiency Improvement Simulations
  - Material Down Selection, Couple and Module Scale-Up Progress
  - Generation-1 TEG Design
- Accomplishments
- Future Work
- Summary

Overview

Timeline

Start – January 2005
Finish – March 30, 2011

Budget

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

[1] Received 4,423K to date from DOE

[2] Phase 3 funded 4/10 involves a hardware demonstration of a 1kW TEG. Phase 3 original was 1,078K, Phase 4 has been 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 ORT, engine idle reduction reduces fuel consumption and emissions while lowering capital costs
- After testing approximately 75 – 5 watt modules in 50 and 100 watt TEGs, an unsolved technical barrier is mechanical integrity of interfaces

Partners

- Cummins, Iowa State Univ., 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

- 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

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Milestones
(Phase 2, 2009-2010)

- 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, 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

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  - Power Electronics (See backup slides)
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Approach: Integrated Numerical and Experimental Study for Implementation of a Thermoelectric Generator with a Cummins ISX Over-the-Road Powerplant

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

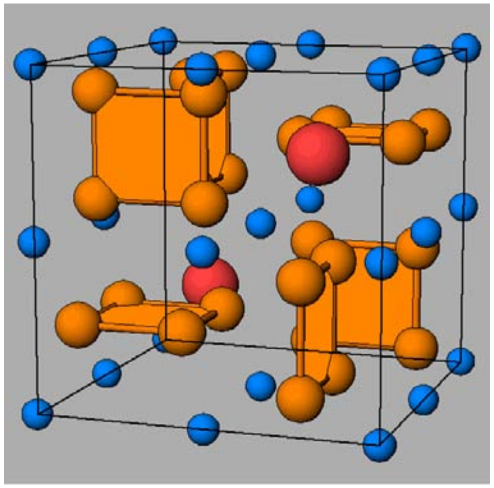
TEG Design and Construction
MSU / JPL / NWU / Tellurex

- 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

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



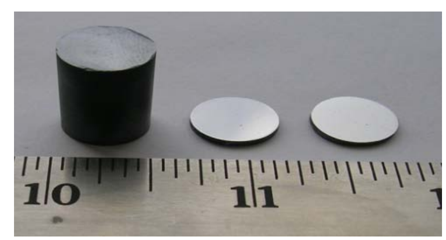
Skutterudite crystal structure

- **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

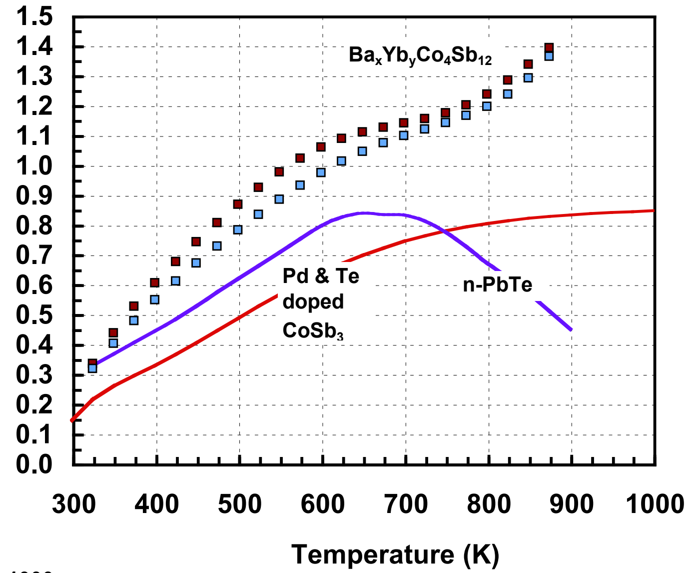


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

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

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



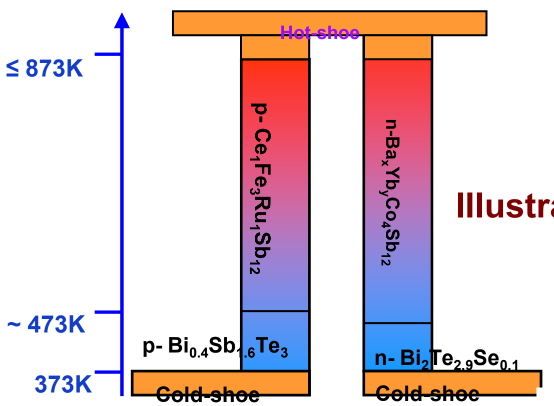
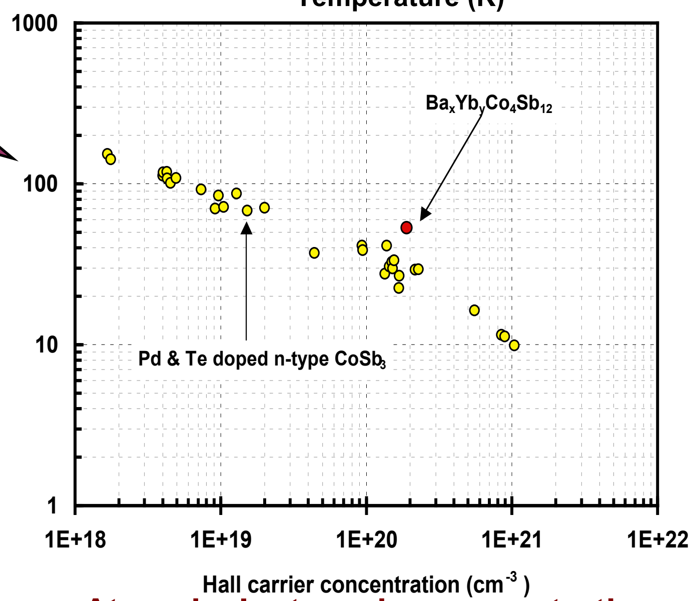


Illustration of skutterudite-Bi_2Te_3 couple

Couple efficiency (%)

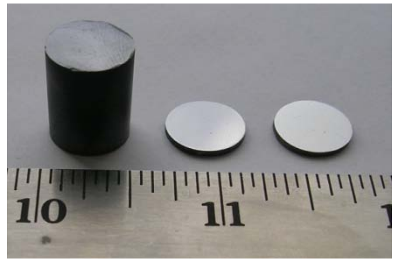
	T_H= 873K - T_C=373K	T_H= 773K - T_C=373K	T_H= 673K - T_C=373K
With Bi_2Te_3 segments	11.8	10.0	7.9
Without Bi_2Te_3 segments	10.7	8.8	6.75



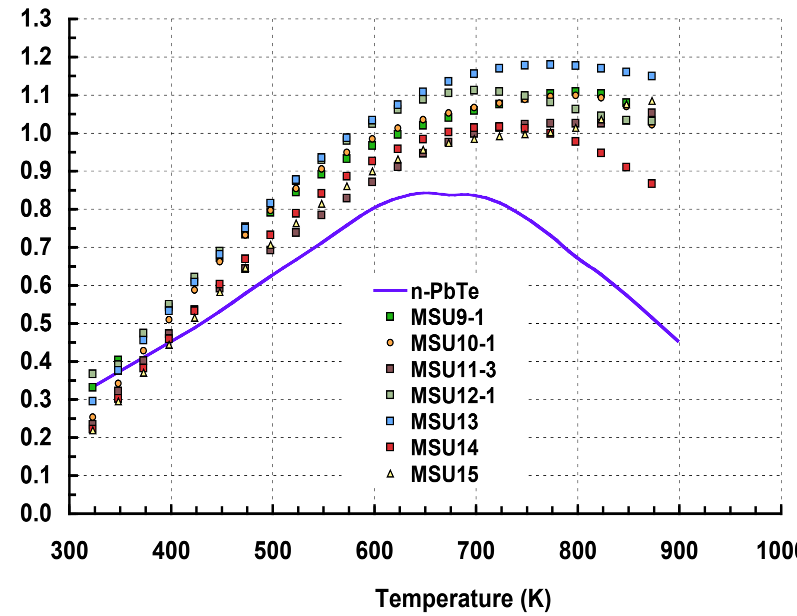
At equivalent carrier concentration, the Hall mobility for $Ba_xYb_yCo_4Sb_{12}$ is higher than that for doped $CoSb_3$

NMSD: 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

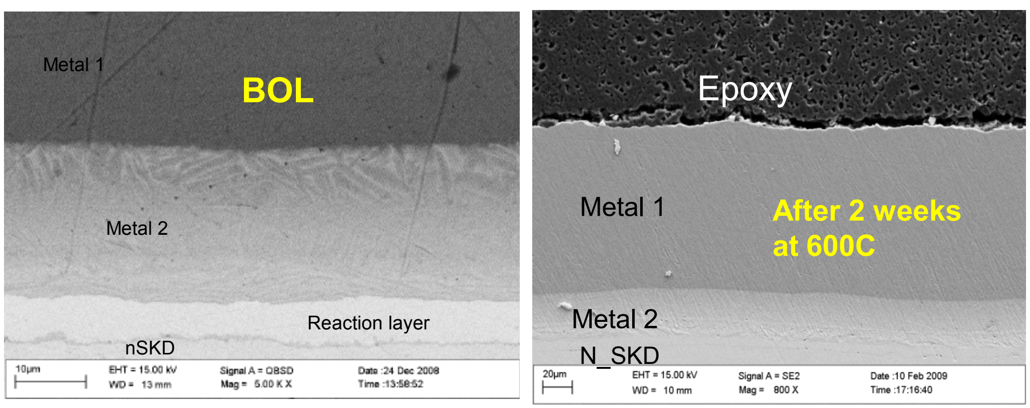


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

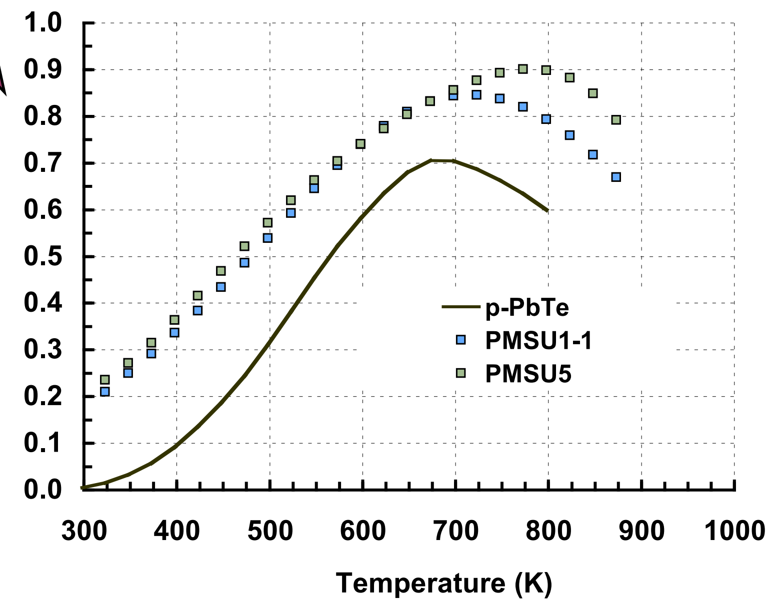


ZT values for n-type $Ba_xYb_yCo_4Sb_{12}$ ball milled materials. Each set of data corresponds to a separate 100 g batch.

- 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

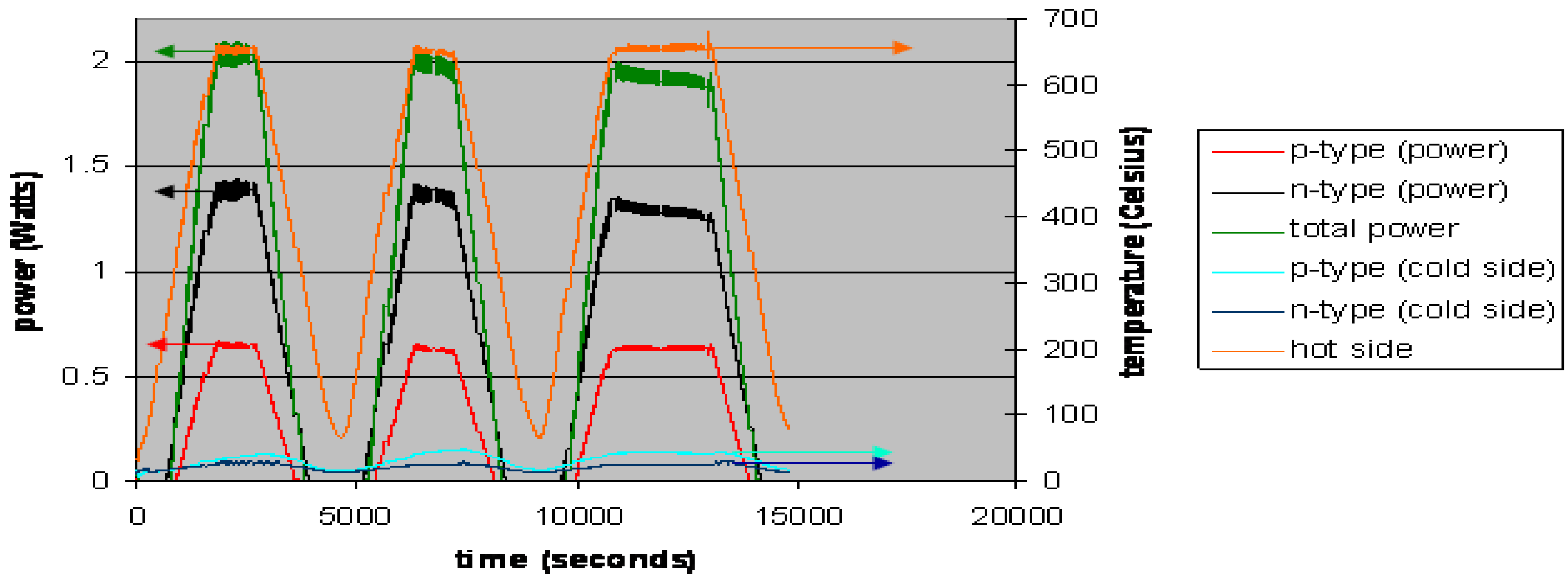


SEM images showing the SKD/metallization interface at beginning of life (BOL) and after 2 weeks aging at 600C. After aging, no degradation of the interface and no significant metal/SKD diffusion is observed.



