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

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Prepared by:

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IOWA STATE UNIVERSITY

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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

TEG Design and Construction
MSU/JPL

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

6 Cyl. Engine Test Data
Cummins

P2 - Single cylinder +TEG Demo
MSU

3D CFD Analysis
Iowa State / 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.)

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

Goals and Objectives

- Using a TEG, provide a 10% improvement in fuel economy by converting waste heat to electricity used by the OTR truck
- Evaluate currently available thermoelectric materials to determine optimum material selection and segmentation geometry for this application
- Develop TEG fabrication protocol for module and system demonstration
- Determine heat exchanger requirements needed for building TEGs of reasonable length
- Determine power electronic/control requirements
- Determine if Phase 2 results make an engine demo in Phase 3 reasonable

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**
    - **Techniques for fabricating hot pressed LAST/LASTT still being developed**
    - **Module production methods are still under development**
- Material strength and thermoelectric properties must meet life cycle performance criteria ….nanostructures in LAST have survived for six months at 600C
- 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

Accomplishment to date

- Systems for ingot synthesis and leg preparation demonstrated
  - 70 hot pressed pucks of LAST, LASTT and skutterudite at MSU since 4/07
  - Tube furnaces (~500 gms) and extensive powder processing facilities at MSU
  - Segmented legs with an efficiency of 14.5% demonstrated at JPL
- Module fabrication during past year at MSU
  - Fabrication of 2, 4 and 8 leg LAST/LASTT modules
  - Fabrication of 2, 4 and 16 leg (40 watt) skutterudite modules
  - Demonstrated aerogel insulation technique for 16 leg module
- Power electronic modules being designed and tested at MSU
- Temperature dependent elastic moduli and thermal expansion coefficients have been measured for LAST in collaboration with Oak Ridge National Lab
- Transport measurements conducted by MSU have been verified by Northwestern, JPL, Iowa State and the general literature
- New material systems based on skutterudite composites and PbTe-PbS systems have been examined and appear to offer promising improvements
- Analytical studies performed for various operation modes and conditions
  - Geometries for high efficiency heat transfer rates evaluated
  - Finite element analysis of pressing, contact metallization has been conducted and generator design is next
  - Efficiency improvements for various operational modes for the Cummins ISX engine evaluated for various geometries
  - Heat transfer studies excellent insulation and hot side convection required

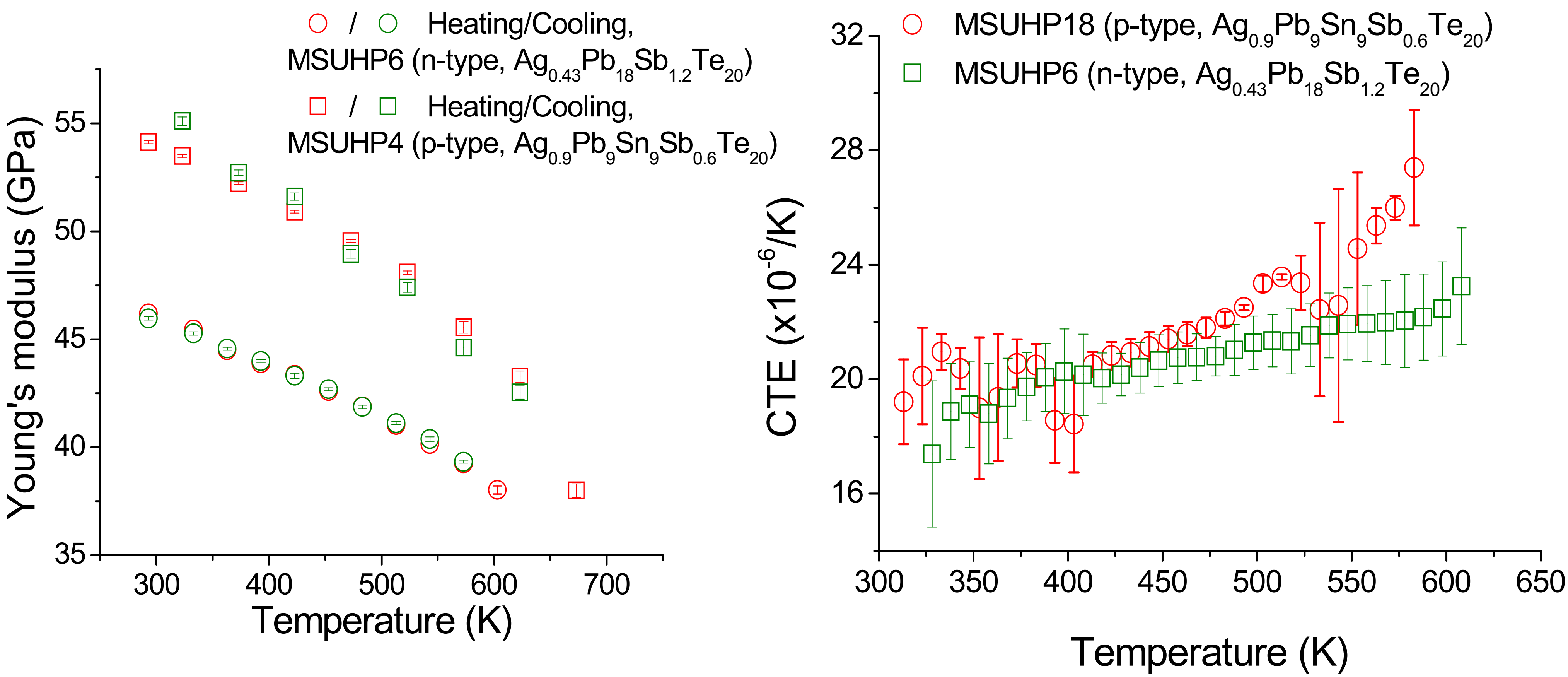
Mechanical and thermal characterization of LAST and LASTT

- 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

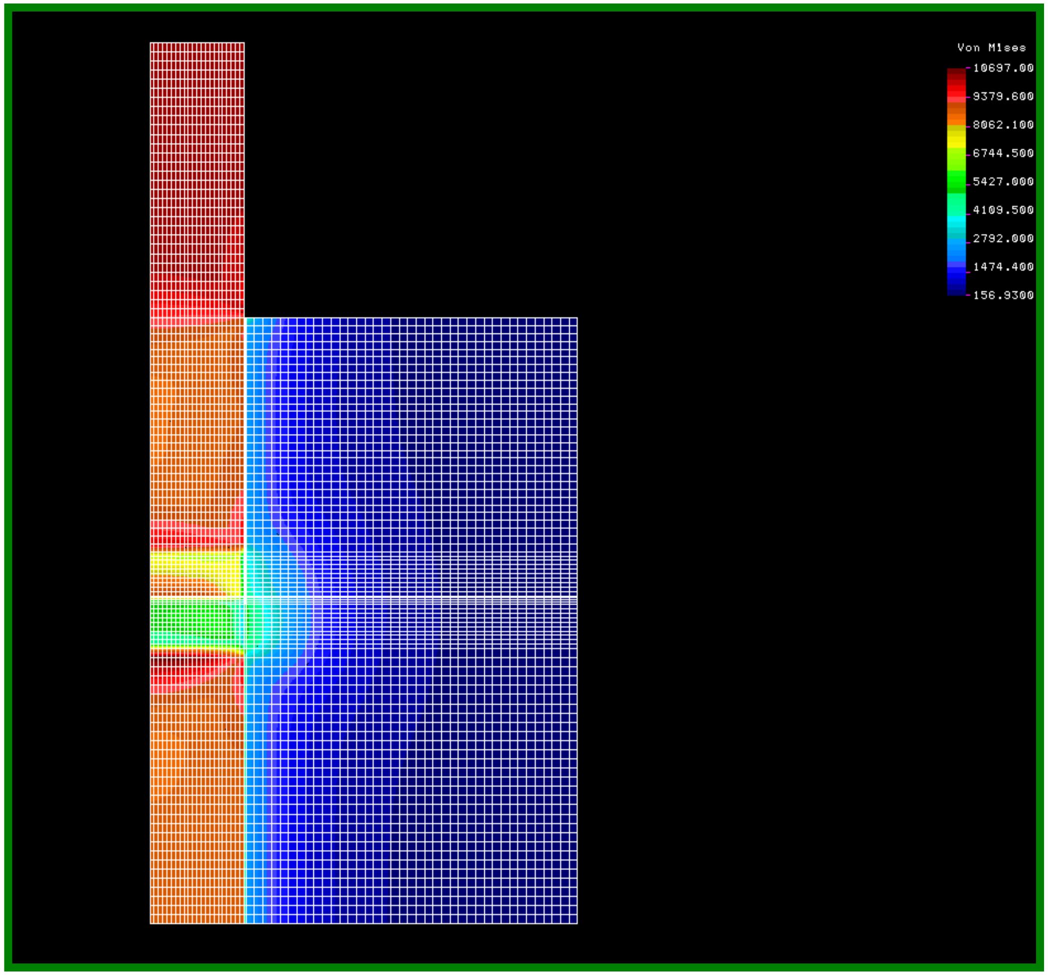
- For both LAST and LASTT, we have determined the elastic moduli by the Resonant Ultrasound Spectroscopy technique and the coefficient of thermal expansion by thermal-mechanical analysis and by high temperature x-ray diffraction.

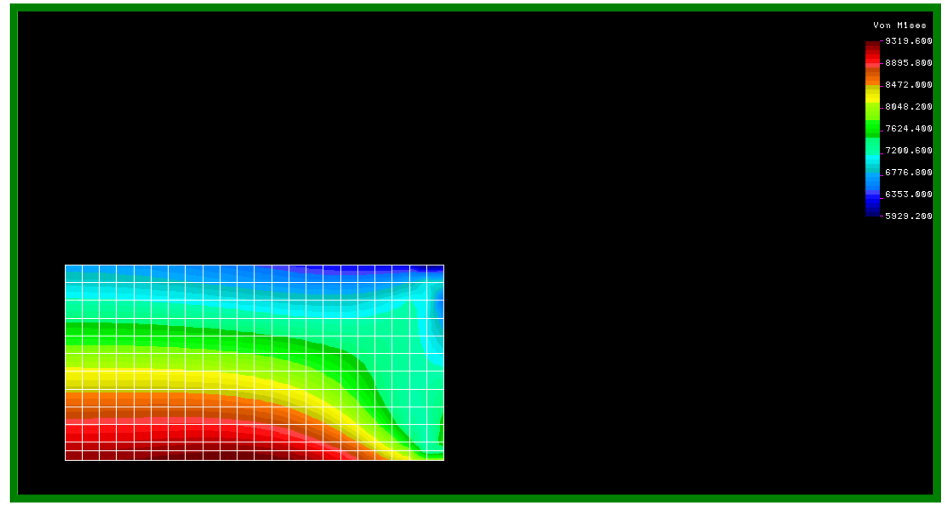
Temperature dependent elastic moduli and thermal expansion coefficient



- 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.