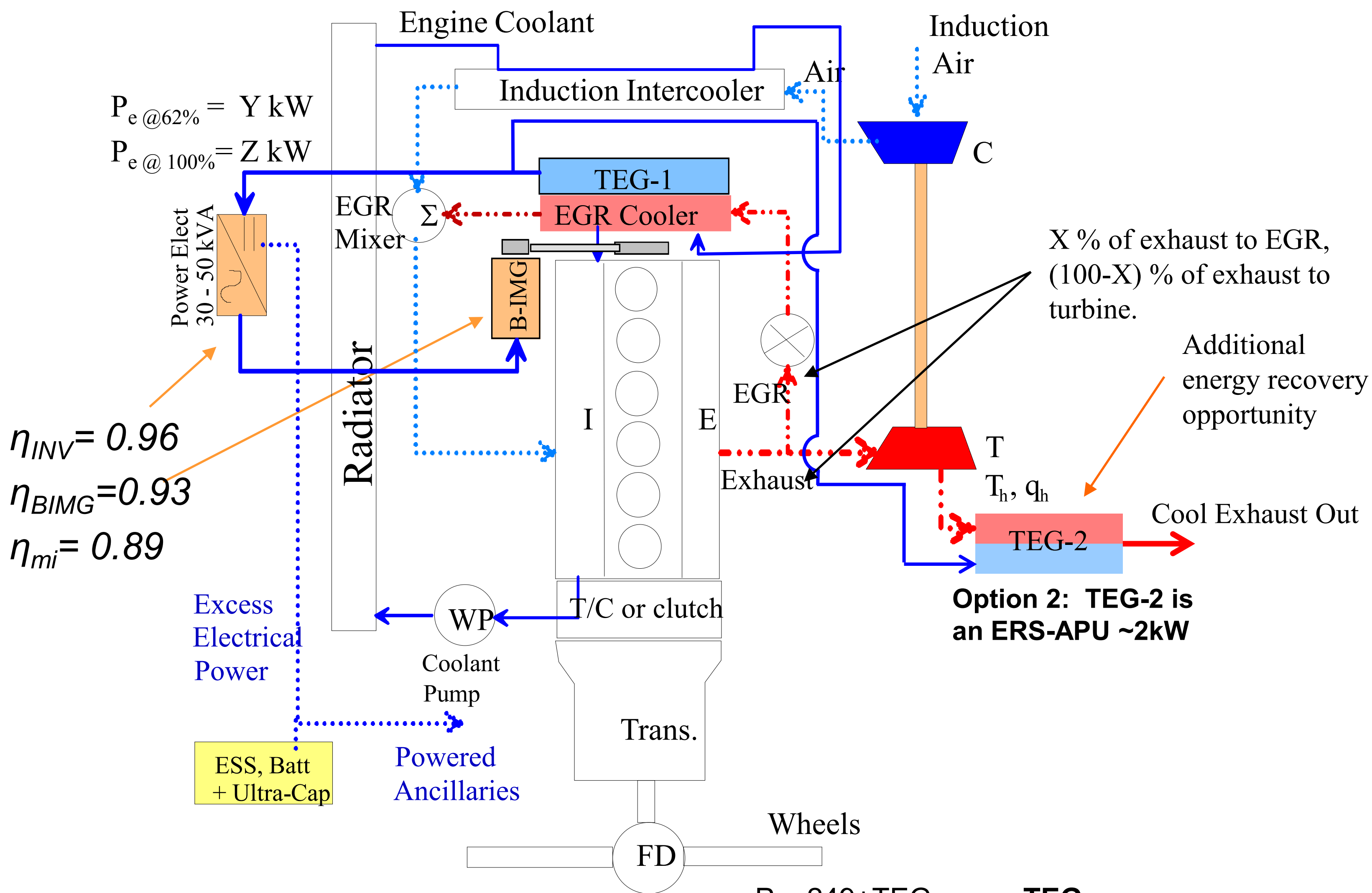
ZT values for p-type $Ce_xFe_{4-y}Co_ySb_{12}$ ball milled materials. Each set of data corresponds to a separate 50 g batch.

Couple and Module Scale-up Progress at MSU



- In 2010, demonstrated unicouple power output **~ 2.0 watts** versus **1.2 watts** with old n-type formulation during previous year! New modules averaged 5 watt vs 3 watts for old materials at a ΔT of 500C using same heat transfer and fabrication methods
- Three of ten thermal cycles are shown, a 20% power reduction at 10th cycle
- Sublimation and bond integrity degradation on n-type experienced …remediation of this problem underway
- N-type and P-type improvements are expected during Phase 3

Efficiency Improvements: Option 1: Thermal Power Split Hybrid, Option 2: Energy Recovery System-Auxiliary Power Unit (ERS-APU)

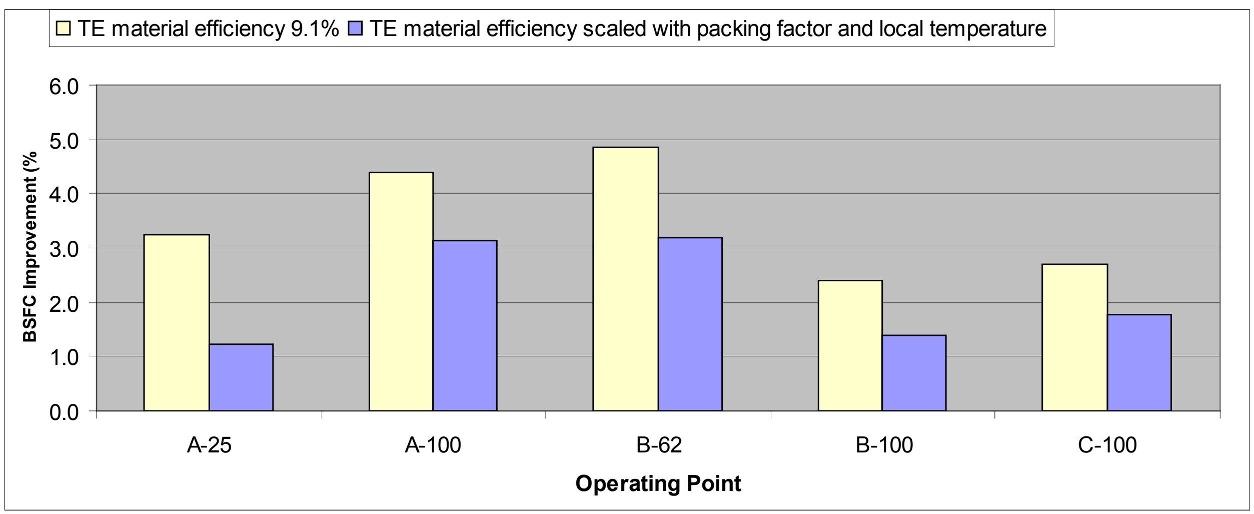


Option 2: TEG-2 is an ERS-APU ~2kW

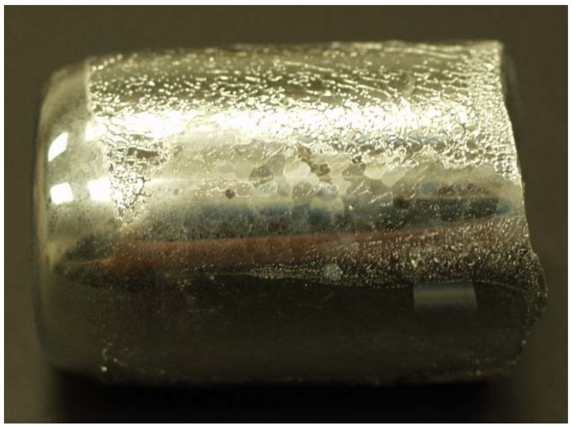
P_m=249+$TEG_{@\,100\%}$, $\mathbf{TEG_{@\,62\%}}$

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

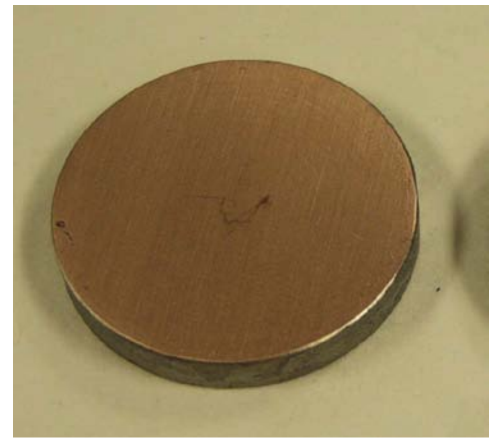


Material Down Selection, Couple and Module Scale-up Progress, Current SKD Thermoelectric Module Production at Michigan State University

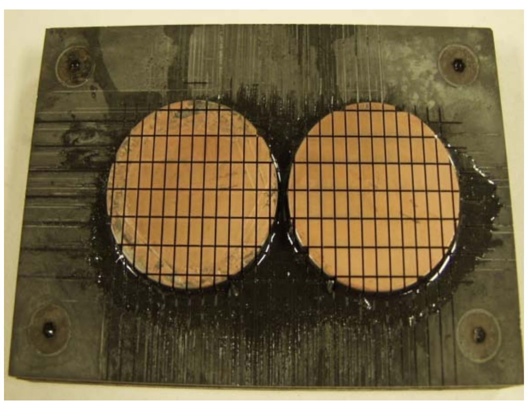


INGOT

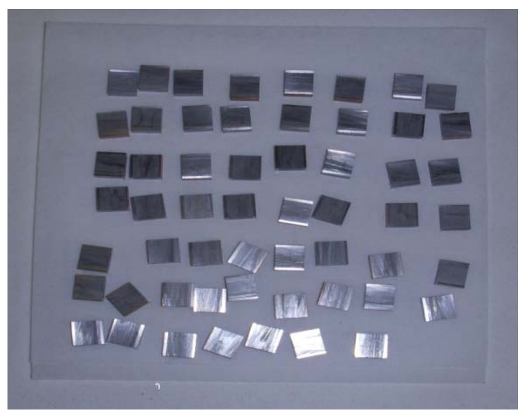
POWDER



HOT PRESSED PUCK



CUT HOT
PRESSED PUCK



LEGS FROM PUCK
> 95% YIELD

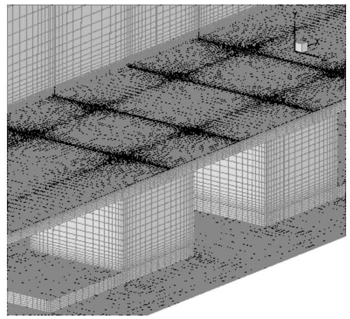
5 COUPLE, 13W -
THEOR. SKD MODULES

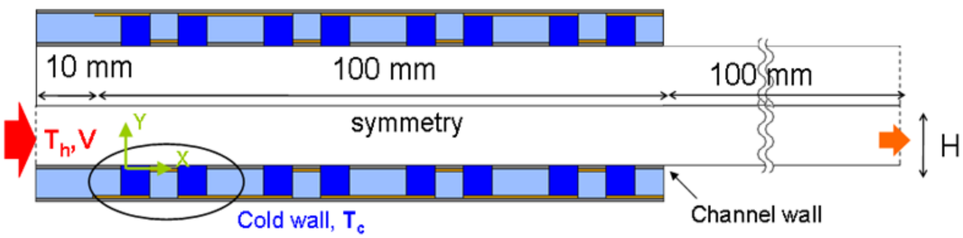
Heat Transfer Studies:

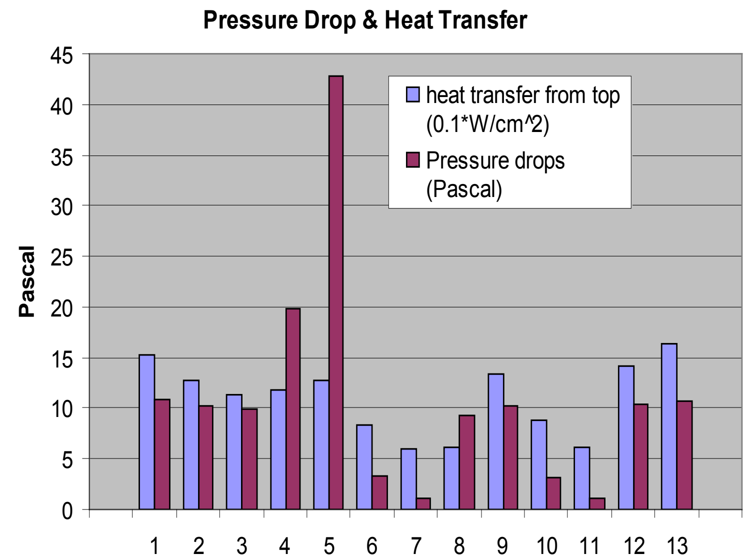
Accomplishments in 2008-09 – Implemented in 2009-2010

Developed and evaluated two HX concepts:

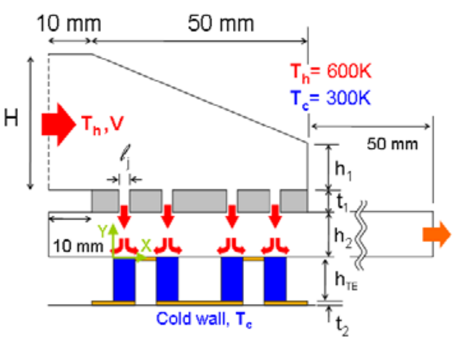
- starting boundary layer: can yield up to 1 W/cm^2