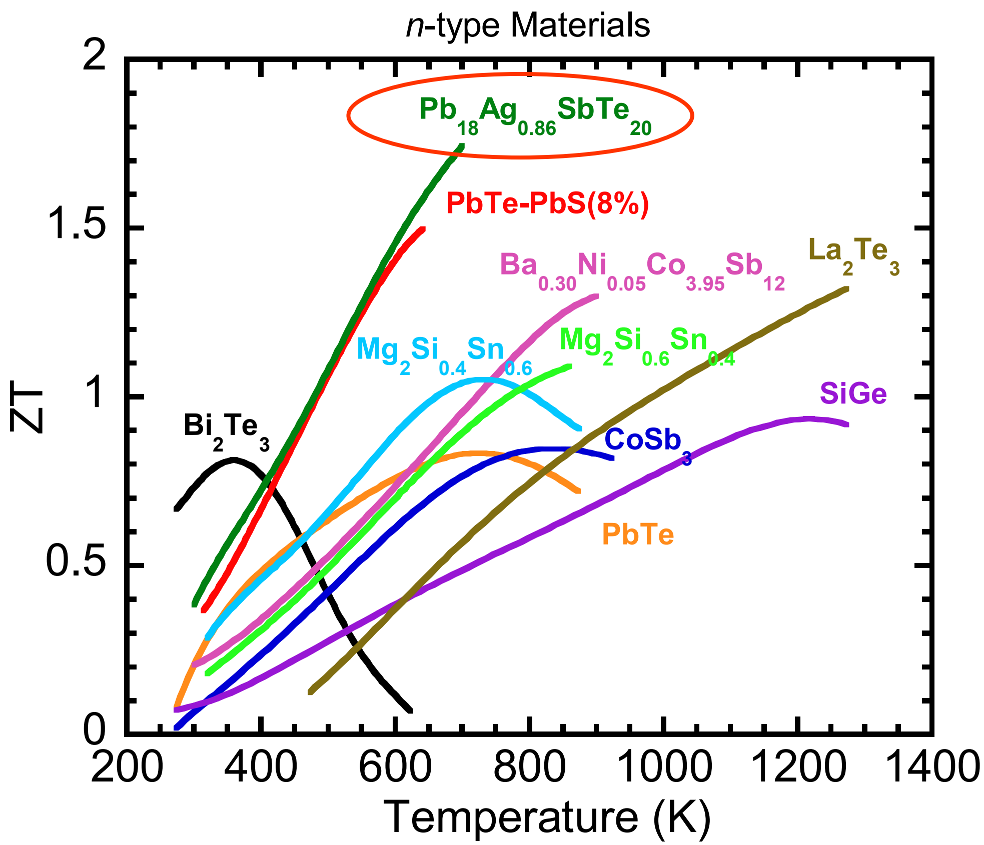
FEA Analysis of Metallization Process

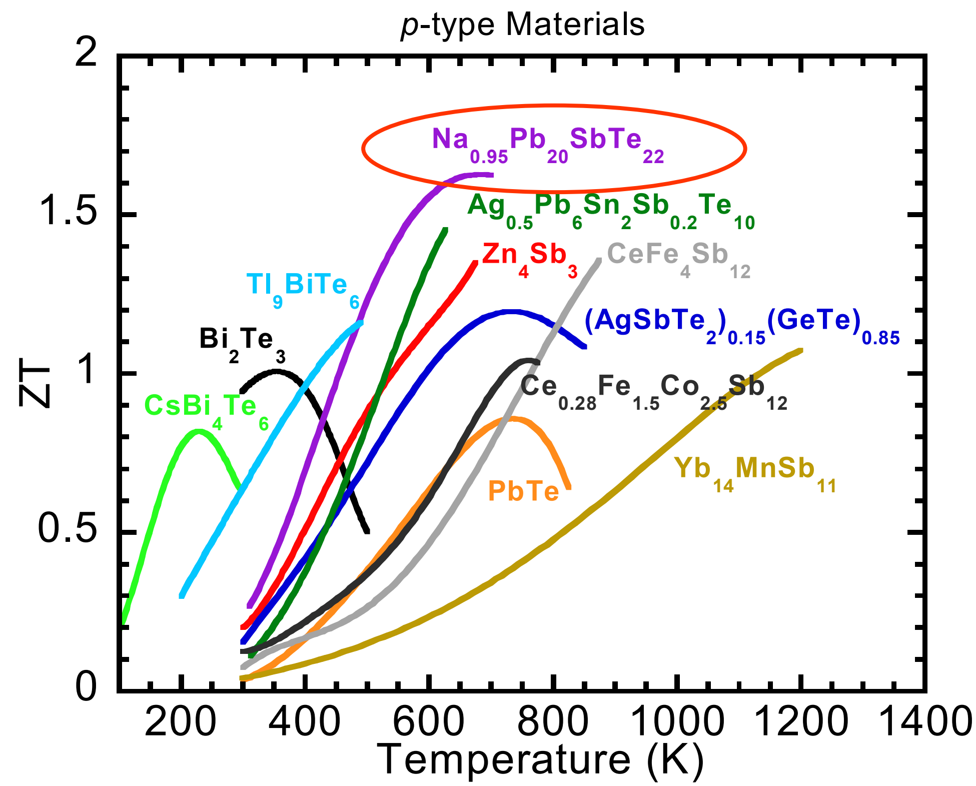


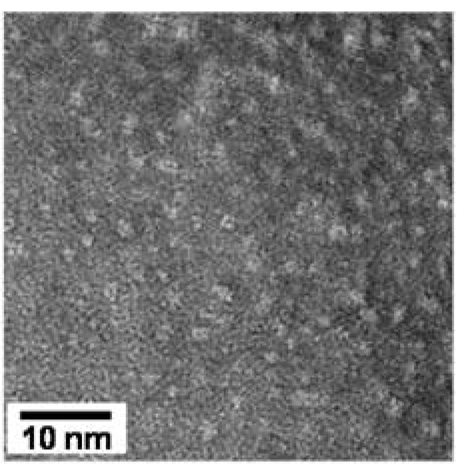


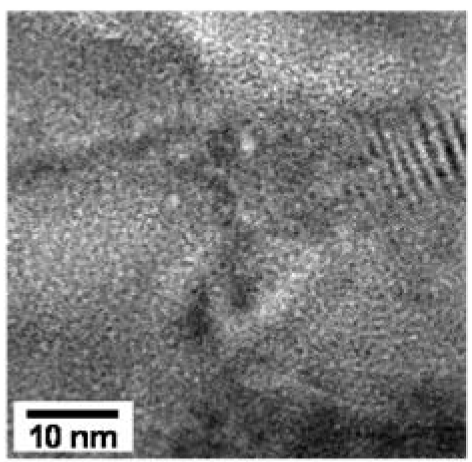
1. **Materials in this analysis: N,P type skutterudite, Cobalt and Titanium**
2. **Study's goal was to determine stress concentrations in regions of metallization**
3. **Temperature dependent material properties including CTE and elastic modulus needed for FEA and later material fatigue properties**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

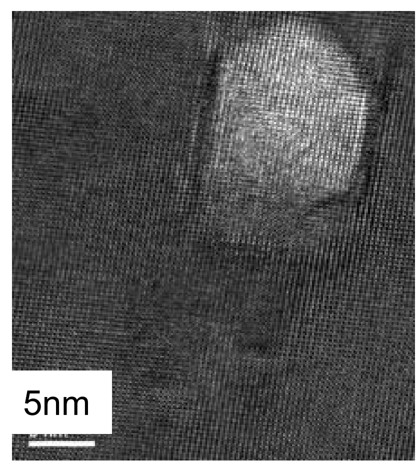
Bulk Thermoelectric Materials

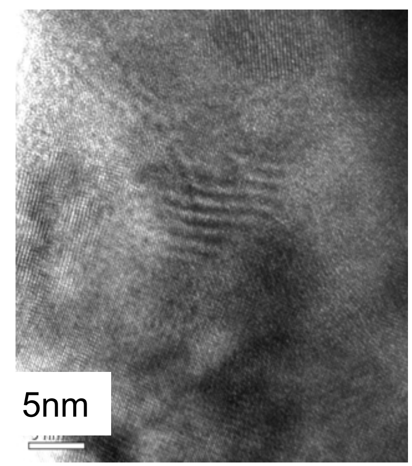






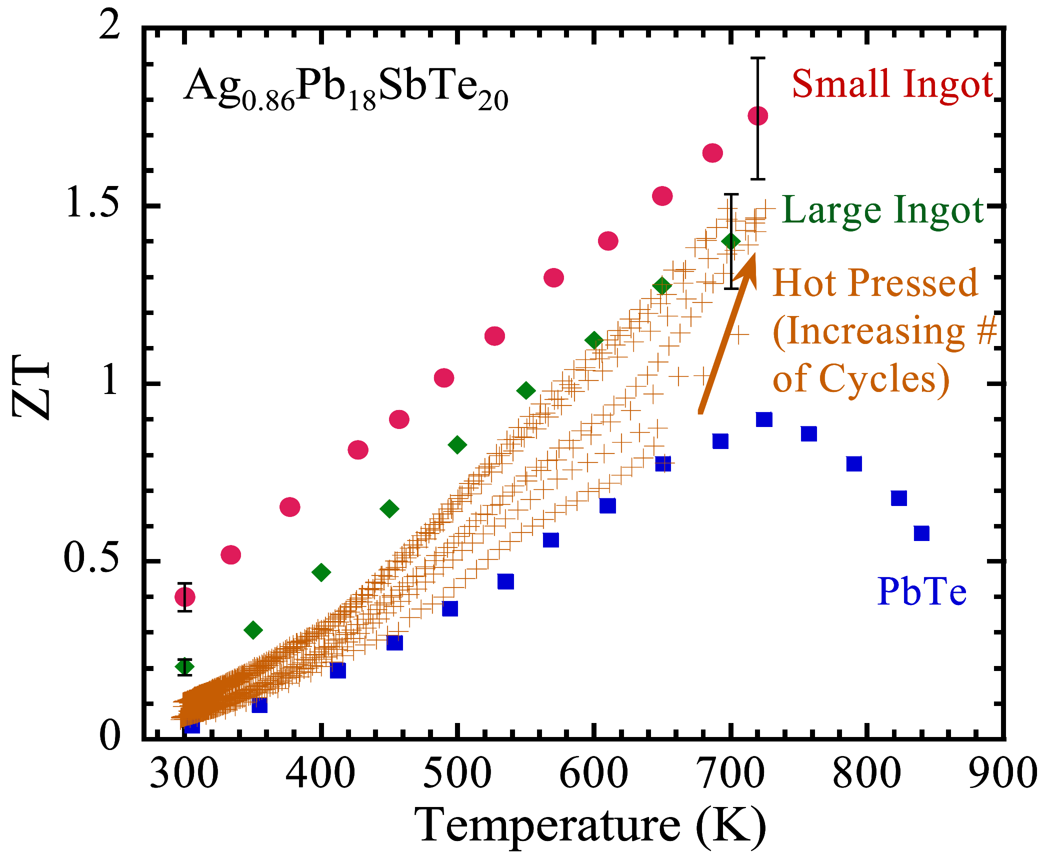






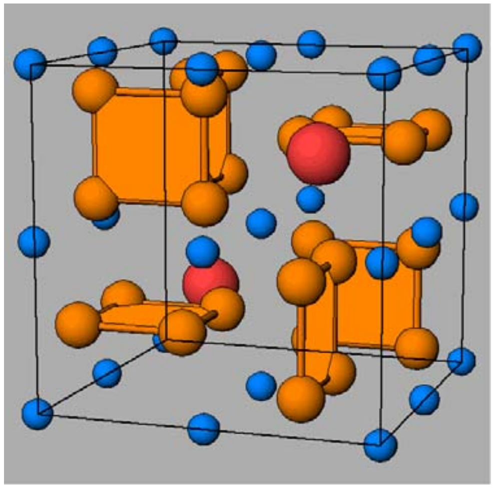
Best Hot Pressed Samples

- Hot pressed samples initially exhibit lower ZT than ingot, but improve with repeated temperature cycling (healing of grain boundaries? stress relaxation?)
- Nanostructures persist after powder processing and hot pressing



- ZT calculated above using thermal conductivity from measured cast samples.

N-type skutterudite material development



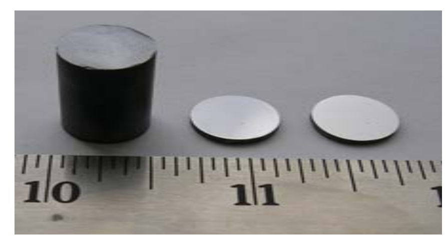
Skutterudite crystal structure

- 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

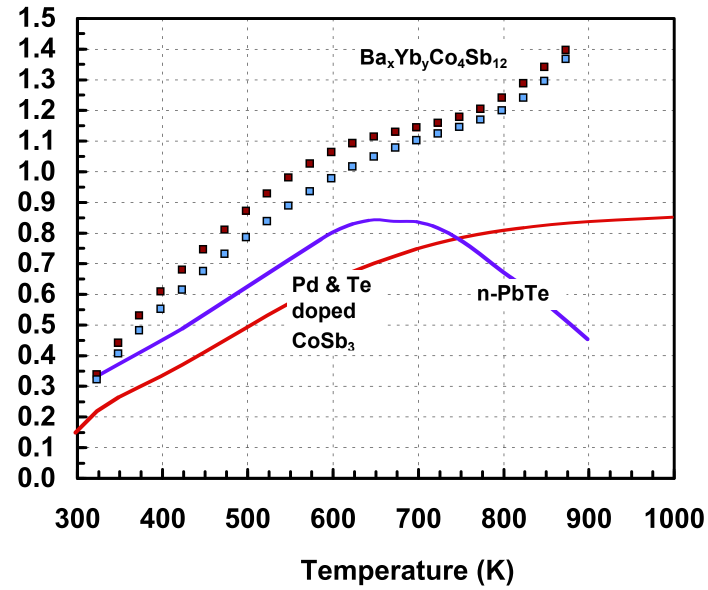


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

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

$Ba_xYb_yCo_4Sb_{12}$: 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



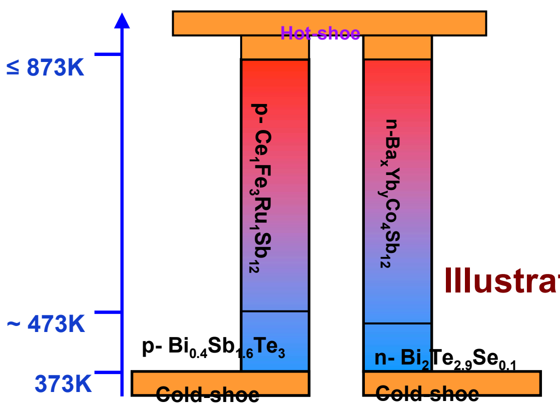
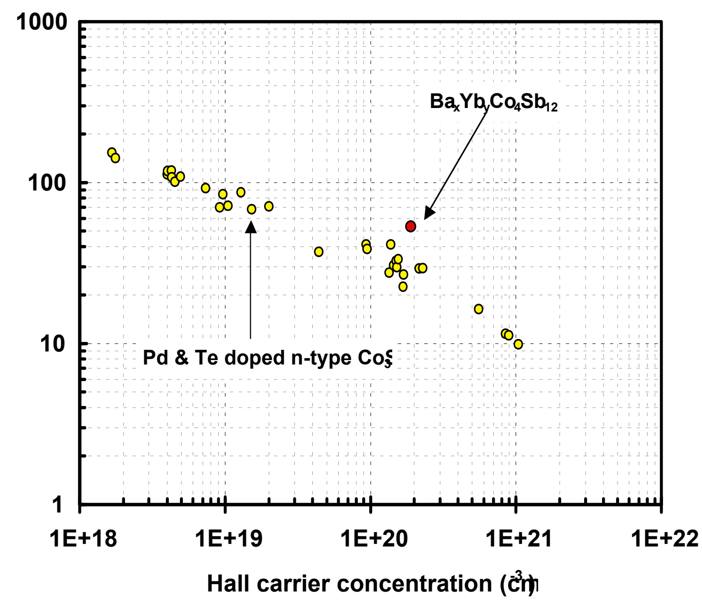


Illustration of skutterudite-Bi_2Te_3 couple



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

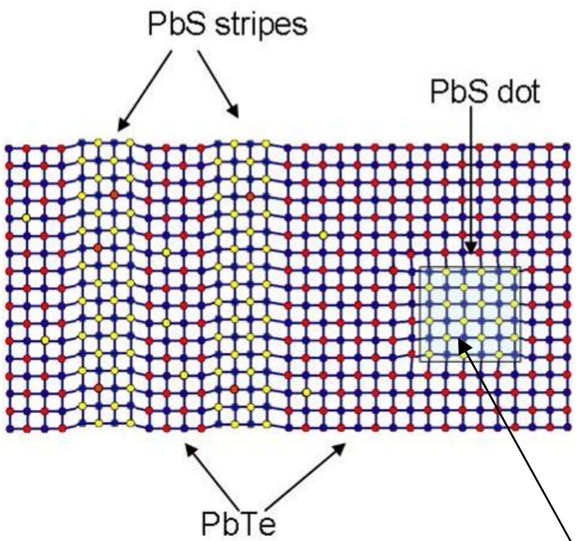
At equivalent carrier concentration, the Hall mobility for $Ba_xYb_yCo_4Sb_{12}$ is higher than that for doped $CoSb_3$

PbTe – PbS system

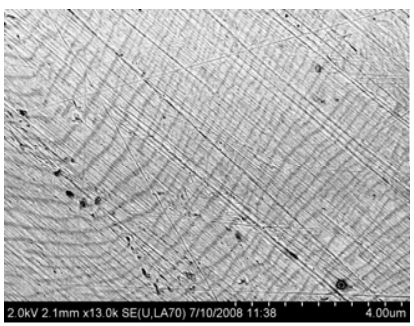
Kanatzidis effort

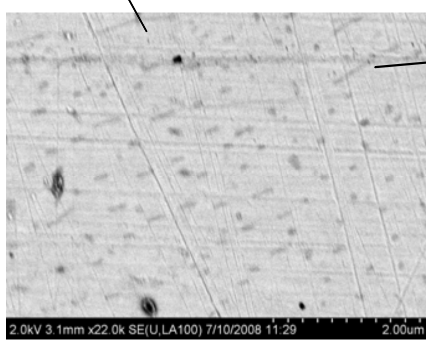
Background

- The material PbTe – PbS 8% has been shown to exhibit at enhanced ZT ~1.4[1] 700 K.
- Reason for high ZT:
  - high power factor at 700 K (17-19 uW/cmK2))
  - Very low total thermal conductivity (0.8 W/mK)
- Low lattice thermal conductivity is the result of nanostructures formed by the spinodal decomposition and nucleation and growth phenomena

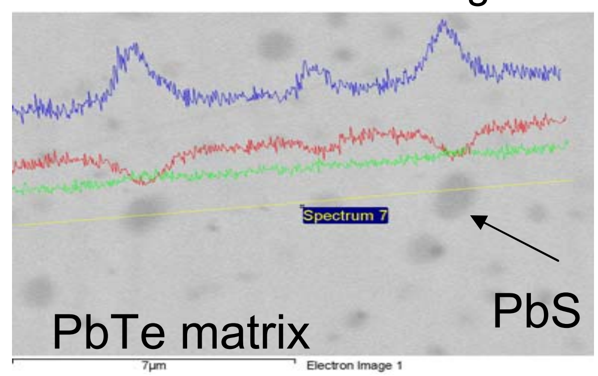


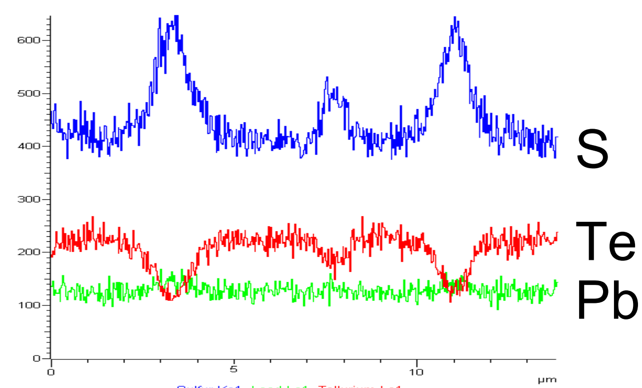
EDS analysis





PbTe – PbS 8% nucleation and growth creates inhomogeneities on the micro and naoscale



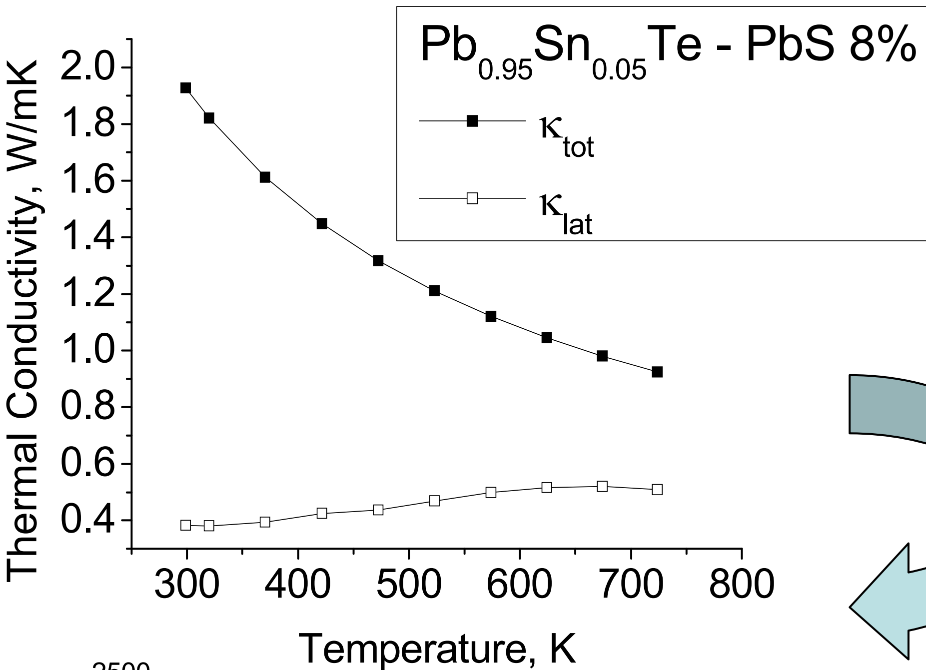


EDS linescans show presence of PbS particles within the PbTe matrix.

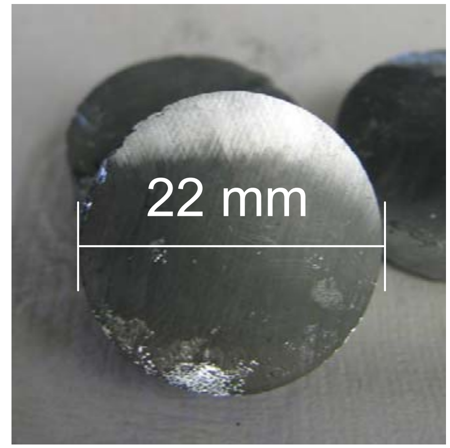
SEM micrographs show presence of spinodal decomposition, nucleation and growth

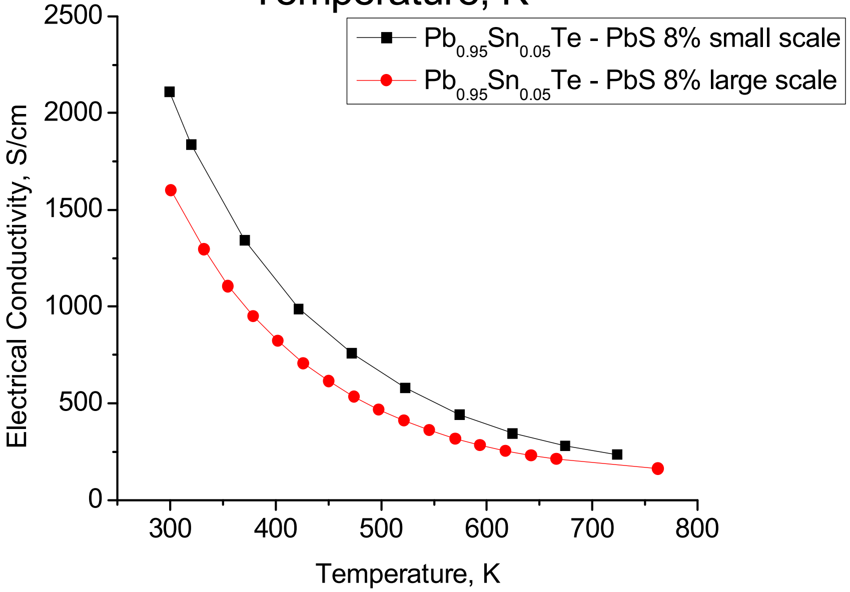
[1]Androulakis, J. et al., *JACS* **2007,** 129, (31), 9780-9788.