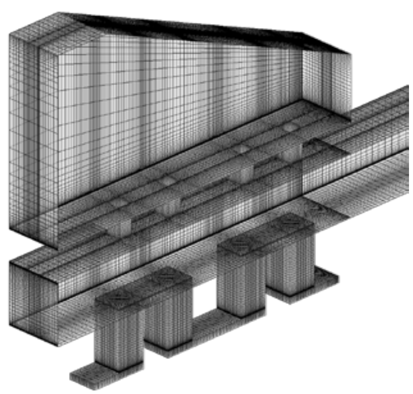


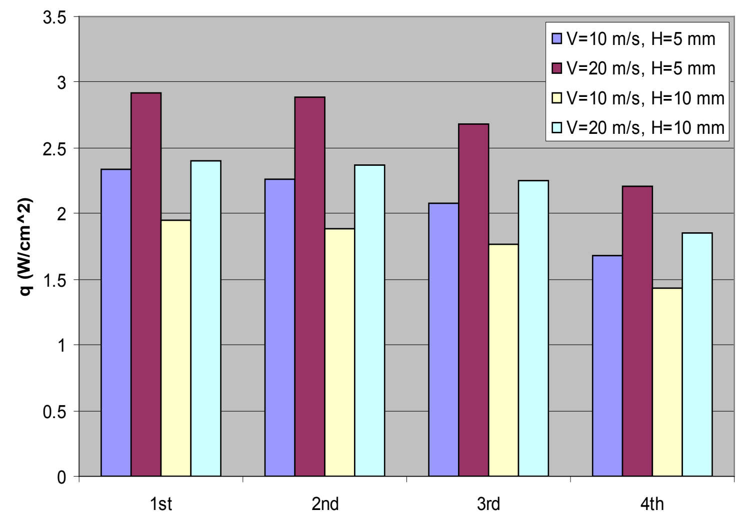




- jet impingement: can yield up to 3 W/cm^2

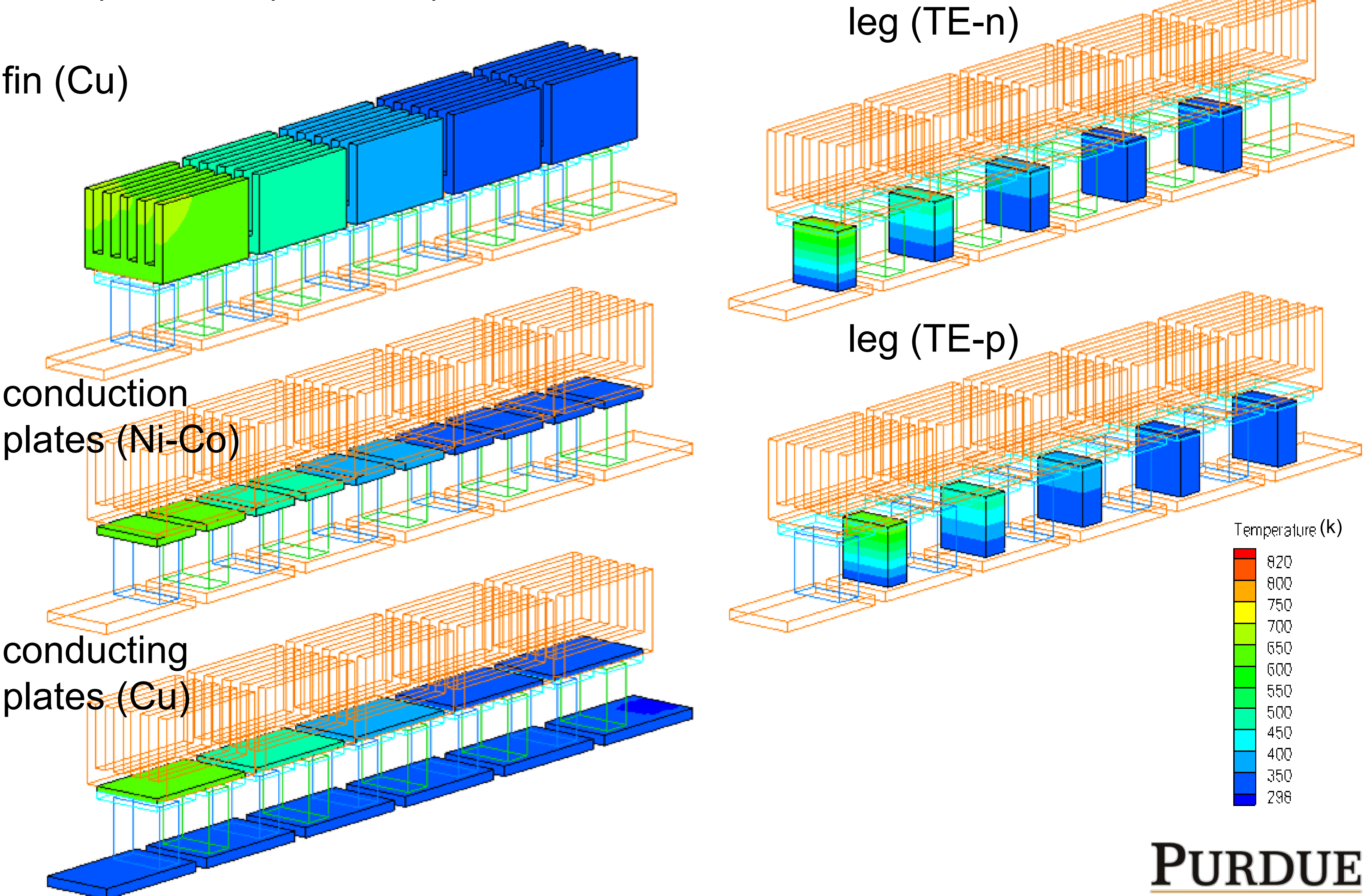






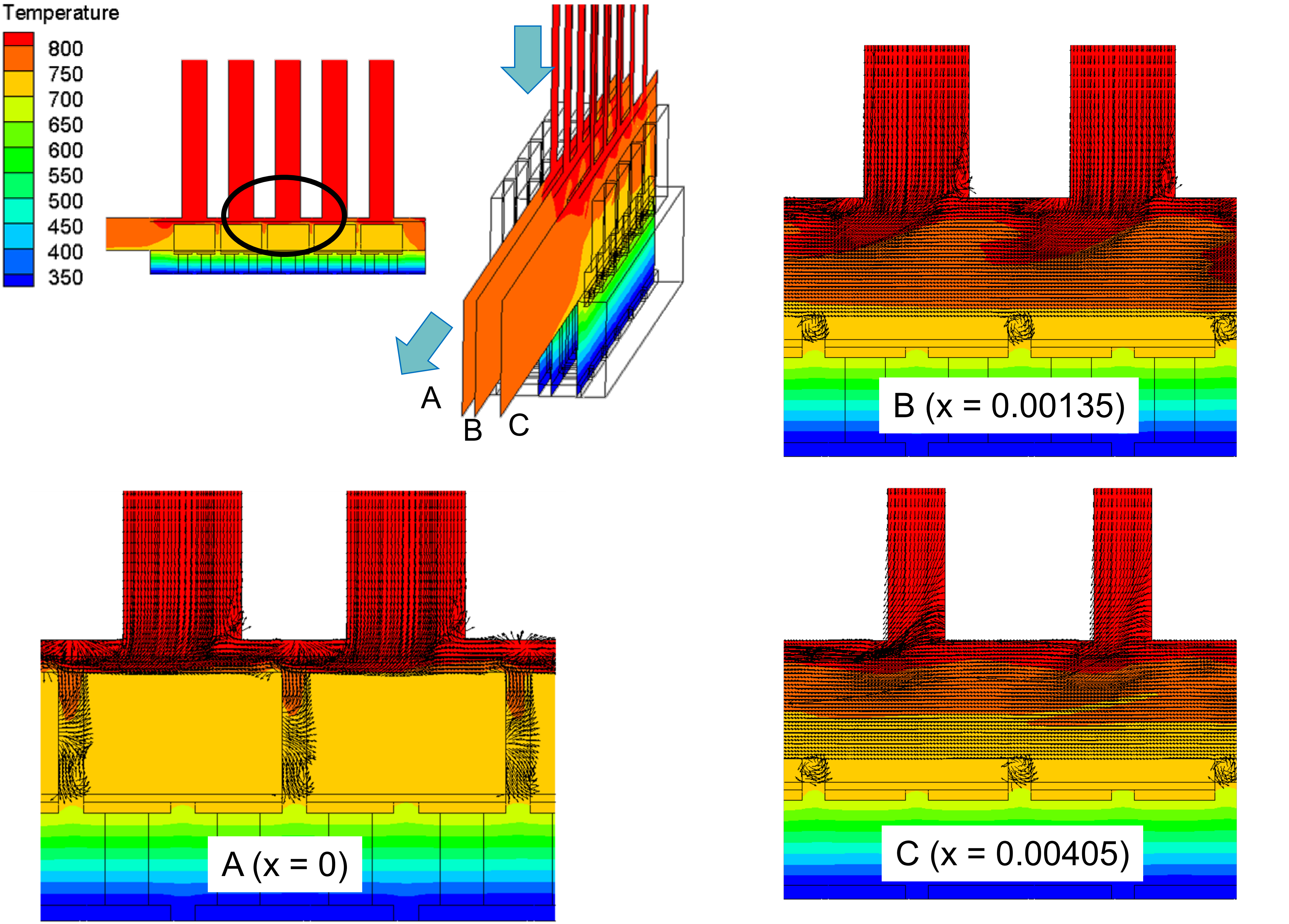
Temperature Distribution

- fins placed on top of TE couples

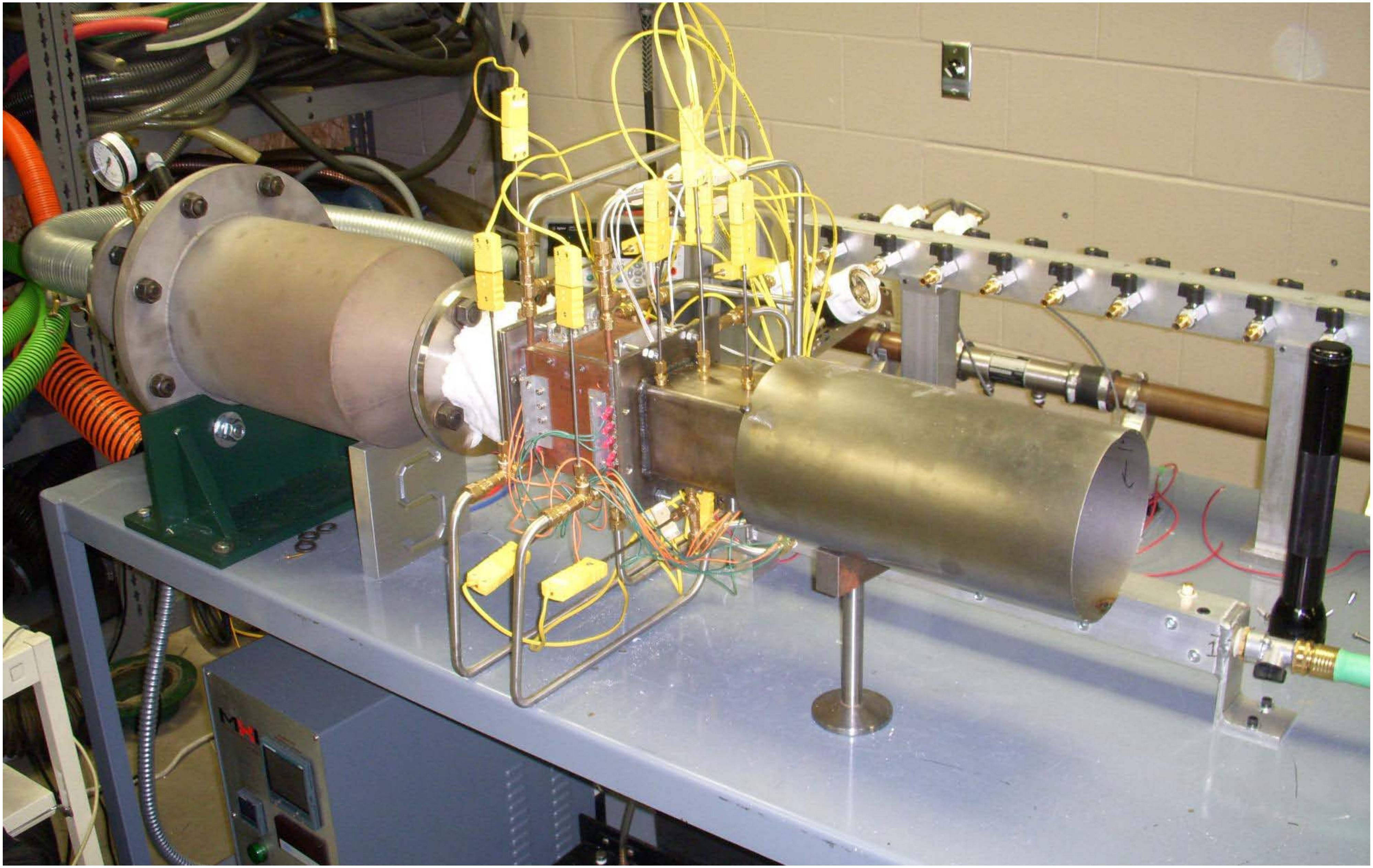


PURDUE UNIVERSITY

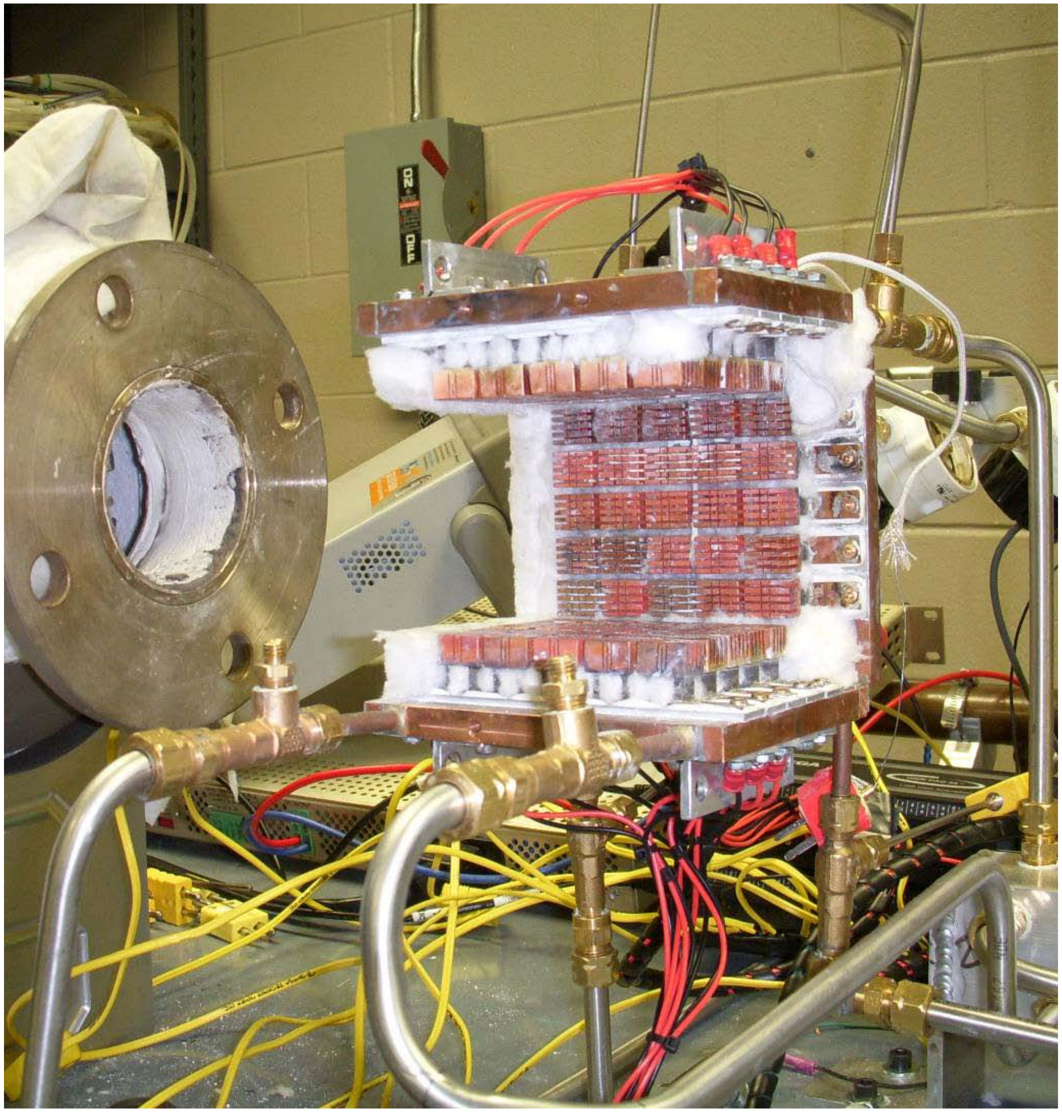
Flow Pattern (Velocity Contour)