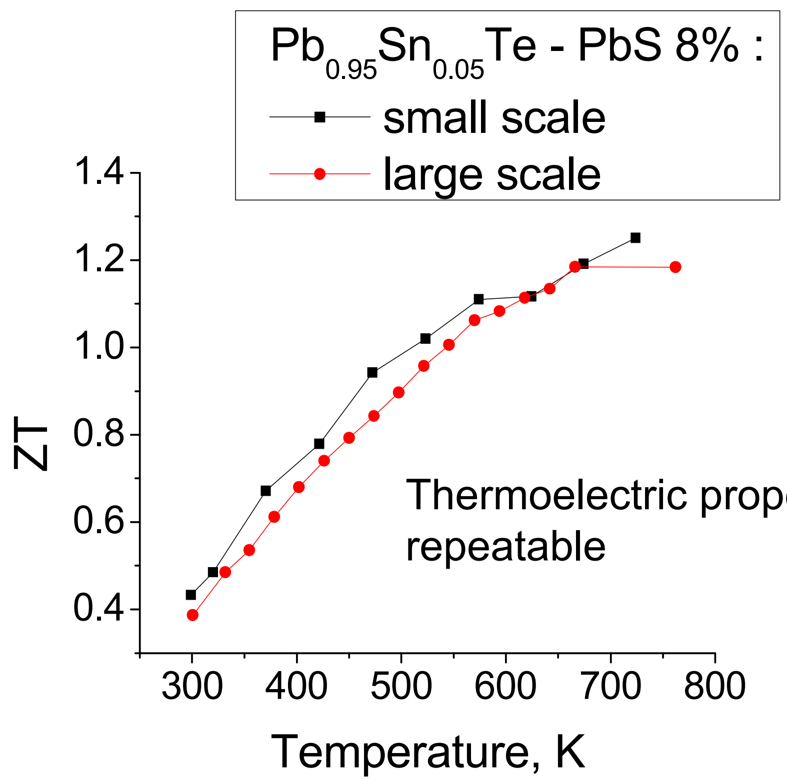
Large-scale Synthesis of $(Pb_{0.95}Sn_{0.05}Te)$ – PbS 8%



•Successful preparation of ~100 g material per batch



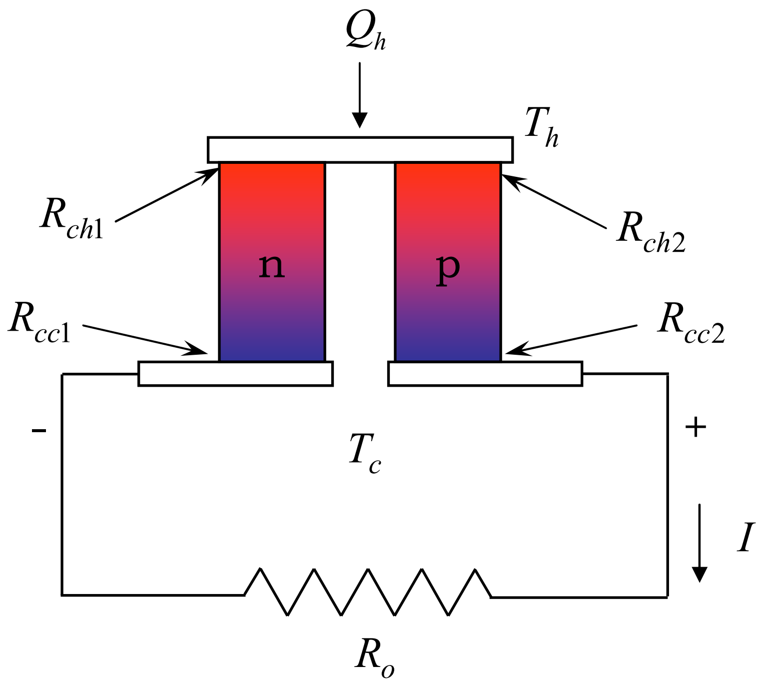




Thermoelectric properties are repeatable

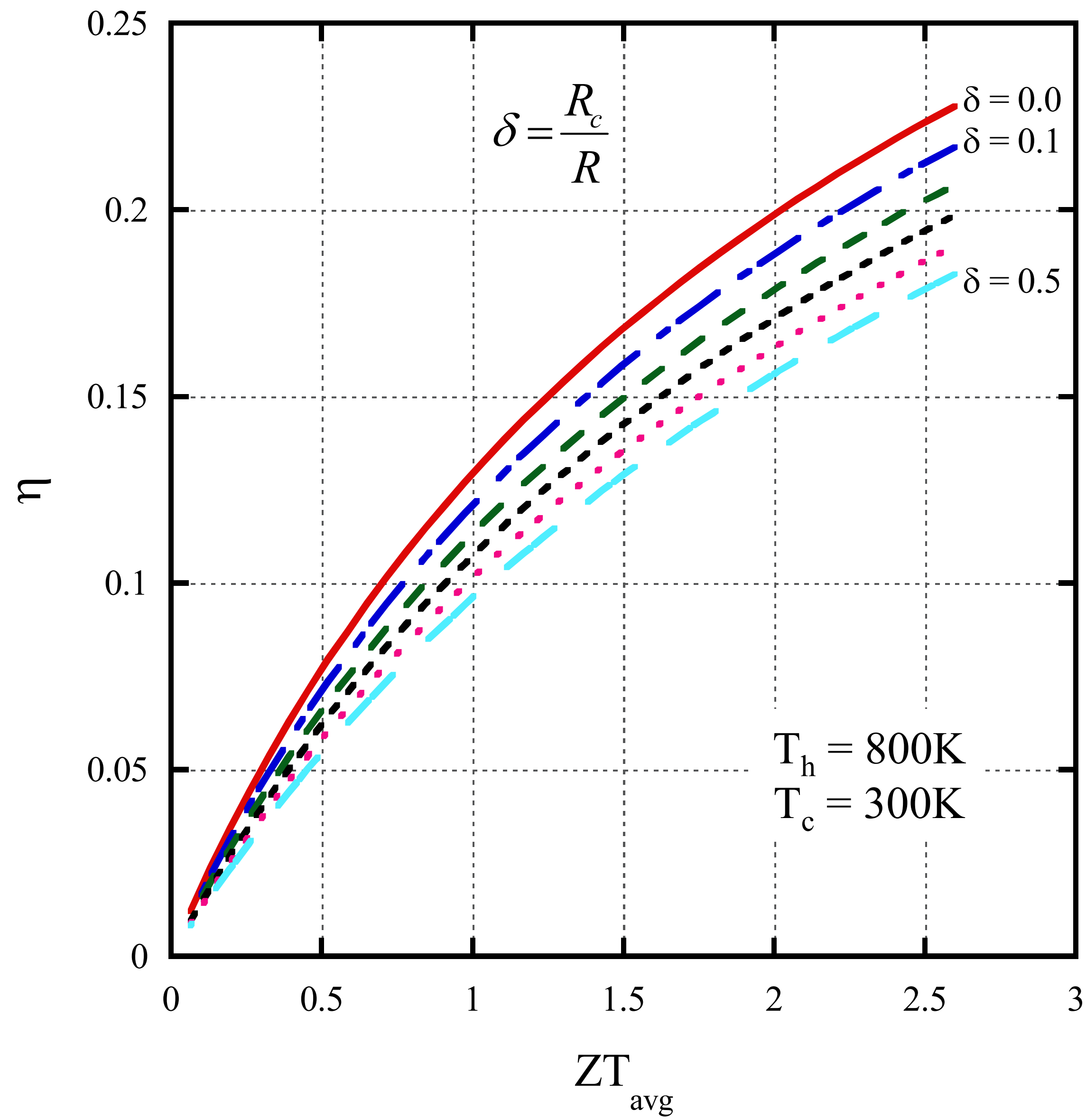
Nanostructures in PbTe – PbS reduce lattice thermal conductivity, increasing ZT.

Parasitic Contact Resistance and Efficiency



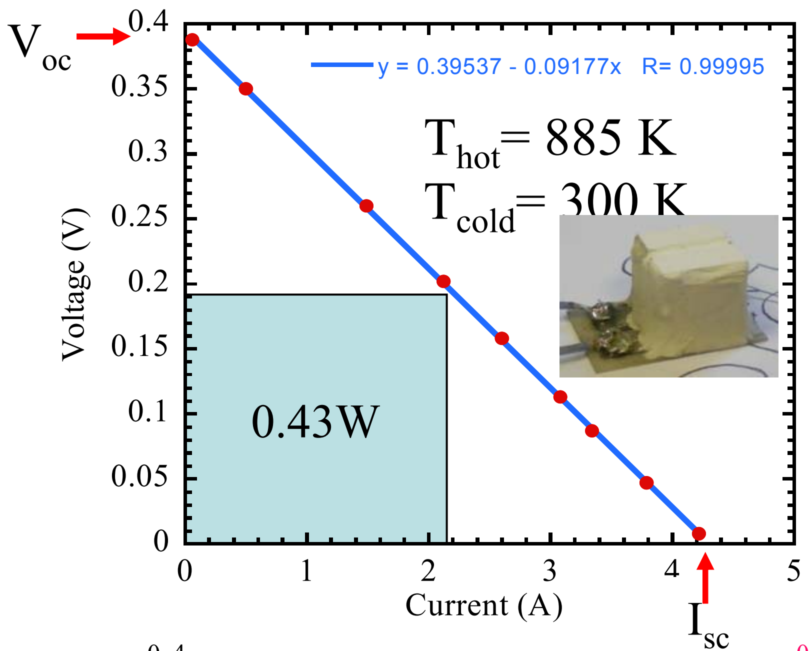
$$\eta = \frac{P_o}{Q_h}$$

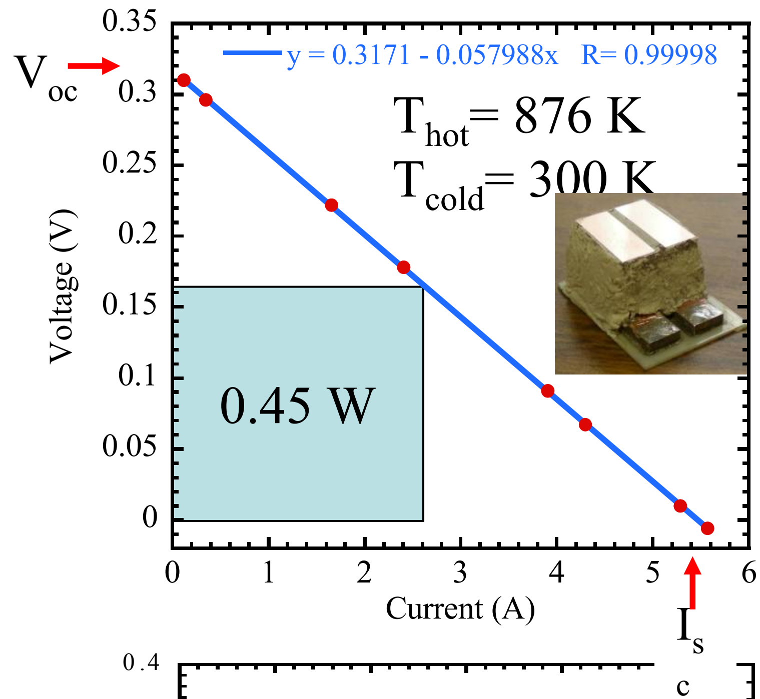
$$\delta = \frac{R_c}{R} = \frac{R_{cc1} + R_{cc2} + R_{ch1} + R_{ch2}}{R_n + R_p}$$

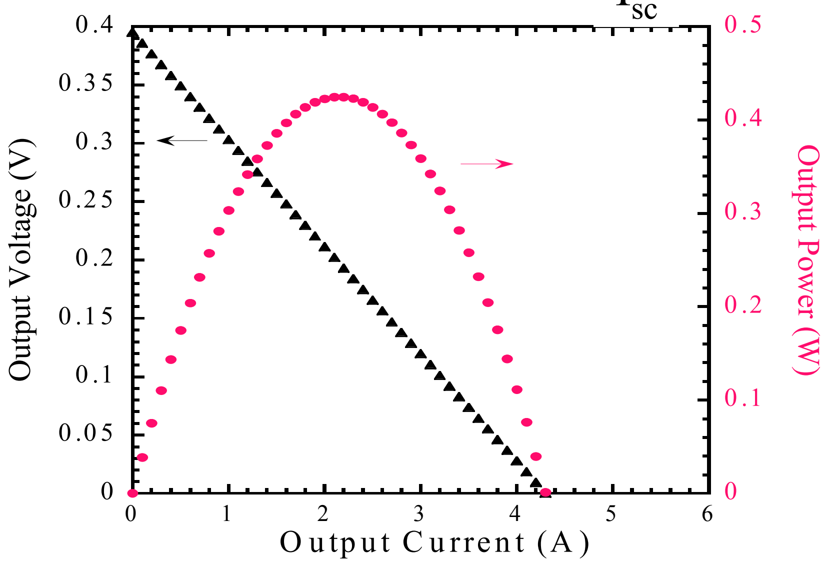


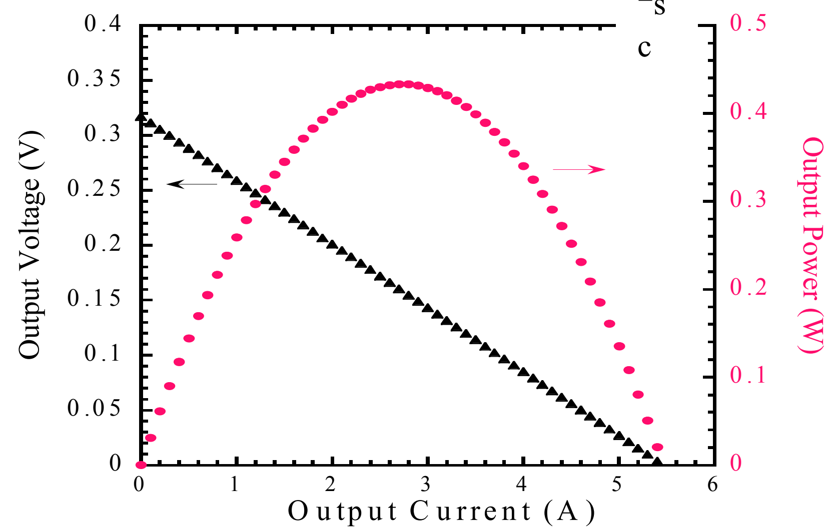
M. H. Cobble, "Calculations of Generator Performance," *CRC Handbook of Thermoelectrics*, CRC Press, 1995.

Four Leg Modules – Soldered Contacts







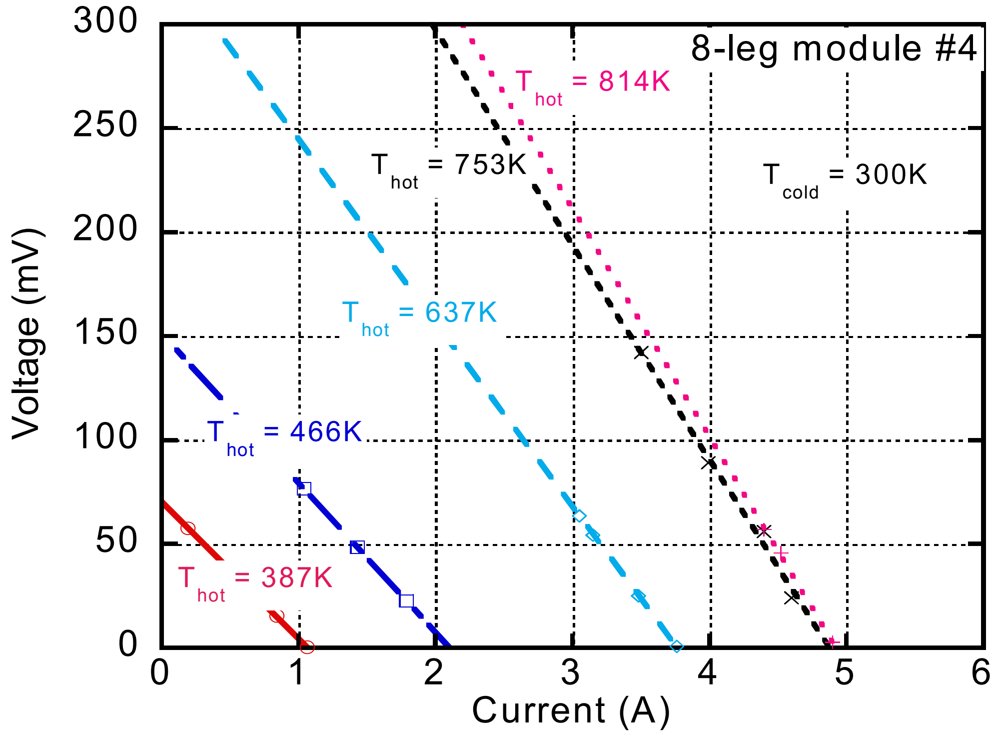


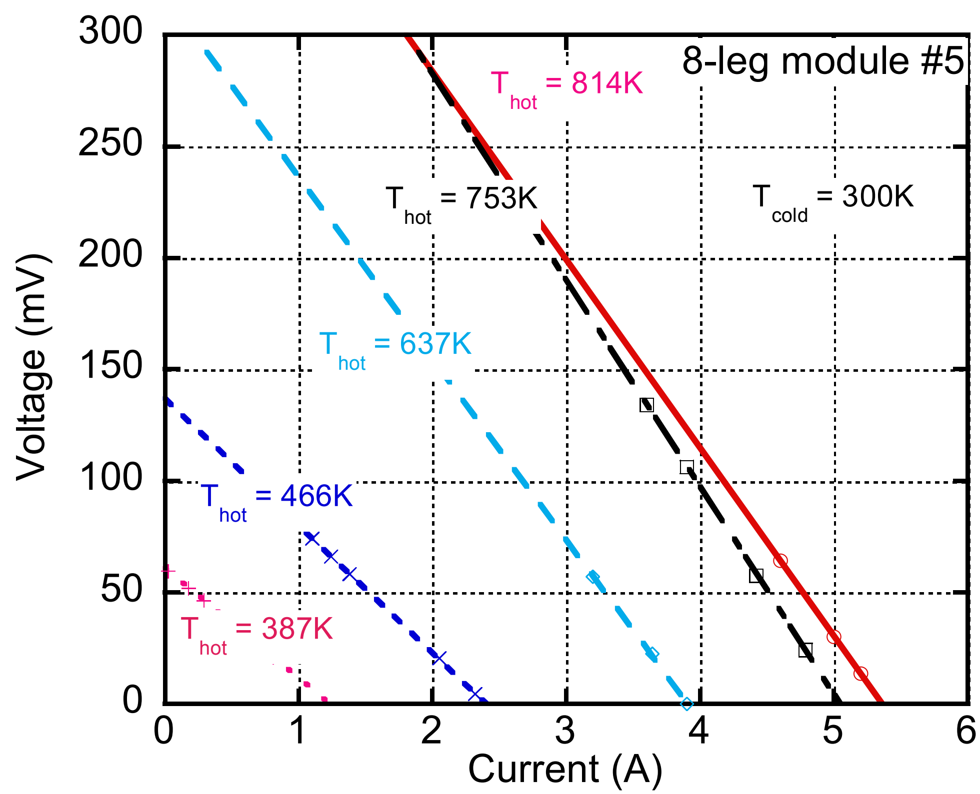
8-Leg Modules

Module #	Module RT Resistance	n-type leg	p-type leg
Module 1	0.026 Ω	ETN204	ETP44
Module 2	0.026 Ω	ETN204	ETP44
Module 3	0.027 Ω	ETN204	ETP44
Module 4	0.027 Ω	ETN204	ETP44
Module 5	0.026 Ω	ETN204	ETP52
Module 6	0.027 Ω	ETN204	ETP52
Module 7	0.025 Ω	ETN204	ETP52

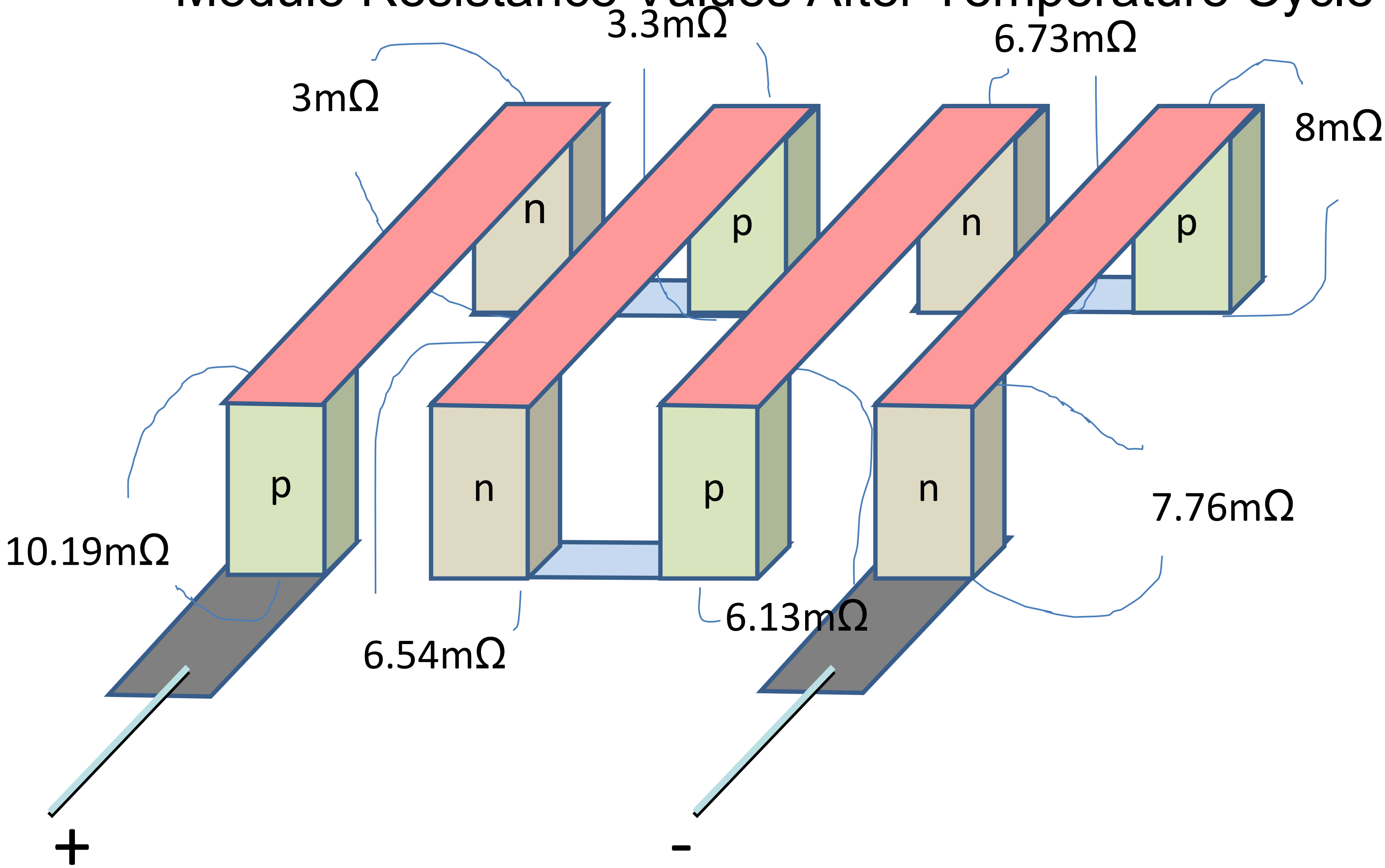
Expected module resistance = 24mΩ (~3mΩ per leg)