50/100W Generator Shown Without External Insulation

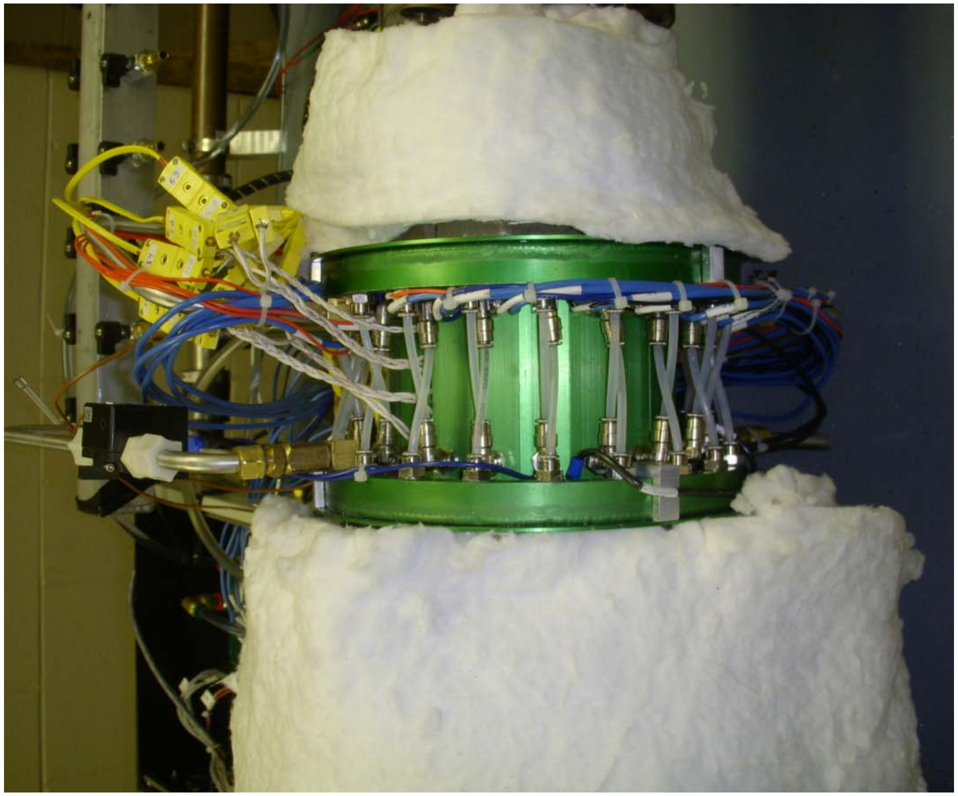


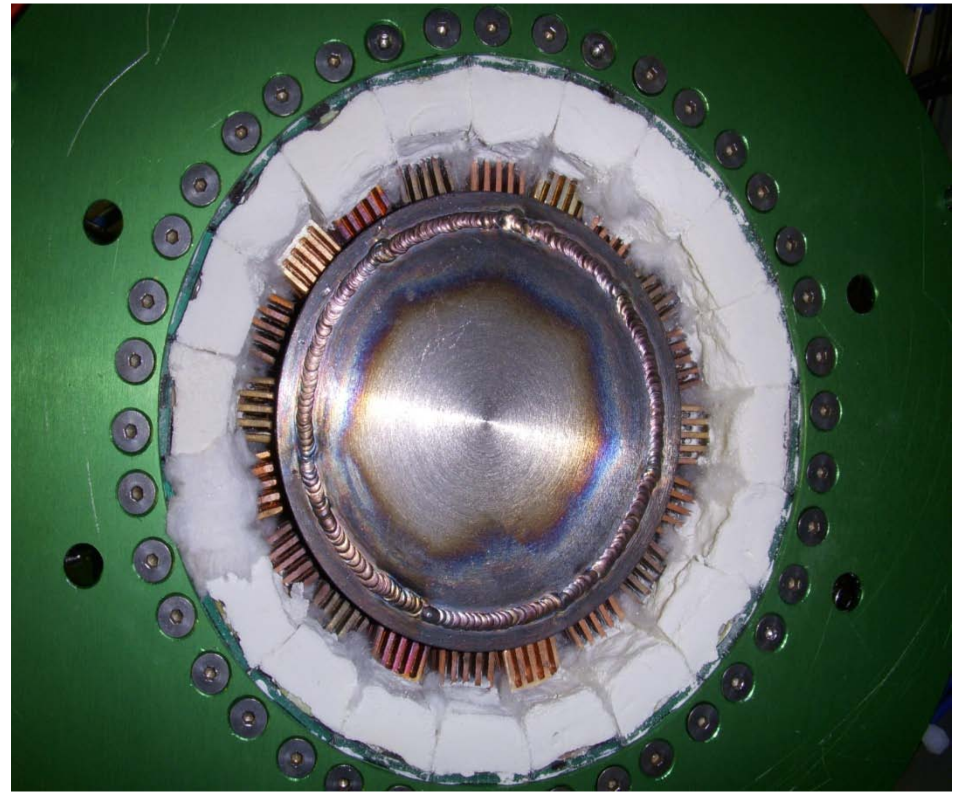
50/100W Generator Geometry



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

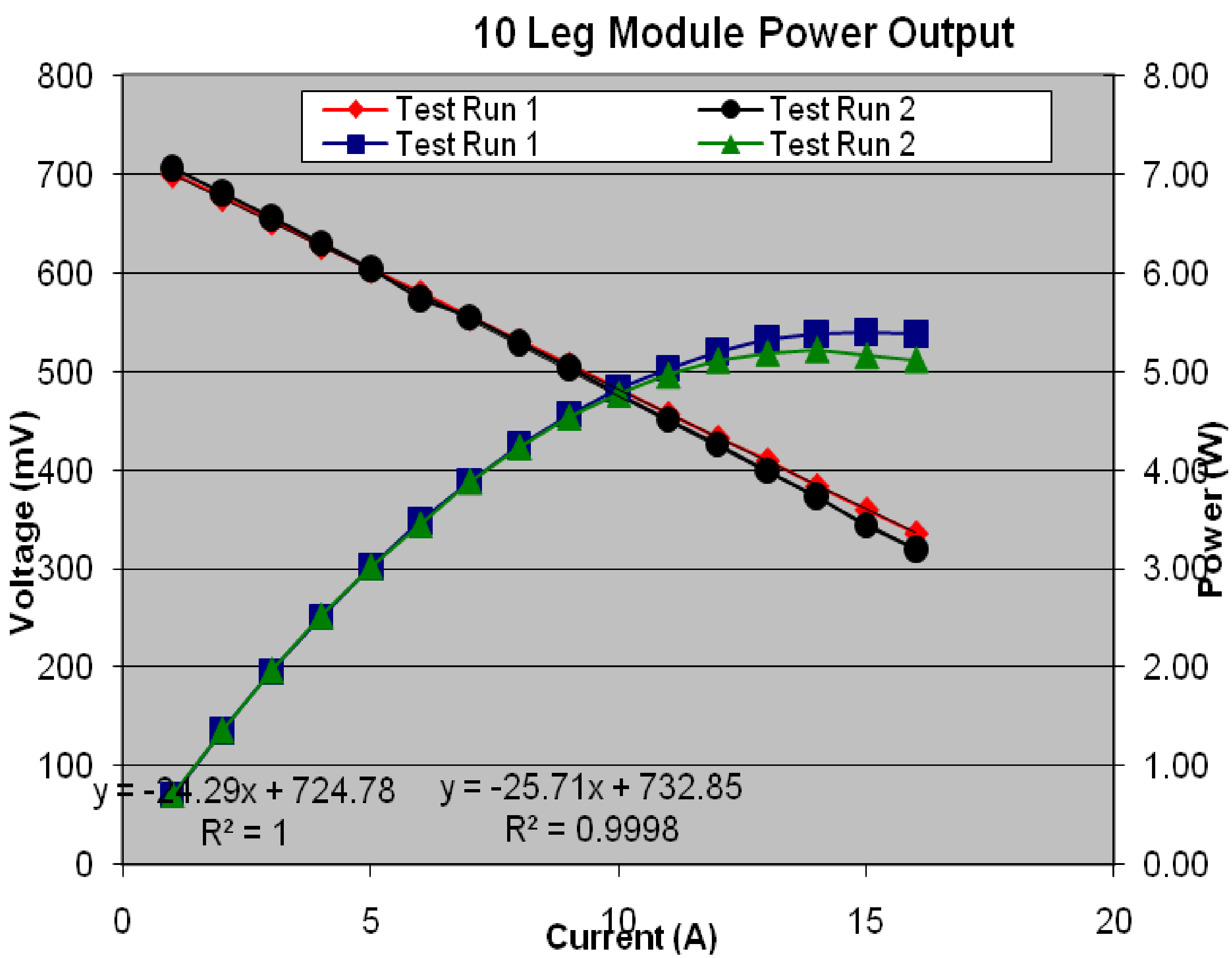
Gen 2 -100W Generator Geometry



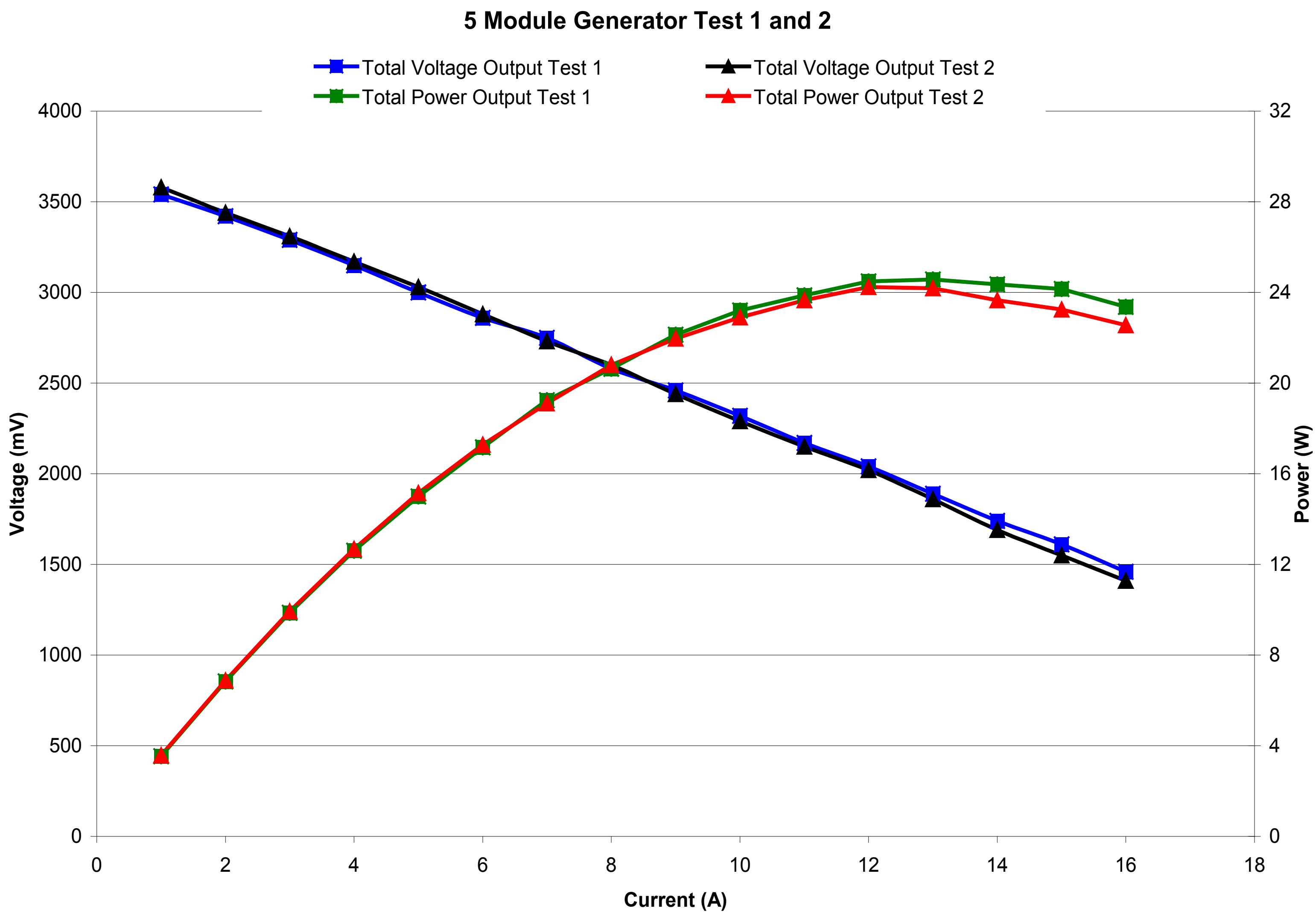


- Water lines to cool copper plates on cold side
- Electric lines to measure voltages and currents
- Thermocouples to measure temperatures and laminar air flow element and rotameters measure flows used in energy balance calculations
- First tested at MSU on 4/22/10, Produced 70 watts at a ΔT = 500 C, 4 of 20 modules failed

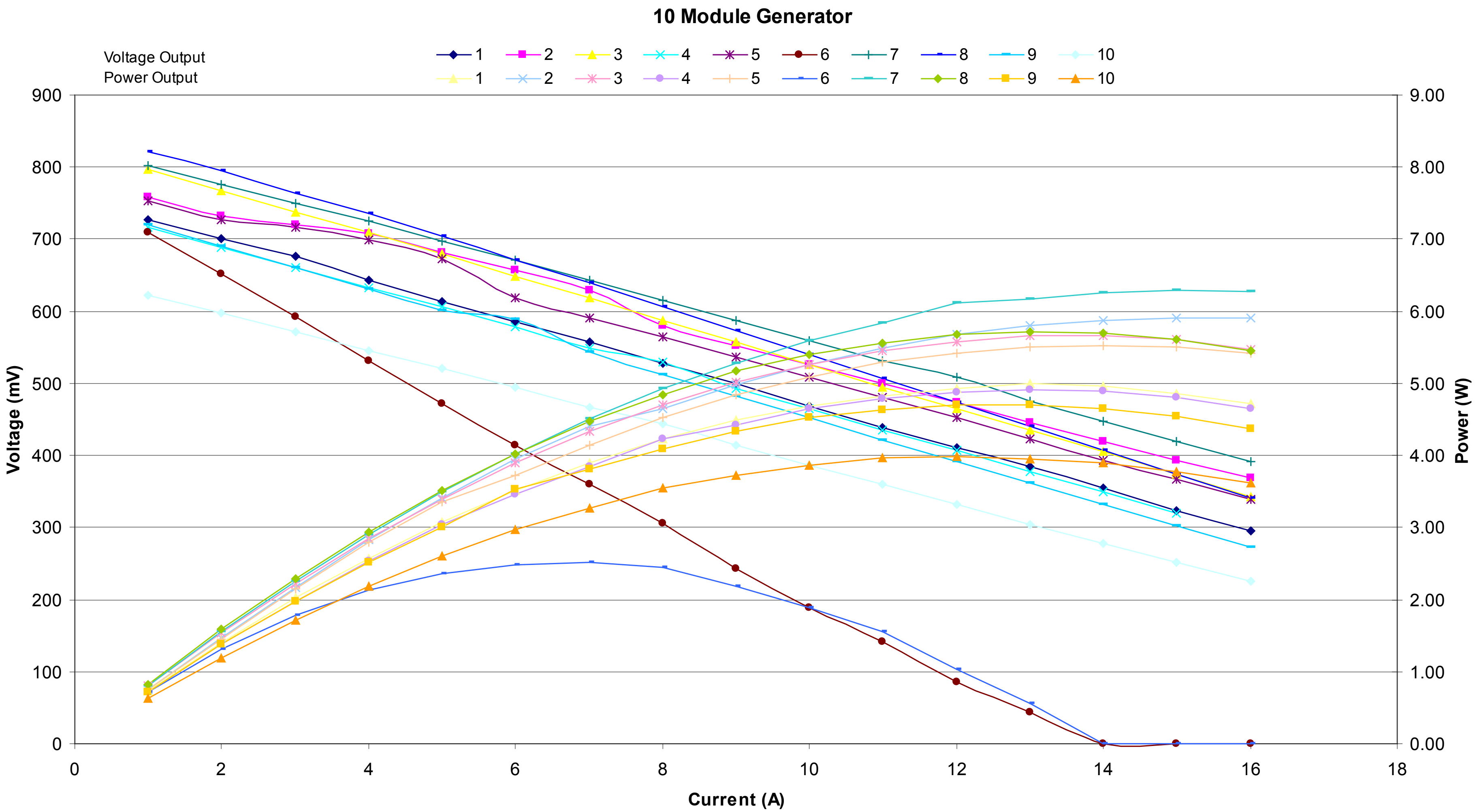
Voltage and power curves for a single 10 leg module for 2 different test runs. The module produced 5.4 Watts



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

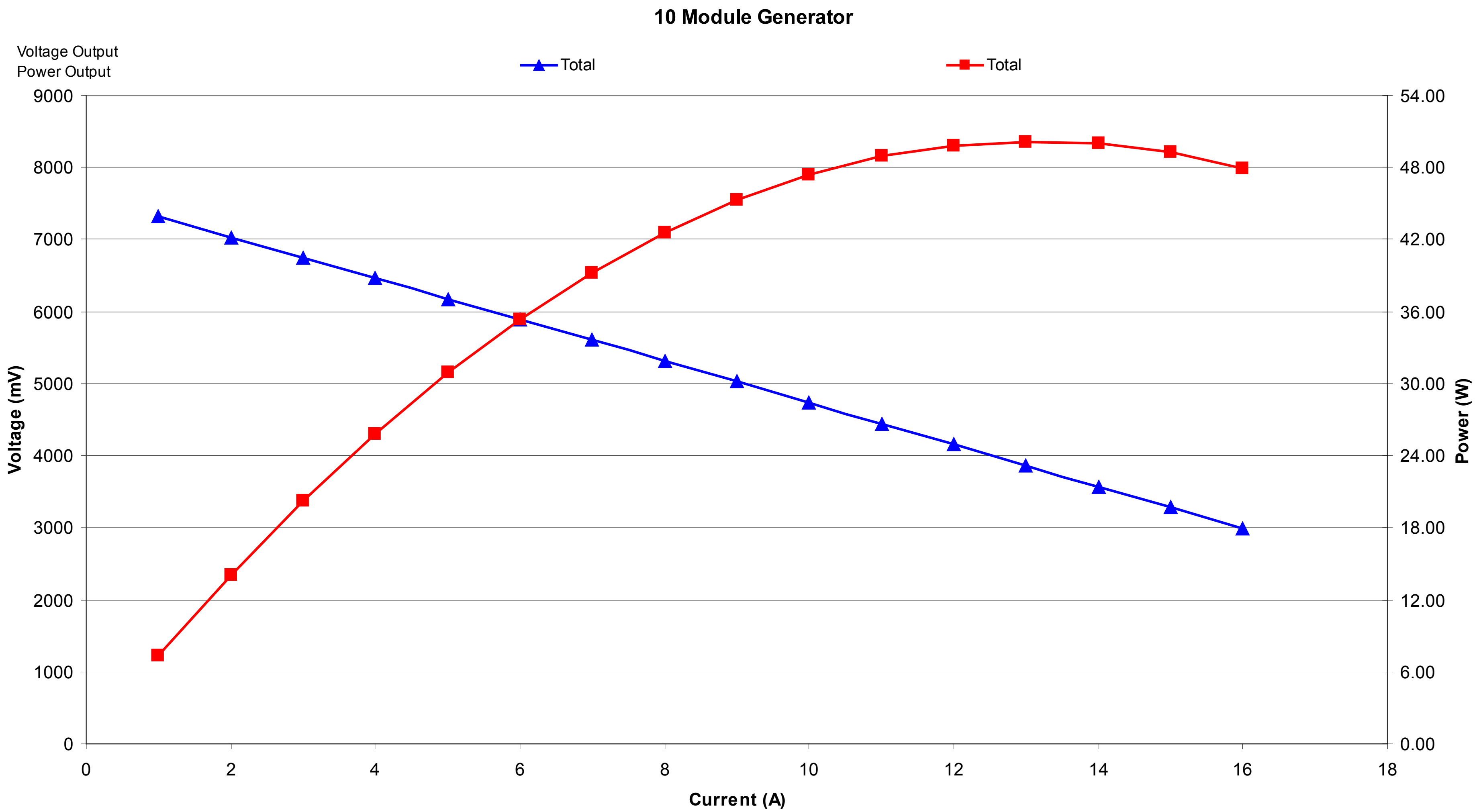


Output of 10 Module TEG (8/4/09)



10-Module TEG output ~50.12W, ΔT~550°C (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)



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

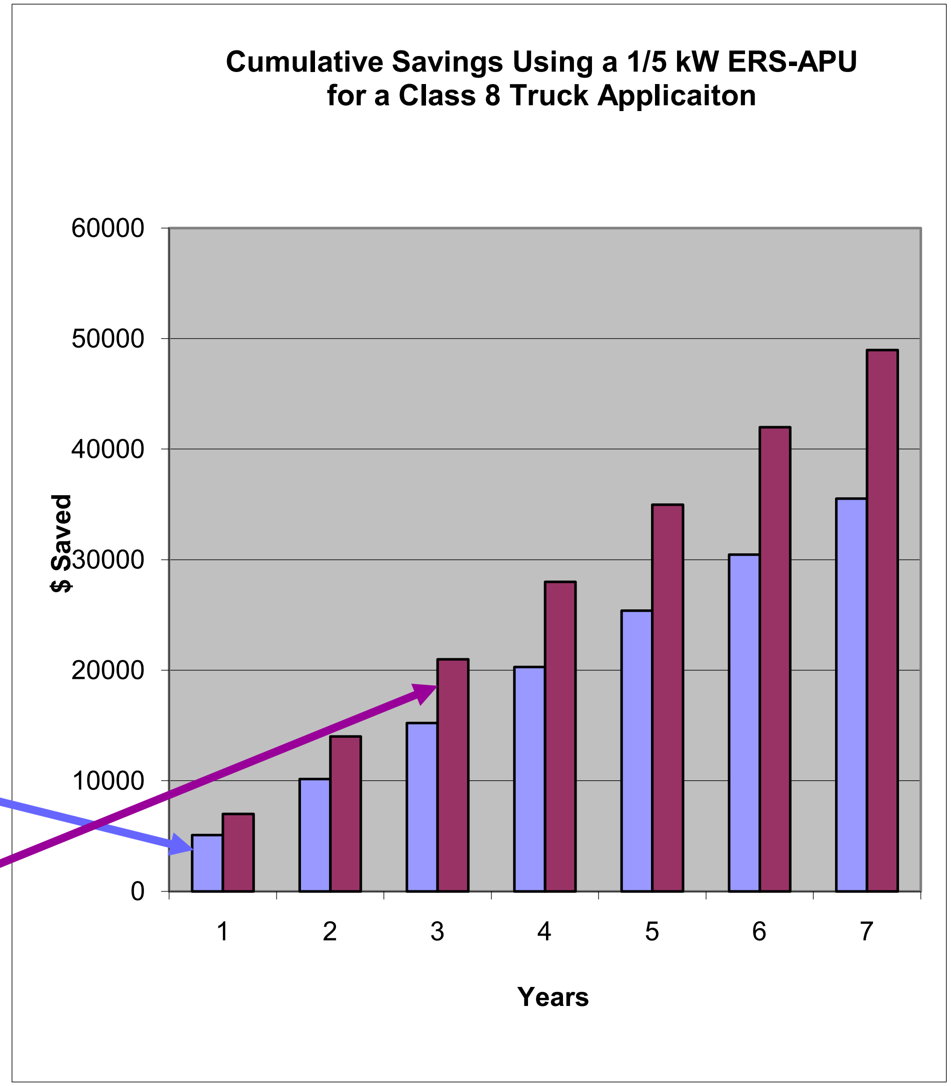
Total 1 kW System Price Based on Four Subsystems

- 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*

(* Arrows point to payback date)



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Accomplishments to Date

- **Systems for ingot synthesis and leg preparation demonstrated**
  - LAST, LASTT, PbTe-PbS and skutterudite (current and advanced) systems and their segmented variants have been shown to have the potential of efficiencies from 11-14 % from 300-830K at the material level (not including heat transfer losses)
  - Routine synthesis of skutterudite legs and modules demonstrated (150 couples every four days possible, 95% throughput efficiency)
- **MSU has reached lab-scale mass production of skutterudite TE couples**
- **Skutterudite technology has been down-selected for the TEG due to efficiency, ability to operate at high temperature and reproducible mechanical and thermoelectric properties**
  - **In 2010, a 60% improvement in unicouple efficiency demonstrated (2.0 watts vs 1.2 watts per couple at ΔT = 600C, JPL formulation, MSU synthesis, improved bonding methods are still required)**
- **Power electronic modules for voltage boost (η>97%) and fault bypass have been designed and tested at MSU (completed in Phase 2)**
- **Temperature dependent elastic moduli and thermal expansion coefficients have been measured for skutterudite and LAST/T in collaboration with Oak Ridge National Lab**
- **Analytical studies performed for various operation modes and conditions**
  - Geometries for high efficiency heat exchangers have been evaluated.
  - Efficiency improvements for various operational modes for the Cummins ISX engine evaluated for various geometries. A 3-5% improvement in bsfc has been estimated.
  - A new concept, the thermoelectric energy recovery system-auxiliary power unit (ERS-APU) has been proposed and appears to be economically feasible.
- **During the past year, Generation 1 and 2 - 100W thermoelectric generators have been designed, built and tested**

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- **Future Work**
- Summary

Future Work: Major Plans for Remainder of Phase 3 Effort

- June to August 2010: Complete redesign of unicouples to eliminate failures at interfaces
- June – Dec 2010: Fabricate 1000+ of next generation of p-type, n-type couples
- August 2010: Complete final design of 1kW TEG based on 5-couple modules previously demonstrated
- June to August 2010: With Cummins evaluate the design and plans for a powertrain demonstration waste heat energy recovery system-auxiliary power unit (ERS-APU). System to be tested at MSU's Heavy Duty Vehicle Laboratory
- August to December 2010: Complete construction of 1kW TEG
- January 30, 2011: Demonstrate 1 kW TEG
- March 31, 2011: Complete final report on Phase 3 activities

Outline of Presentation

- Overview
- Objectives and Relevance
- Milestones
- Approach
  - New Material and System Development (NMSD)
  - Mechanical Property Characterization and Powder Processing (MPCPP)
  - Heat Transfer Studies
  - Projected Efficiency Improvement
  - Power Electronics
  - Material Down Selection, Couple and Module Scale-Up Progress
  - Generation-1 TEG Design
- Accomplishments
- Future Work
- **Summary**

Summary

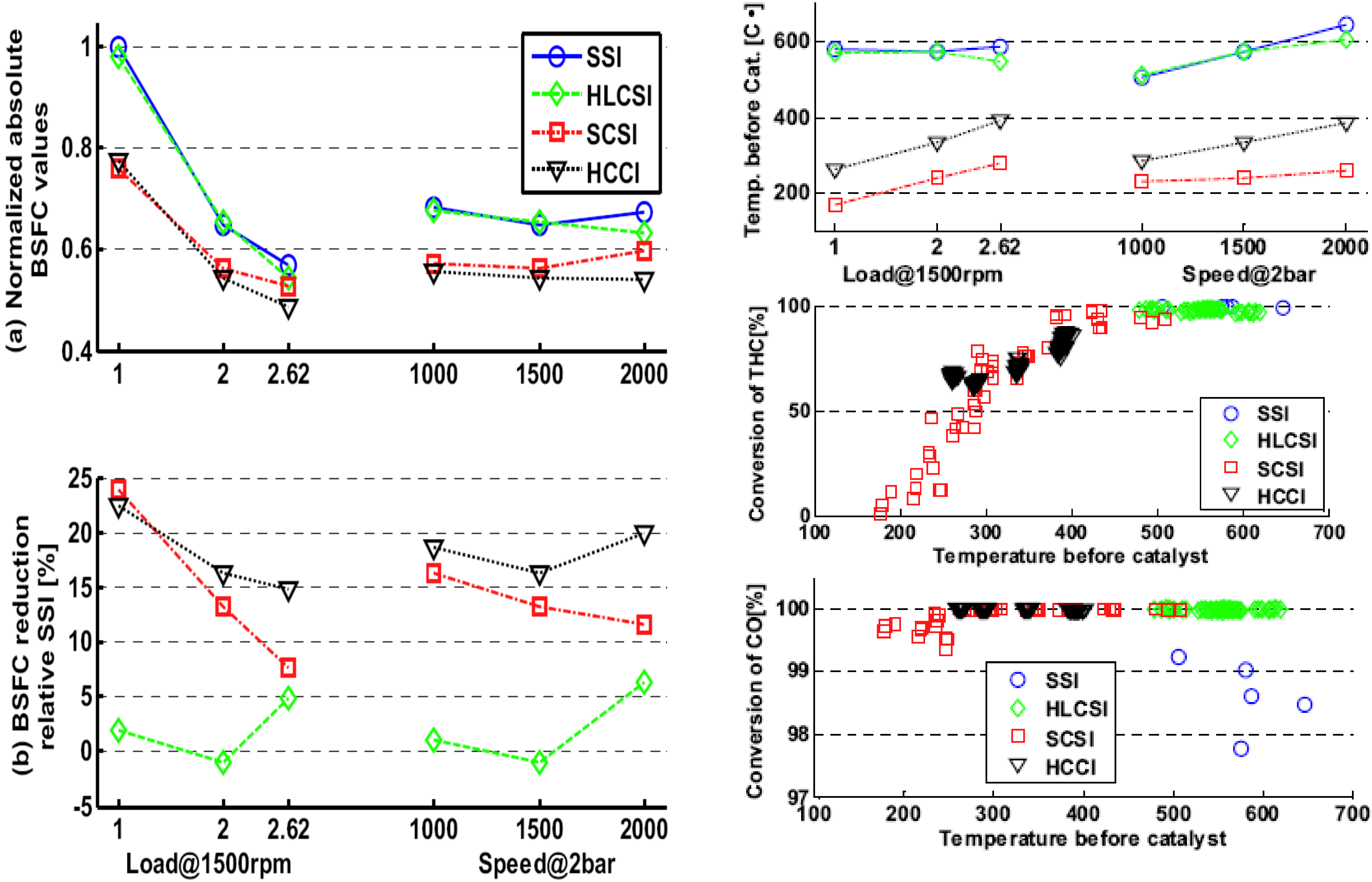
- Systems for material synthesis, powder processing, hot pressing, leg and SKD module fabrication are operational at MSU (ingot to couple 95% utilization of material)
- Performance testing of legs and modules at MSU is in agreement with others doing similar measurements
- Can produce modules required for a 1kW TEG in about one month, (2.0W in 2010 per unicouple vs 1.2W in 2009 @ ΔT=600C demonstrated in 2010 at MSU for the same size legs)
- Power conditioning electronics have been designed, tested and are being prepared for the 100W/1kW TEG demonstrations
- 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 1kW TEG from using advanced skutterudite material

Extra Slides to Reviewers

Important Barriers

- Design of heat exchanger is a major challenge with heat transfer coefficients needed which are 5x higher than without enhanced heat transfer modes
- **Reliable thermoelectric module fabrication methods need to be developed for the new high efficiency TE materials**
    - **Status at MSU**
        - **Routine skutterudite production of hot pressed legs underway**
        - **Module production methods are still under development …emphasis on high reliability modules is important**
- Material strength and thermoelectric properties must meet life cycle performance criteria
- Temperature dependant material properties are critical in order to conduct a detailed and accurate generator design
- Powder processing methods are being refined to provide increased strength while maintaining thermoelectric properties of ingot forms of the material
- ZT for the temperature ranges (700K) for best TE materials are about 1.4 and need to be closer to 3.0 to reach the efficiency goals requested by DOE

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

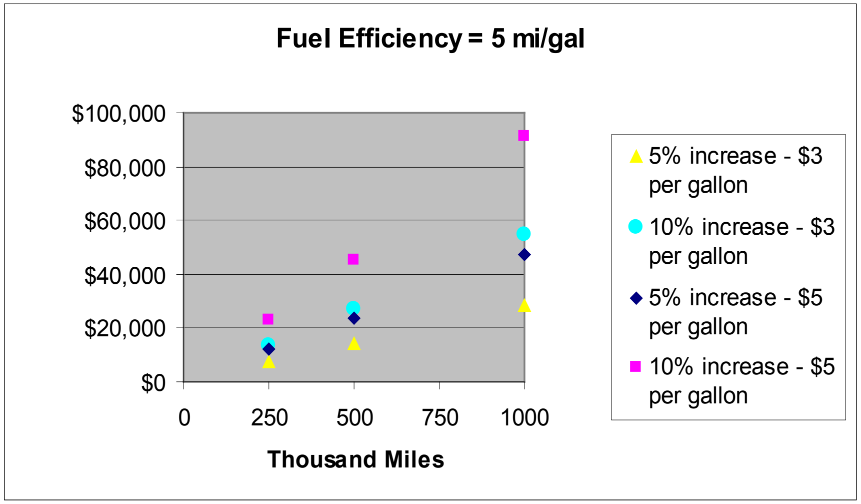


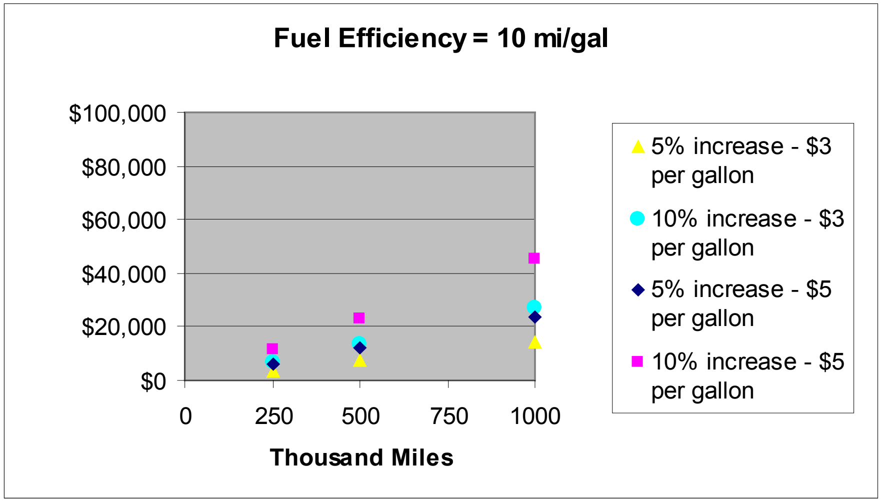
Left- (a) Final BSFC values normalized to the value for SSI at point 1. (b) BSFC reductions for HLCSI, SCSI and HCCI in percentages compared to SSI values at the respective operating points. Right- Temperature measured before the catalyst and conversion of THC and CO vs the temperature measured before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