$\delta = 0.13$





Module Resistance Values After Temperature Cycle

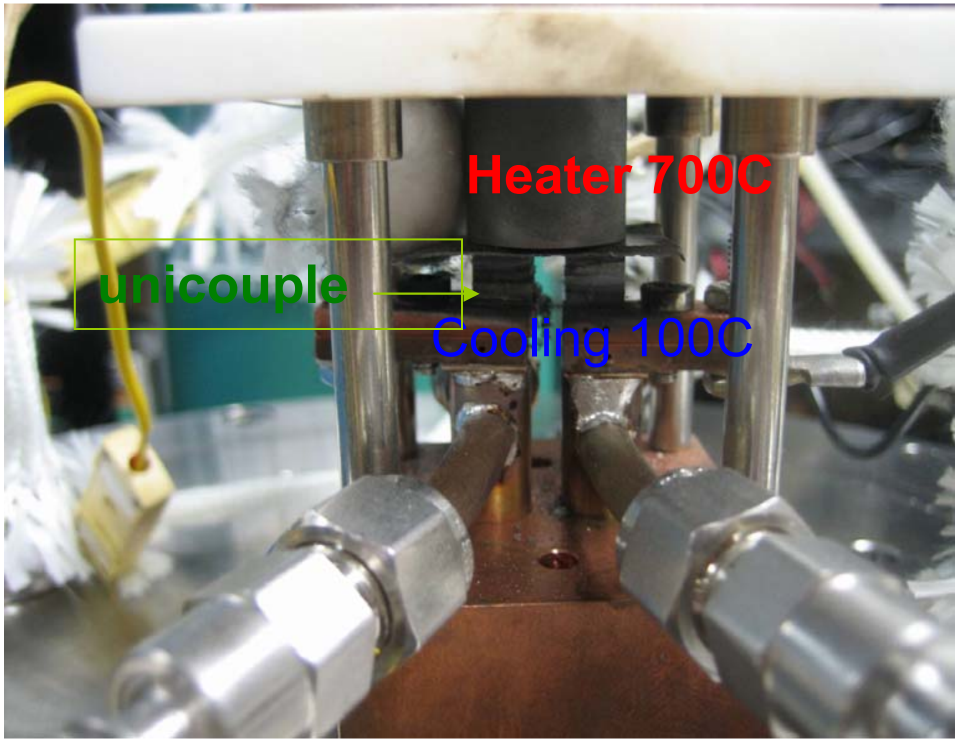


Total module resistance = 51.65 mΩ

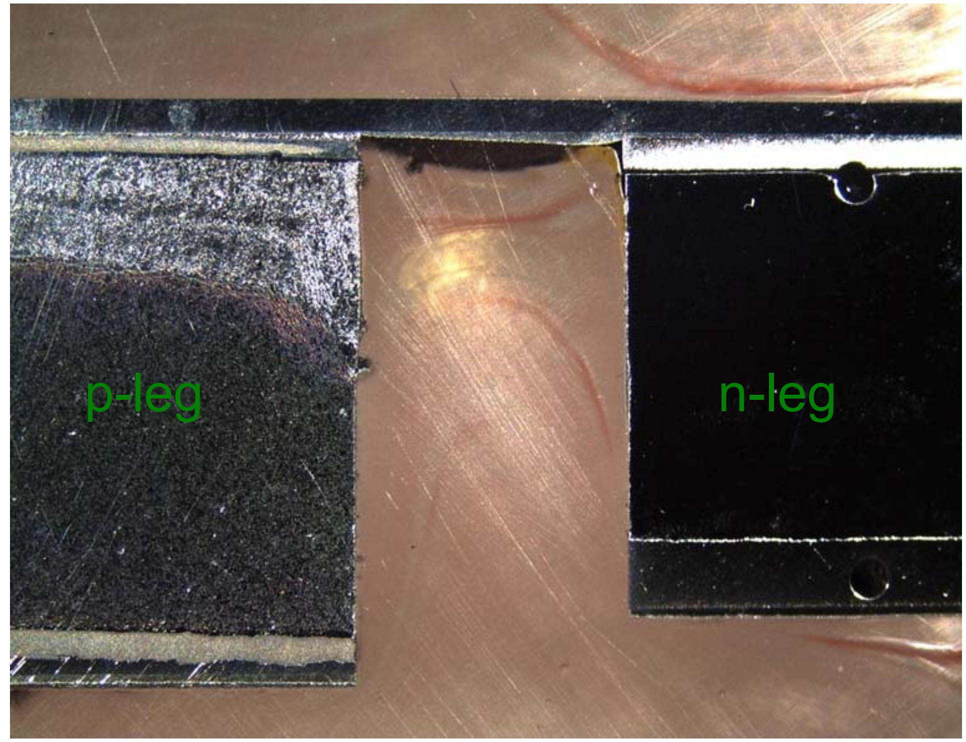
$\delta = 0.91$

Skutterudite Unicouple made and tested at MSU

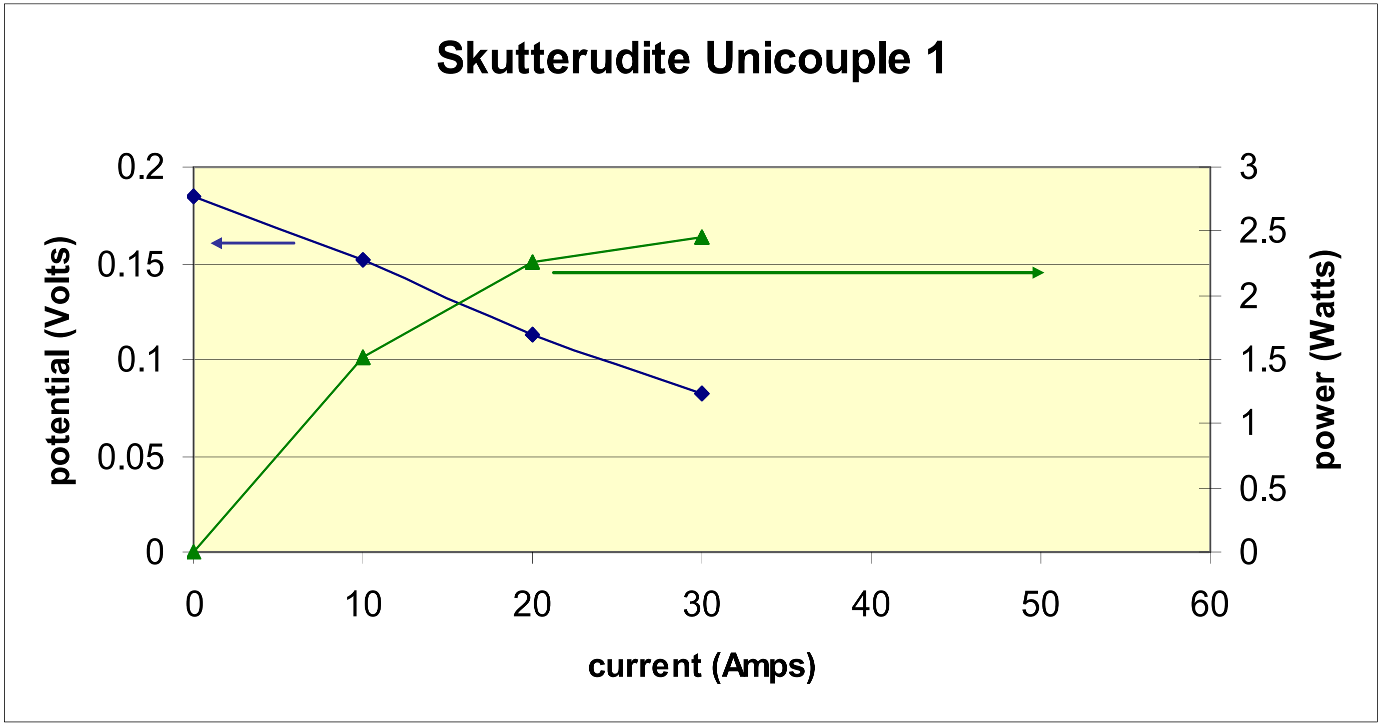
Test set up



After testing

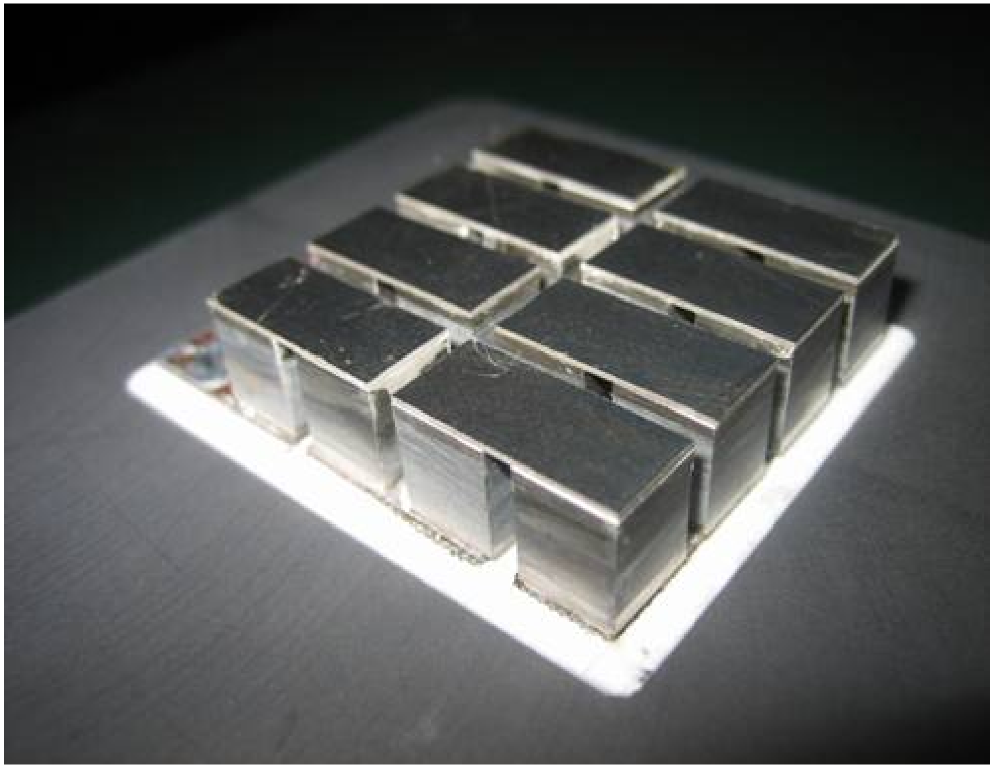
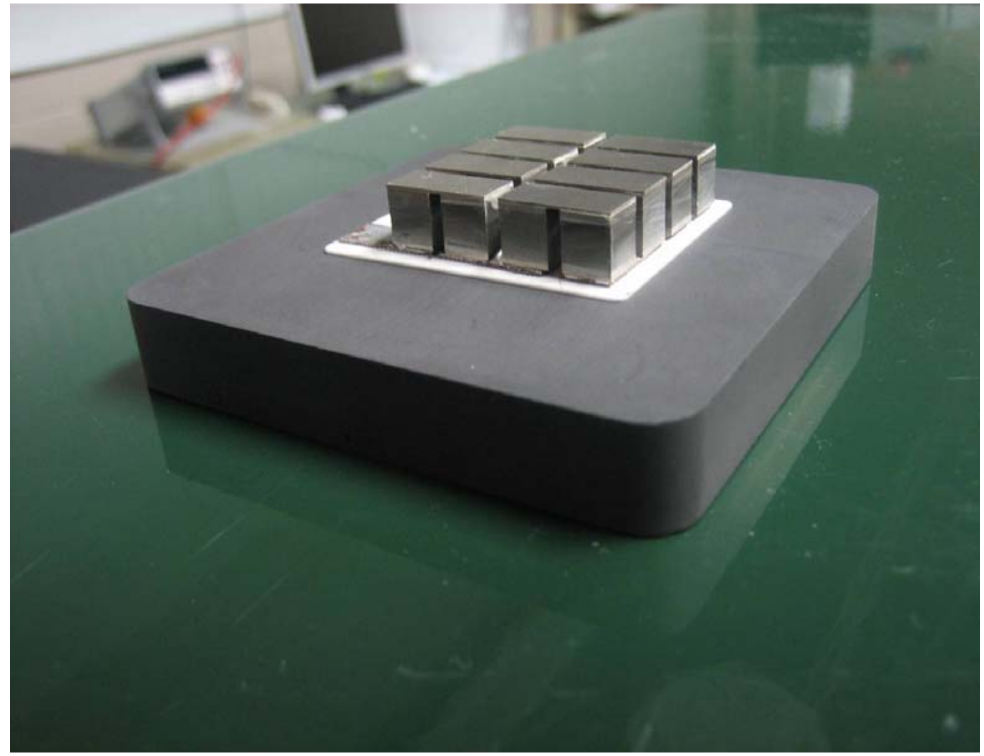