Cummins ISX 6 Cylinder Diesel Engine

(Image used with permission)

Assessment of Economic Feasibility Based on Fuel Savings





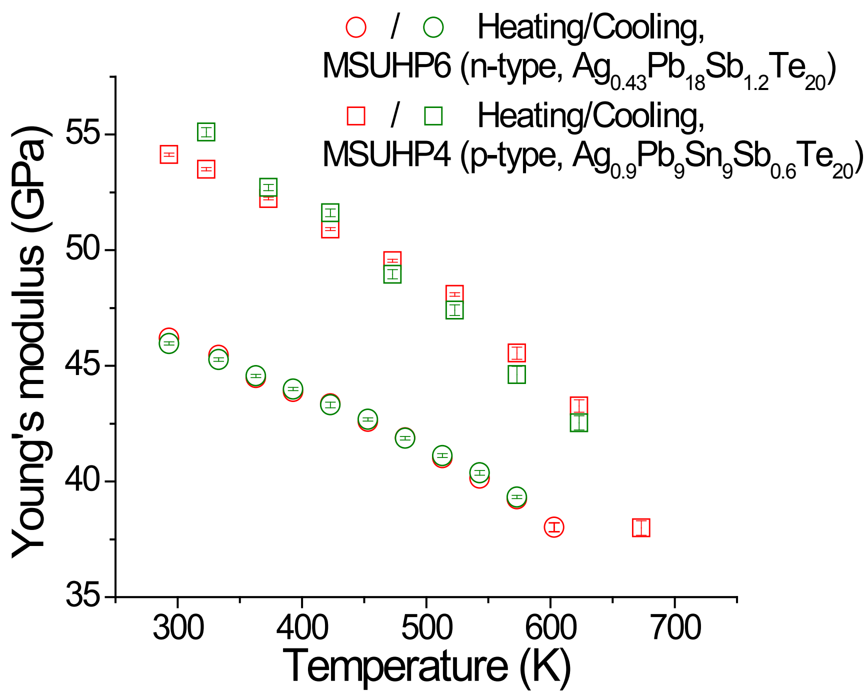
OTR Truck				
	Savings @ $3 per gallon		Savings @ $5 per gallon	
	5% imp. bsfc	10% imp. bsfc	5% imp. bsfc	10% imp. bsfc
250K miles	$7,143	$13,636	$11,905	$22,727
500K miles	$14,286	$27,273	$23,810	$45,455
1M miles	$28,571	$54,545	$47,619	$90,909

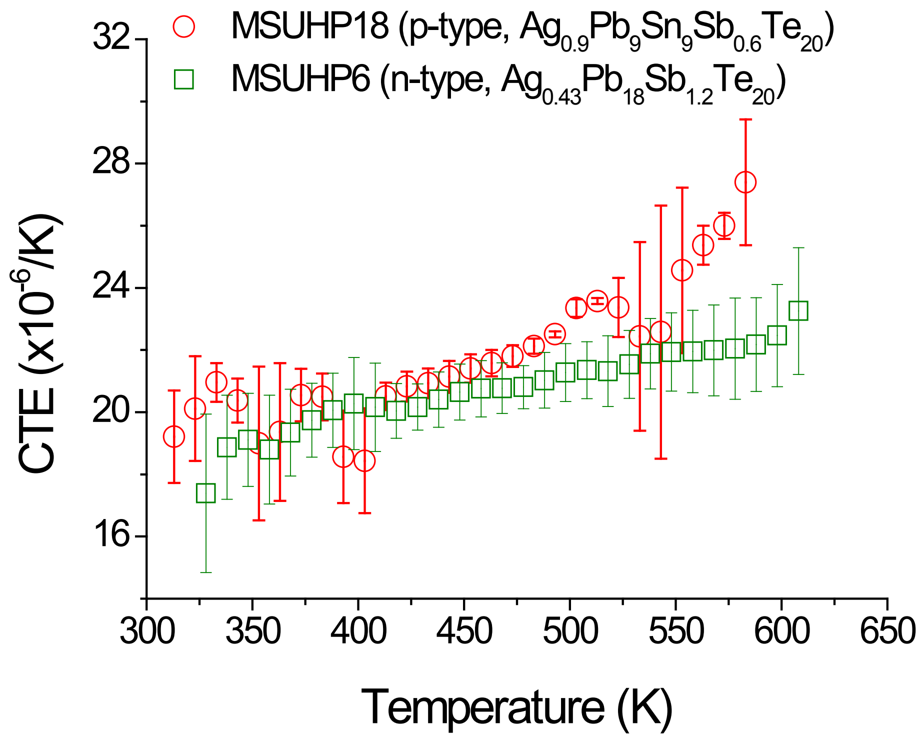
Delivery Truck				
	Savings @ $3 per gallon		Savings @ $5 per gallon	
	5% imp. bsfc	10% imp. bsfc	5% imp. bsfc	10% imp. bsfc
250K miles	$3,571	$6,818	$5,952	$11,364
500K miles	$7,143	$1,3636	$11,905	$22,727
1M miles	$14,286	$27,273	$23,810	$45,455

Mechanical Property Characterization and Powder Processing (MPCPP): LAST, LASTT and Skutterudites

- In service, the TE elements will be subjected to both thermal gradients and thermal cycling.
- Analytical or numerical analysis of the stress-strain behavior requires knowledge of the elastic moduli and the coefficient of thermal expansion as functions of temperature
- For both LAST and LASTT, we have determined the elastic moduli by the Resonant Ultrasound Spectroscopy technique and the coefficient of thermal expansion by thermal-mechanical analysis and by high temperature x-ray diffraction.
- Examples showing mechanical property characterization of skutterudite shown on next two slides

Temperature Dependent Elastic Moduli and Thermal Expansion Coefficient

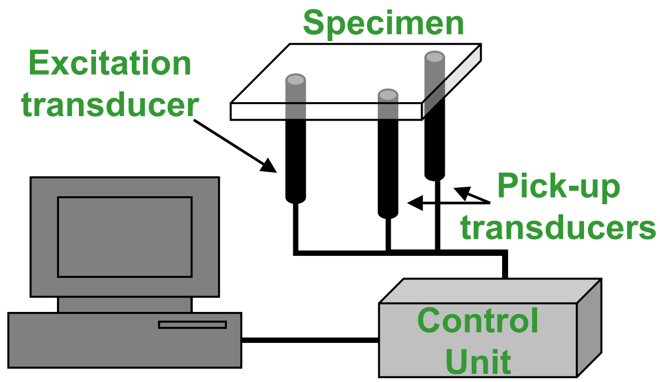




The study on temperature dependent elastic moduli and thermal expansion has been conducted in collaboration with the High Temperature Materials Laboratory, Oak Ridge National Laboratory.

MPCPP: Hardness, H, Shear Modulus, G, Young's Modulus, E, and Poisson's Ratio, ν, of n and p-Type Skutterudites

- Vickers indentation – Microhardness measurements
- Nanoindentation (nano)– Young's modulus and nanohardness measurements
- Resonant Ultrasound Spectroscopy (RUS) – Young's modulus, shear modulus and Poisson's ratio measurements



Schematic for RUS equipment

Specimen Label	Type	# of Samples	Test Methods	Density (g/cm^3)	Relative Density	H (GPa)	E (Gpa)	G (GPa)	ν
SKD4	n-type	4	Nano RUS Vickers	7.55	0.98	Nano = 8.0 Vickers = 6.4	Nano = 146 RUS = 140.2	57.0	0.230
SKD-June16	n-type	2	Nano	7.30	0.94	5.0	121	N/A	N/A
SKD11	n-type	1	Nano RUS	7.62	0.98	8.1	Nano = 141 RUS = 138.5	56.3	0.229
SKD10	n-type	5	Nano RUS Vickers	7.53	0.97	Nano = 8.2 Vickers = 4.3	Nano = 137.7 RUS = 147	56.1	0.228
SKD-17	p-type	1	Nano	Irregularly shaped		6.5	124	N/A	N/A
SKD-18	p-type	8	Nano RUS	7.73	0.97	Nano = 6.6 Vickers = 5.6	Nano = 126 RUS = 131.6	53.5	0.230

N-type = $Co_{0.95}Pd_{0.05}Te_{0.05}Sb_3$ doped with 0.1% Ce

P-type = $Ce_{0.9}Fe_{3.5}Co_{0.5}Sb_{12}$

MPCPP: Characterization of Powders Used for Hot Pressed Specimens

- Particle size distribution was analyzed by laser scattering (Figure A).
- Specimens were hot pressed from powders produced from cast billets.

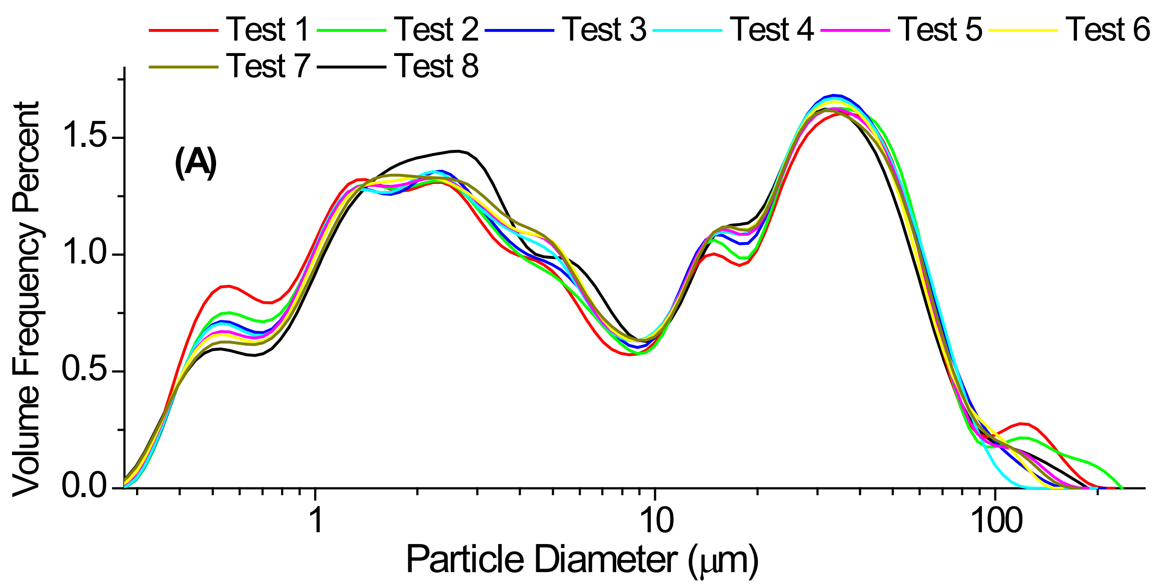
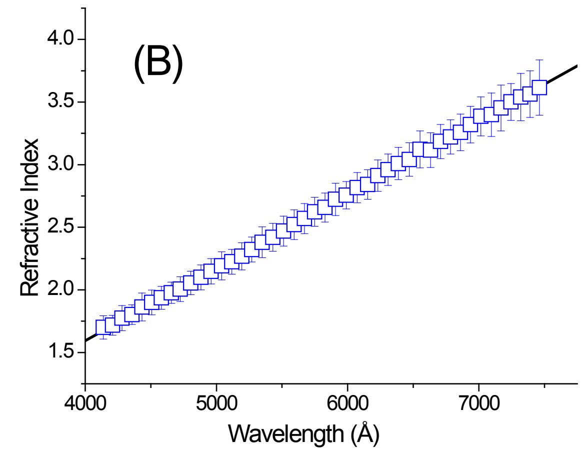
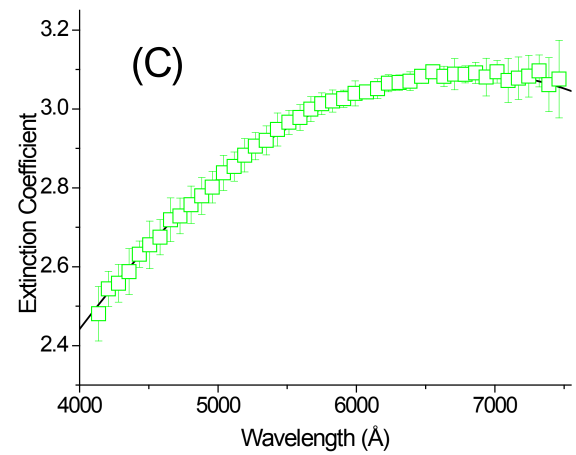


Figure A: Example of the particle size distribution for skutterudite powders

- **Calculation of particle size distributions require the optical index of refraction (Figure B) and extinction coefficient (Figure C), as measured by optical ellipsometry.**



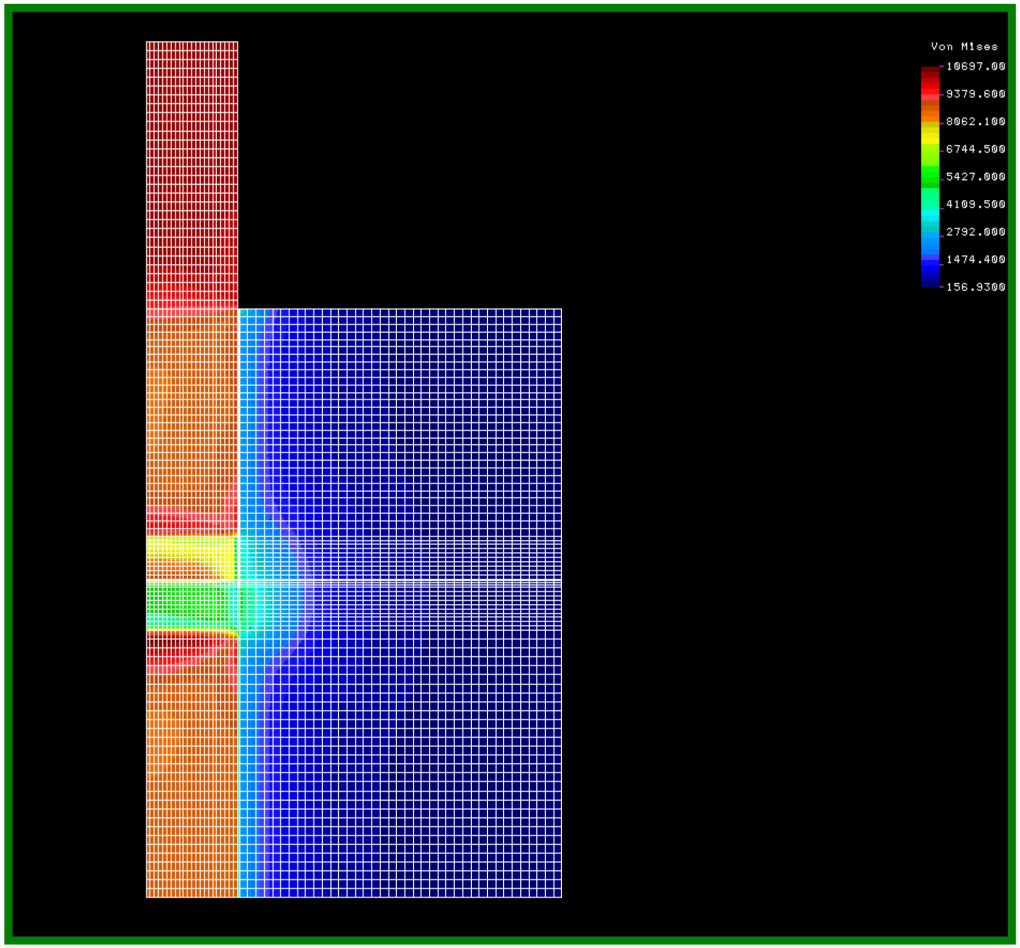


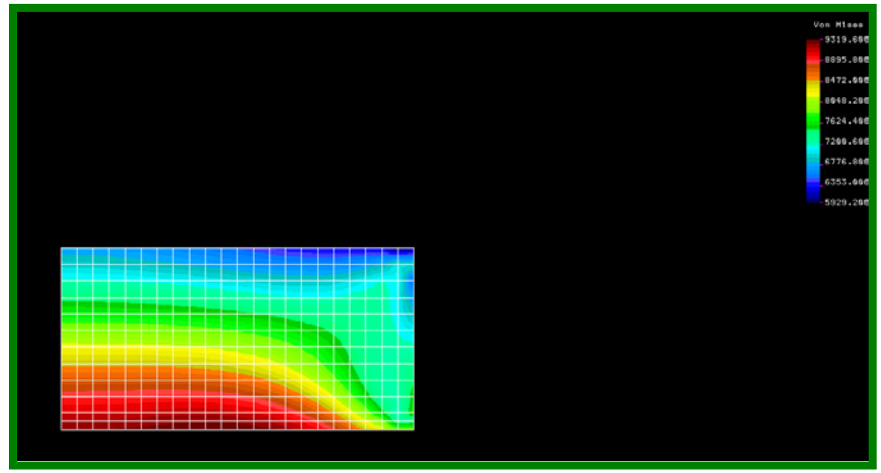
Figures B-C: Optical index of refraction (B) and extinction coefficient (C) for n-type skutterudite powders

Advanced Simulations Used in System Design Studies

- Finite Element Analysis with Temperature Dependent Properties Measured at MSU and Oak Ridge National Laboratory
- Dynamic Simulation of Engine and Transient Flow Processes (WAVE)
- Multidimensional Numerical Simulations of Transient Heat Transfer Processes

FEA Analysis of Metallization Process

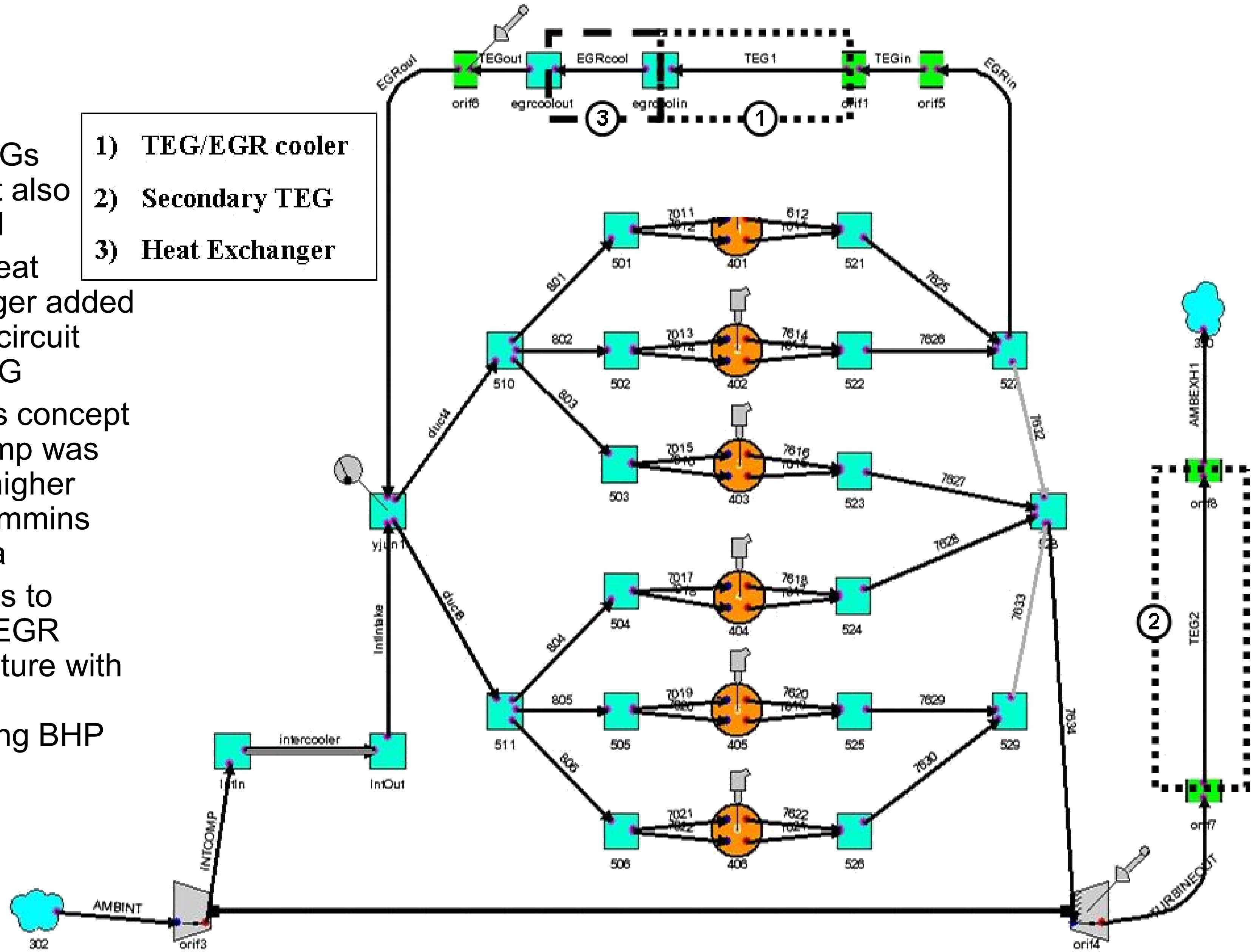




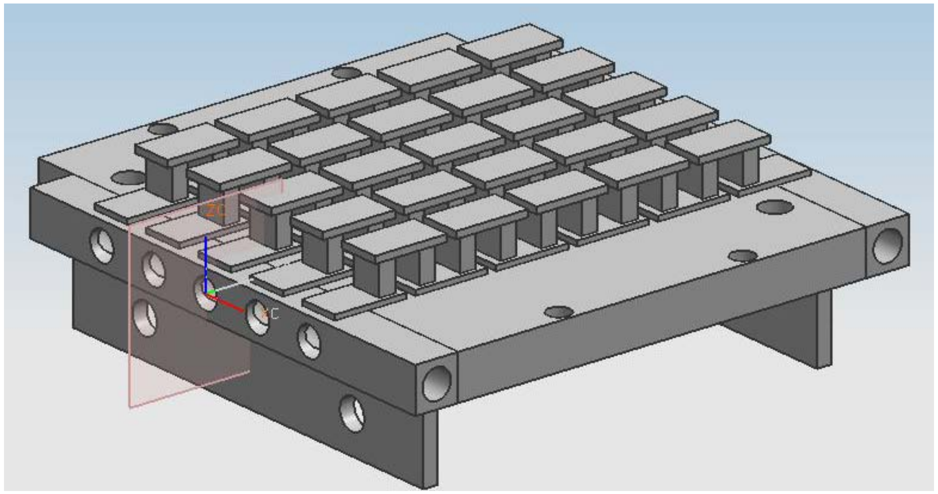
1. **Materials in this analysis: N,P type skutterudite, Cobalt and Titanium**
2. **Study's goal was to determine stress concentrations in regions of metallization**
3. **Temperature dependent material properties including CTE and elastic modulus needed for FEA and later material fatigue properties**
4. **Heat transfer rates on the mold surface can influence cooling rates and stress concentrations**

New Design Concepts w/ Heat Exchanger

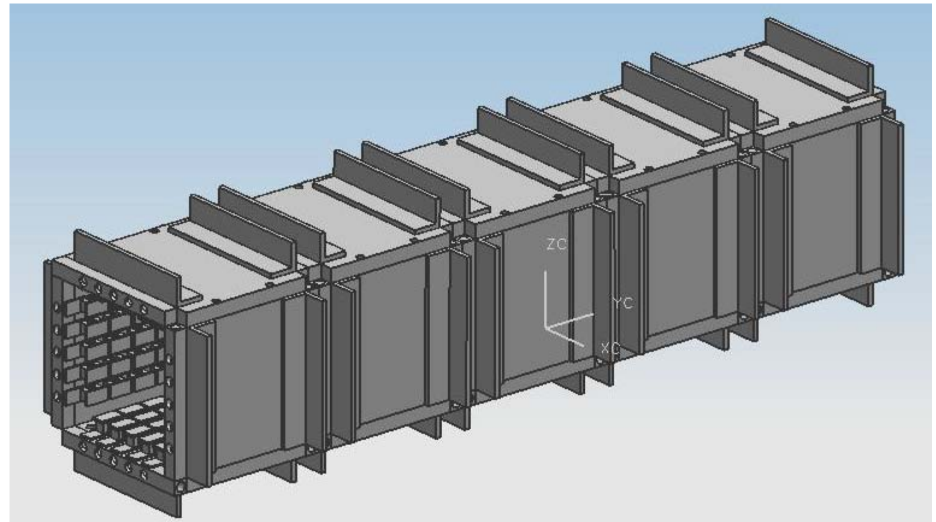
- Dual TEGs Concept also modified
- 50cm Heat Exchanger added in EGR circuit after TEG
- Previous concept EGR temp was ~100K higher than Cummins test data
- Goal was to reduce EGR temperature with hope of increasing BHP



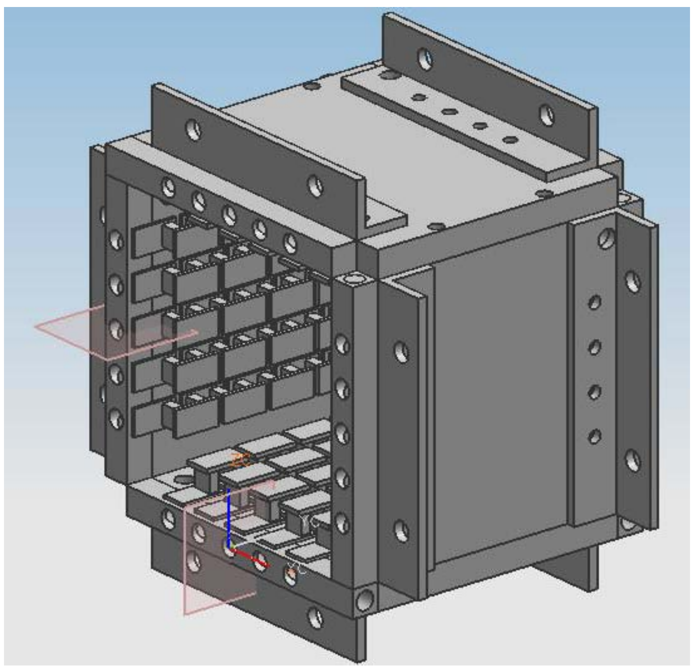
MSU Generation-1 TEG (SKD) Design



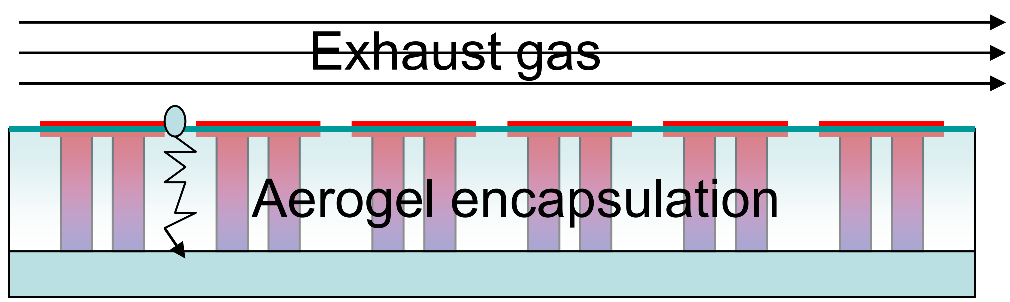
65W (theoretical) section of TEG



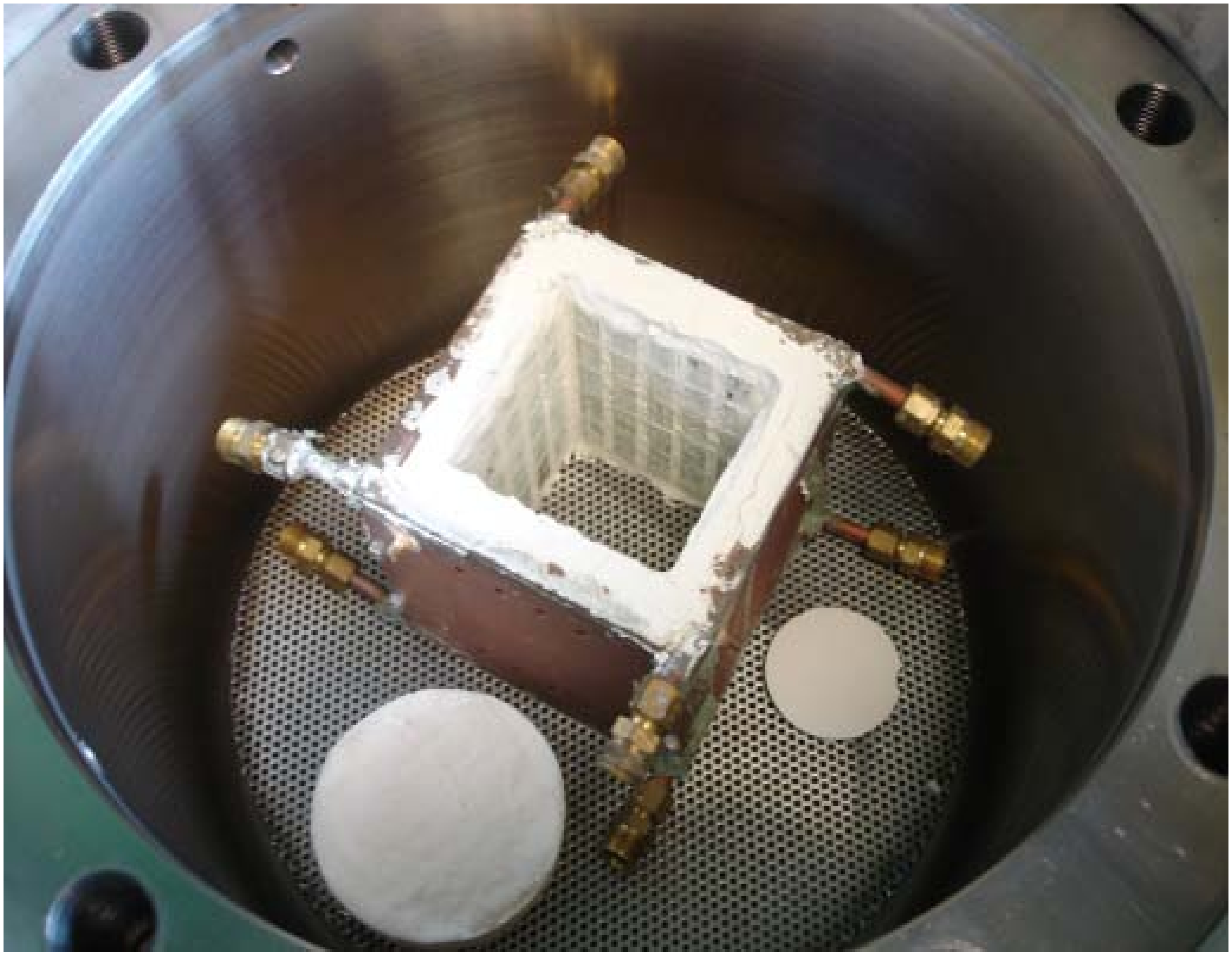
1.3kW (theoretical) 500W (actual est.) TEG
Dimensions 100x100x500 mm