Belljar system (1atm argon)



•Unicouple power output ~ 2.5 Watts per 0.67cc of material

•Peak power at ~30 Amps, test limited by power supply current limitations

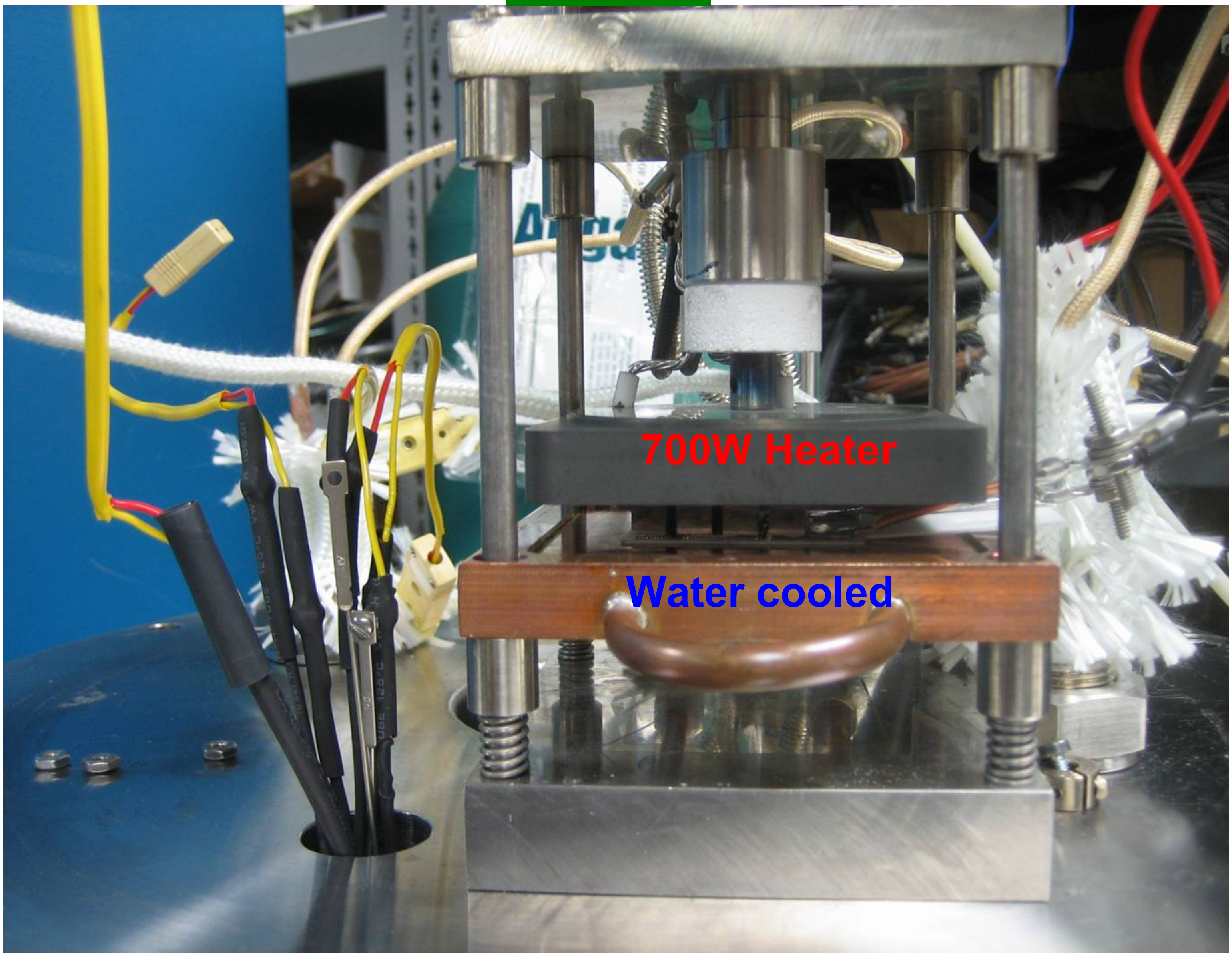



Skutterudite 16-leg module

•Low temperature test confirmed Open Circuit Potential is in good agreement with what is expected

•Materials used in this module have ZT necessary for 40W power output: 700C- 100C assuming no parasitic contact resistance

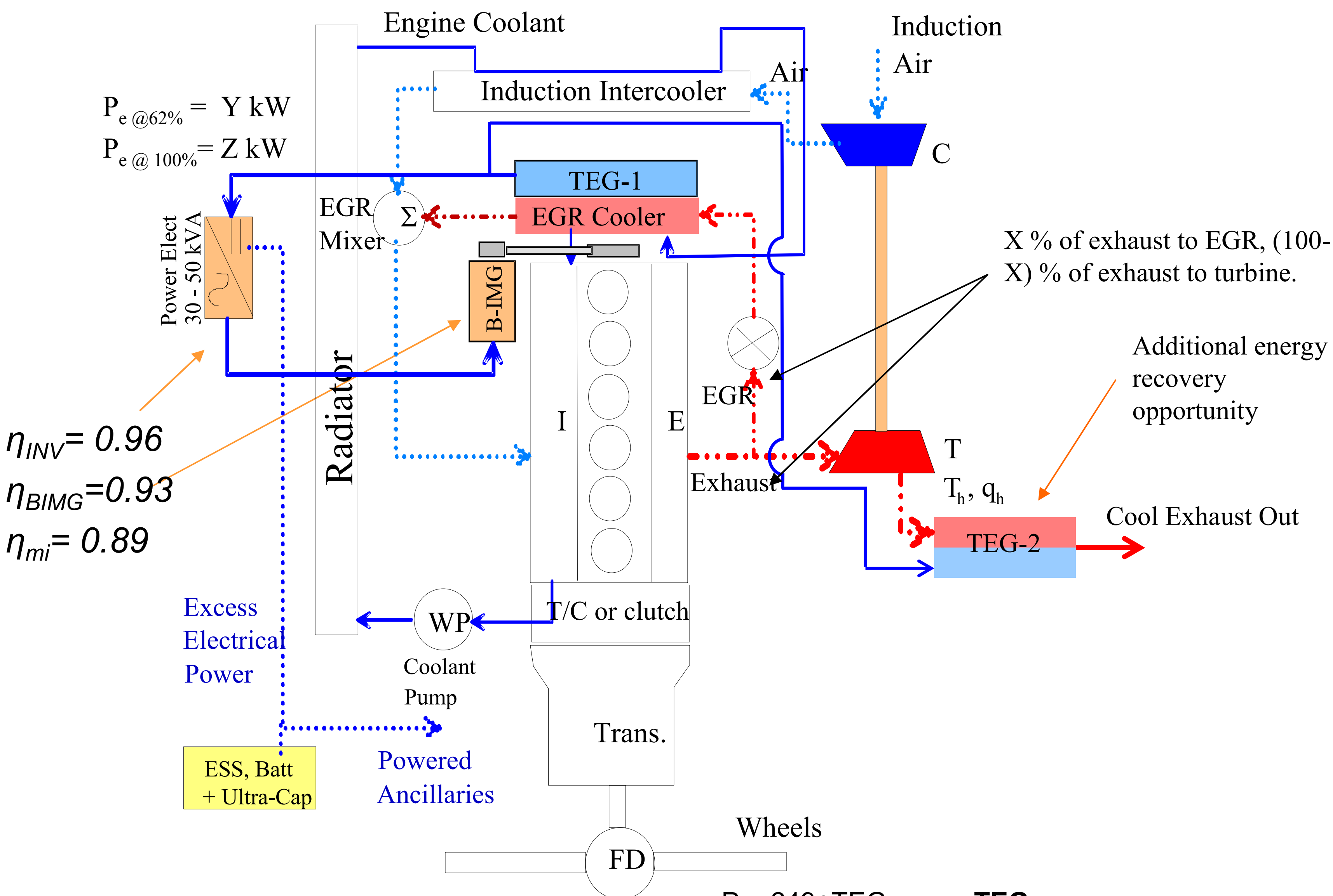
16-leg Skutterudite module Fabrication and Testing



Cummins ISX 6 cylinder diesel engine

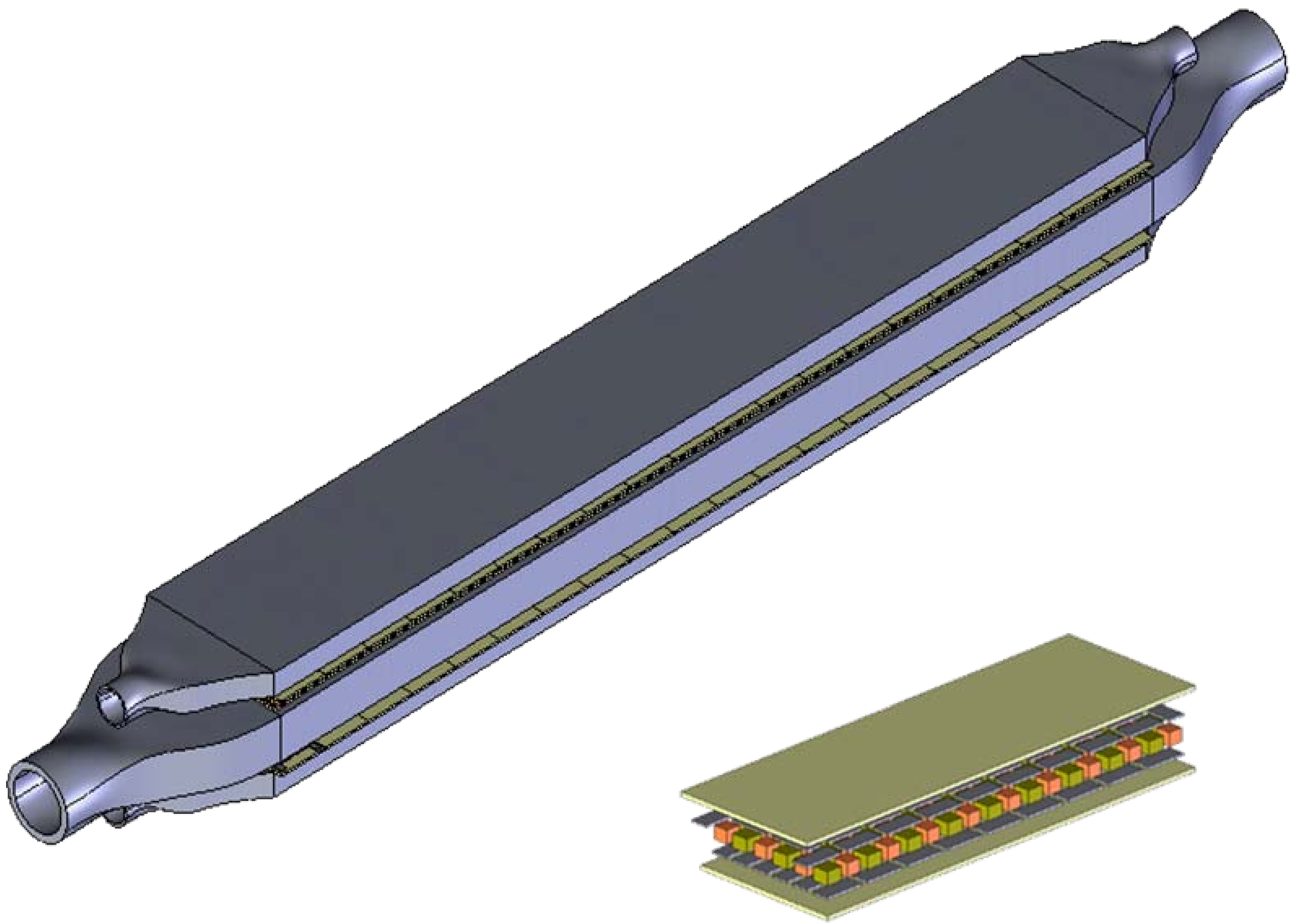
Thermal Power Split Hybrid – Options

Using the electric power recovered from waste heat



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

Single TEG with exploded view of a module



ISX Engine Operating Conditions for ESC Duty Cycle Modes

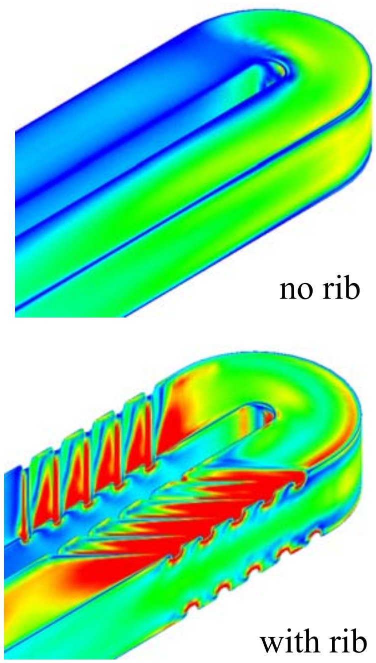
Modes		A-25	A-100	B-62	B-100	C-100
	Units					
Engine Crankshaft Speed	rpm	1230.00	1230.00	1500.00	1500.00	1800.00
Torque	ft-lb	472.15	1886.80	1170.20	1887.30	1577.70
BMEP	psi	78.05	311.92	193.45	312.00	260.82
Power	HP	110.58	441.88	334.22	539.02	540.72
	kW	82.46	329.52	249.23	401.96	403.22