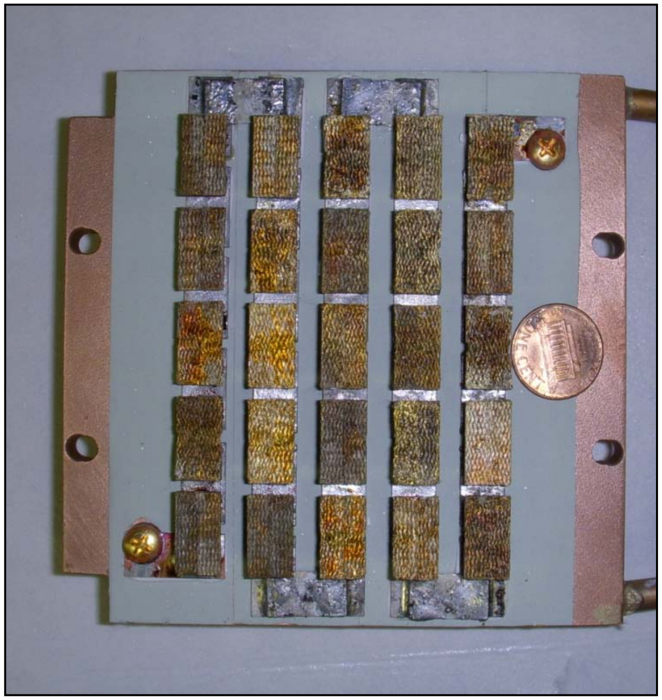


Section of Generator

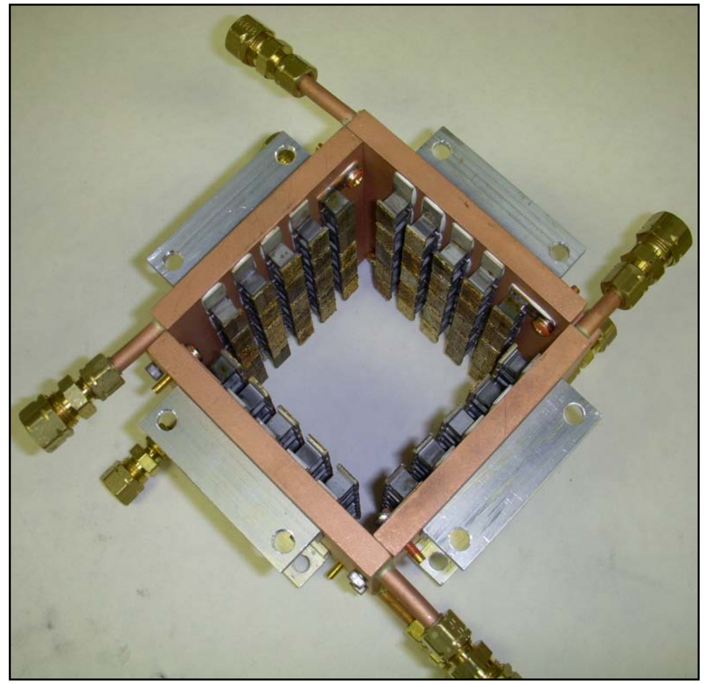


First 100 Couple Aerogel-Insulated TEG at Michigan State University

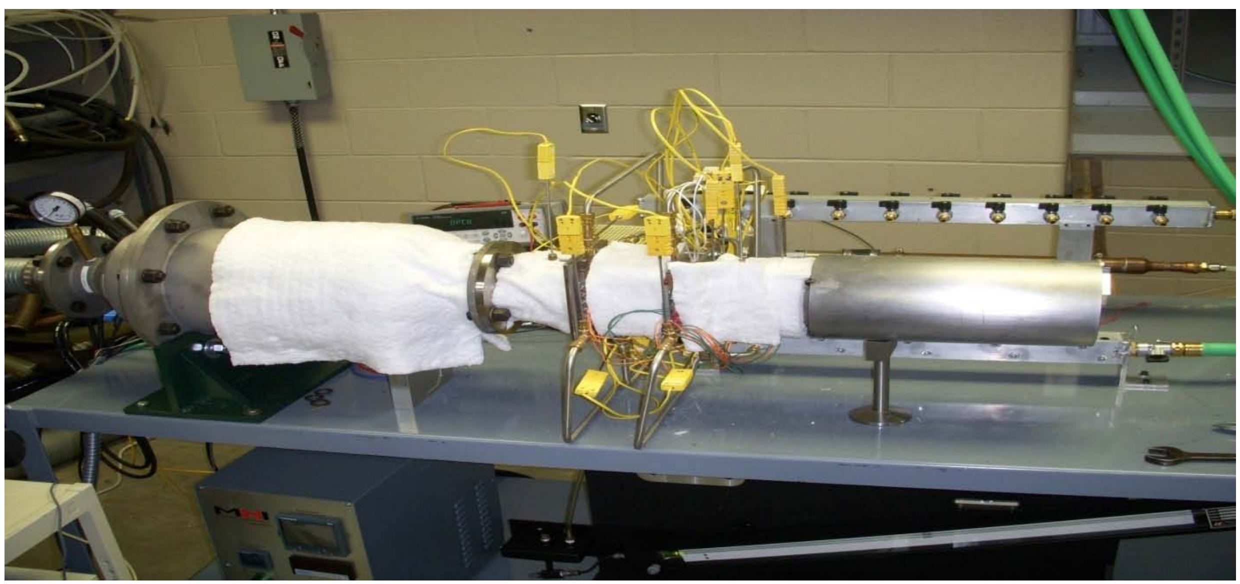




5 - 13W Modules (theoretical @ ΔT=600C) before Insulation

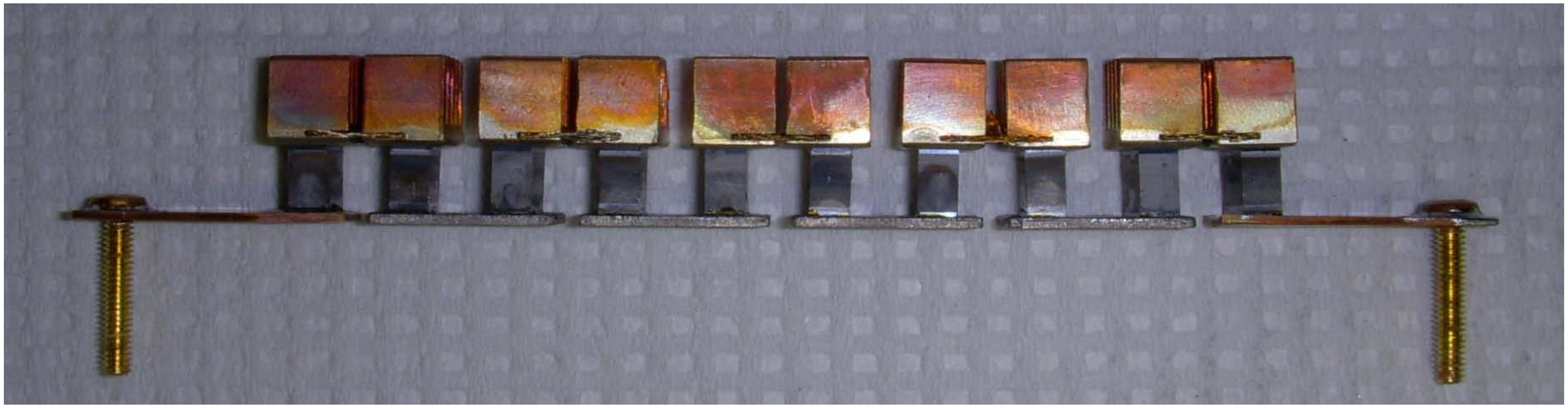


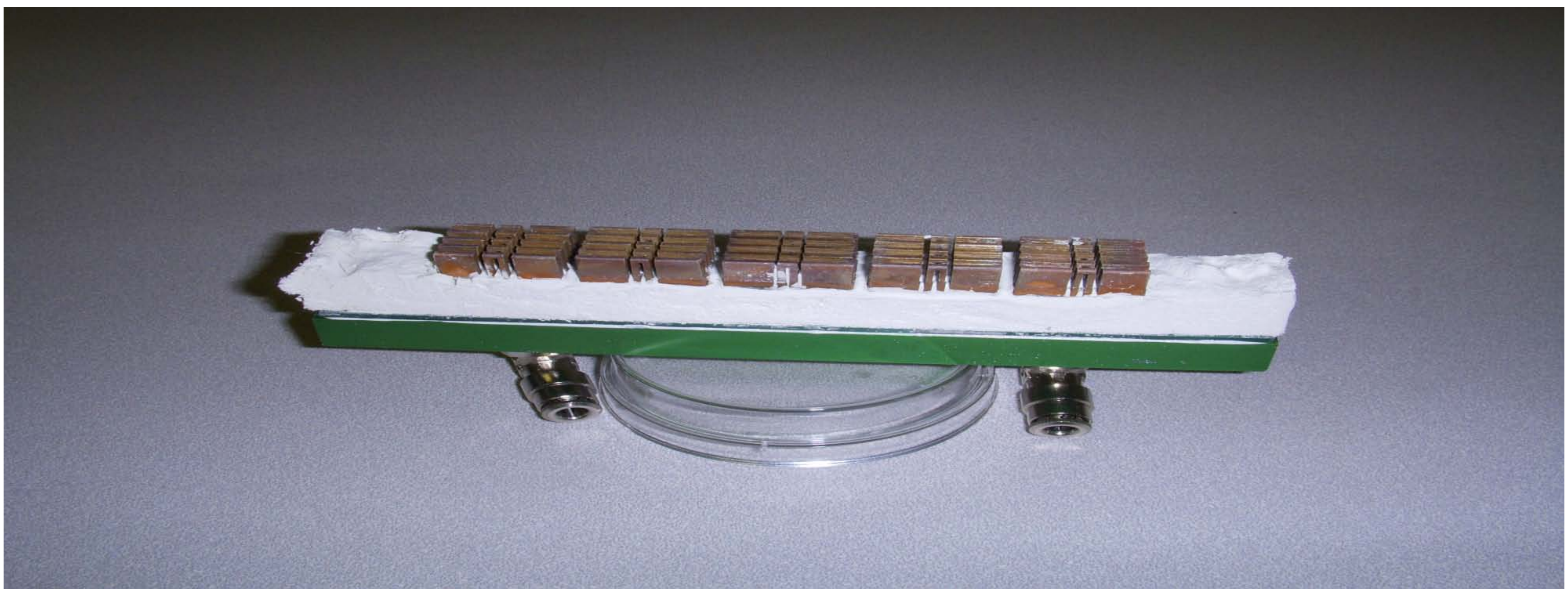
TEG – 260W (theoretical @ ΔT=600C) 20 – 13W Modules



TEG Testing Assembly

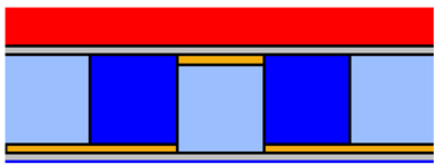
10 Leg Un-insulated (top) and Insulated Modules (bottom) Fabricated at MSU with Heat Collectors (legs are 3x7x7 mm, area of heat collector is >20x area leg top surface)



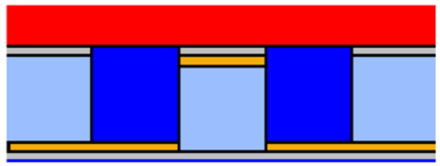


Heat Transfer Studies: Accomplishments in 2008-09

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



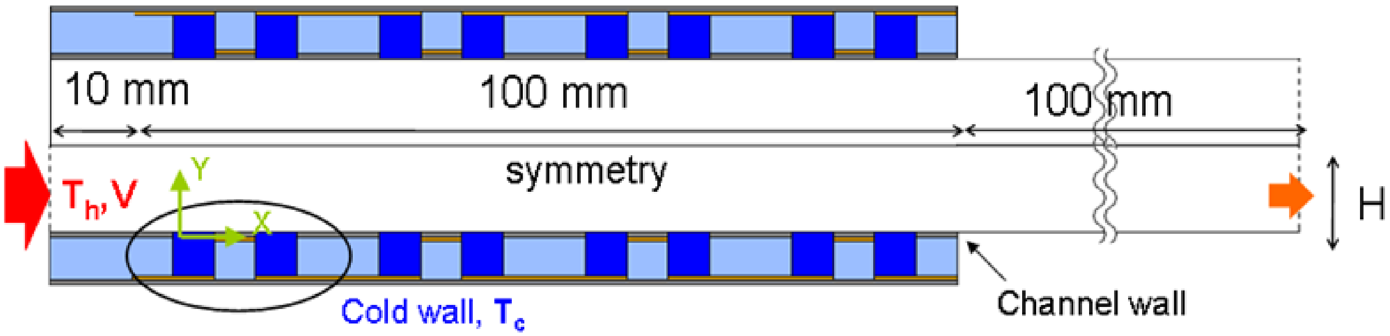
Traditional
Everything is physically & chemically bonded together.
Thus, thermal stress is high!

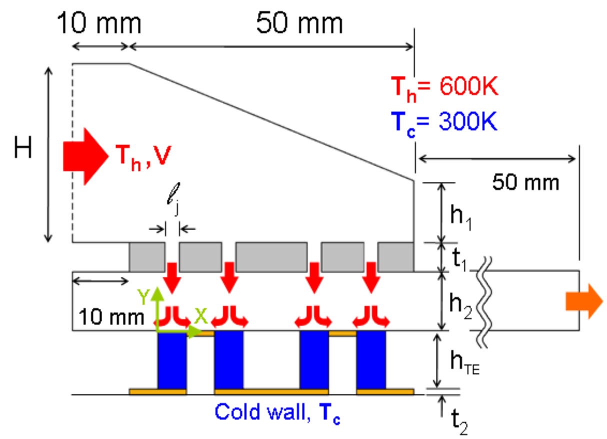


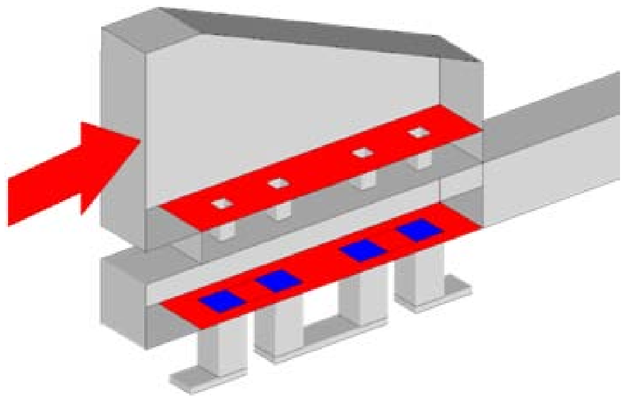
New Design!
Concept: disconnect TE couple from the hot plate to allow expansion.

Developed and evaluated two HX concepts:

- starting boundary layer
- jet impingement







Summary on Heat Transfer Results

- Performed CFD study of a TEPG with fins, and fins with jet impingement
  - With fins only: Energy of the hot gas in the BL is effectively used up after two TE couples. Thus, need new trips to restart BL.
  - Fins with jet impingement: higher heat transfer coefficient, but there are some eddies staying around the corner, which will affect the convective heat transfer efficiency
- Close to the sides of fins, heat transfer was decreasing
- Work still needed: grid refinement study

Heat Transfer Studies: Effects of Soot on TEG Performance

- Thermal resistance of soot layers depends on the thickness of the layer and the kind of soot.
- When heavy soot or slag is present, it is a major part of the exhaust-gas side thermal resistance and so affects power output (Q x TEG efficiency) profoundly
- Experiments are needed to determine the thermal conductivity k of soot from Diesel/JP-8 combustion
- RANS CFD models are being developed to model the exhaust-gas flow and soot transport, together with soot-layer build-up/break-down models at the wall
- They will be used to predict soot-layer thickness in ducts at different exhaust-gas conditions and so improve TEG thermal system design