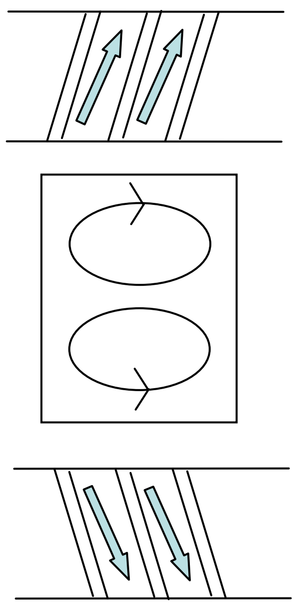
HX: Heat Transfer Enhancement

Goal:

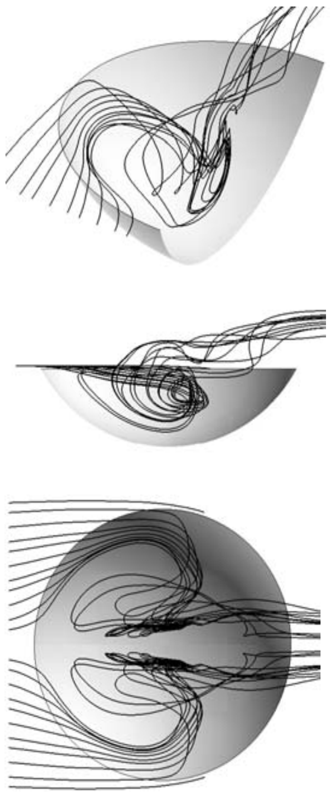
- high heat transfer rate
- low pressure drop

How to get high heat-transfer rate?



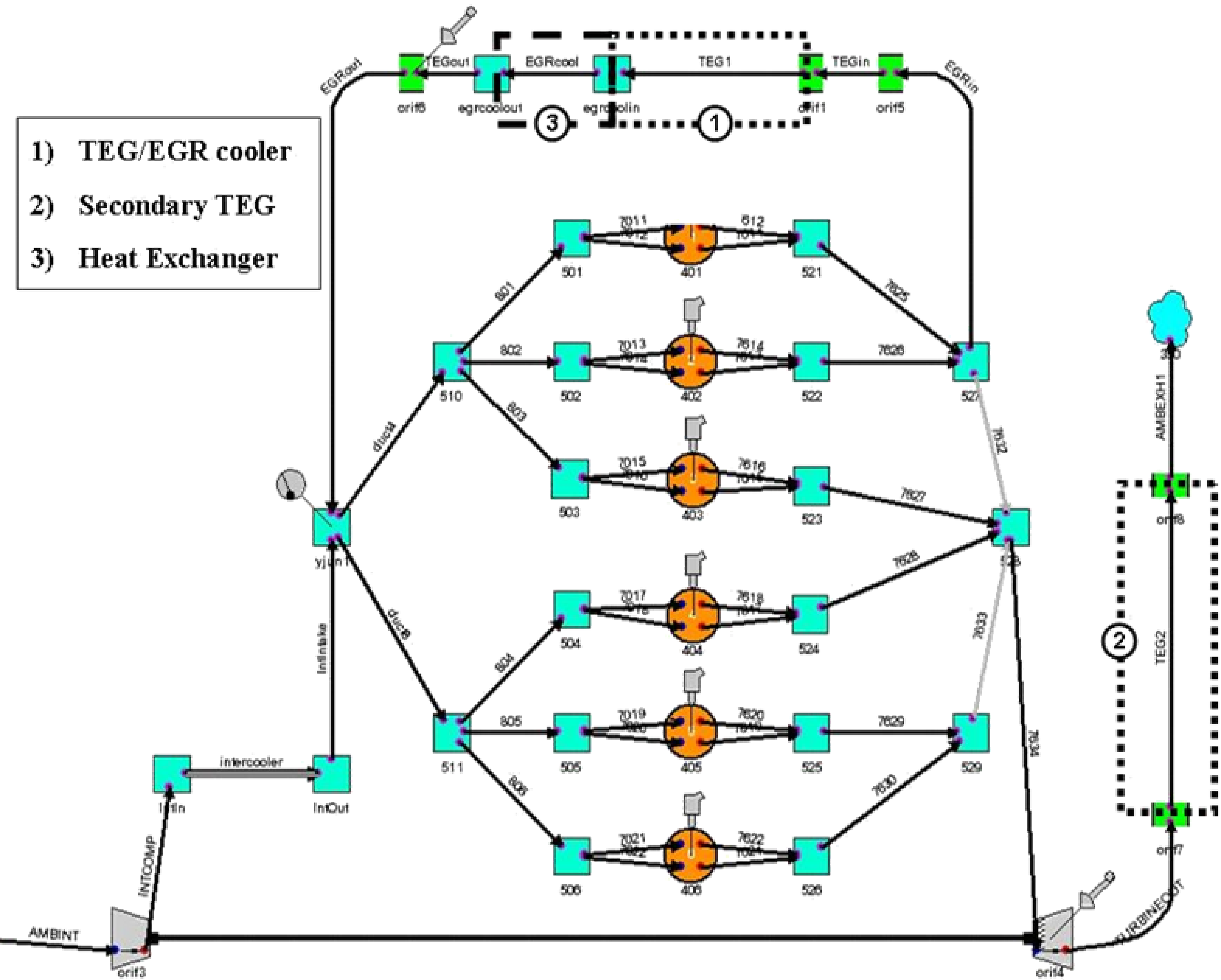


- ribs
- Dimples
- vortex generators
- hybrid (combinations of ribs, dimples, …)

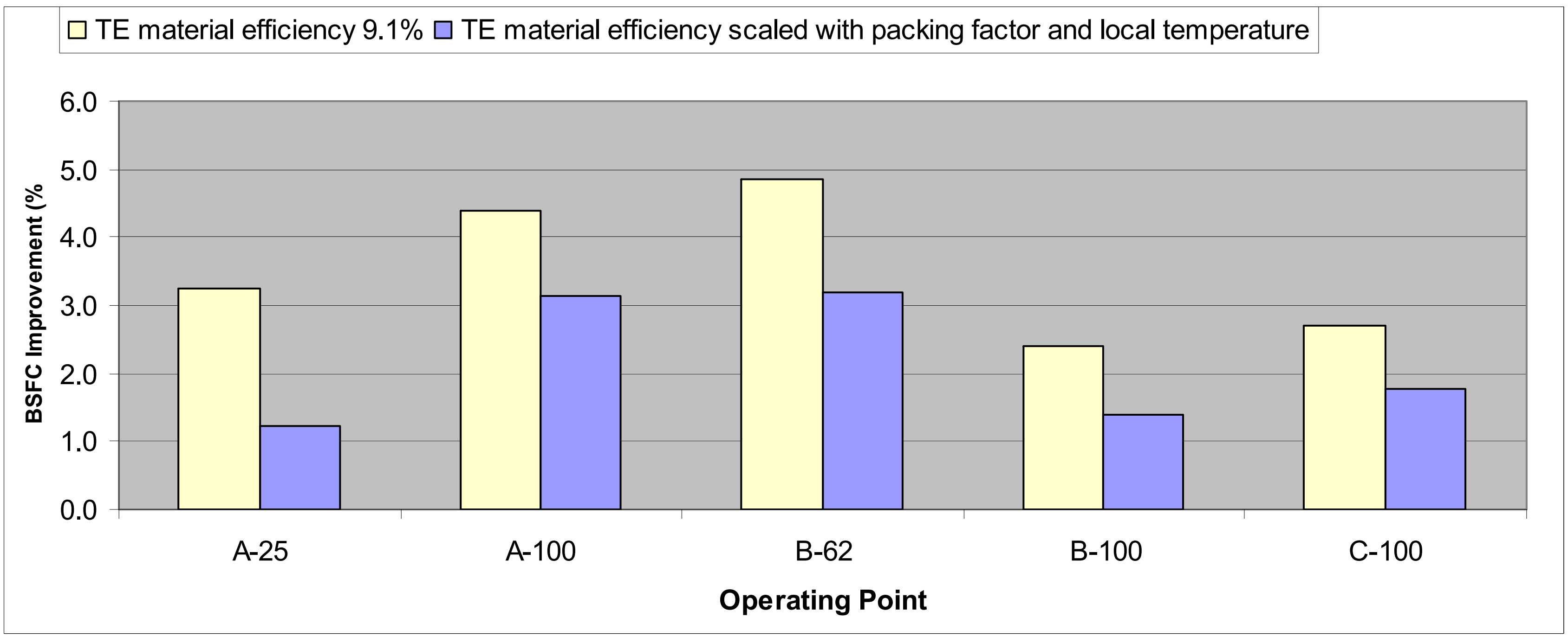


New Design Concepts w/ Heat Exchanger Cont.

- 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



Calculated BSFC Improvement LAST,LASTT-BiTe Materials



Collaborations/Interactions

- MSU, JPL, **Tellurex**, Northwestern, Iowa State and Cummins Team continue to partner in this effort
- Office of Naval Research sponsored effort has provided the basis for new material exploration and assisted in module fabrication developments
- Oak Ridge DOE (High Temperature Materials Laboratory) has provided significant assistance in material property characterization

Publications/Patent

- Pilchak, A.L., Ren, F., Case, E.D., Timm, E.J., and Schock, H.J., (2007). "The Effect of Milling Time and Grinding Media Upon the Particle Size Distribution for LAST (Lead, Antimony, Silver, Tellurium) Powders," Philos. Mag. A.
- Ren, F., Case, E.D., Hall, B.D., Timm, E.J., and Schock, H.J., (2007). "Young's Modulus of N-Type Last Thermoelectric Material Determined from Knoop Indention," Chemistry of Physics and Materials.
- A. L. Pilchak, F. Ren, E. D. Case, E. J. Timm, H. J. Schock, C. -I. Wu, T. P. Hogan, (October 2007). "Characterization of Dry Milled Powders of LAST (lead-antimony-silver-tellurium) Thermoelectric Material," Philosophical Magazine, v.87, Issue 29, pp. 4567-4591.
- Ren, F., Case, E.D., Timm, E.J., and Schock, H.J., (2007). "Young's Modulus as a Function of Composition for an N-Type Lead-Antimony-Silver-Telluride (LAST) Thermoelectric Material," Philosophical Magazine, v.87, Issue 31, pp. 4907-4934.
- Ren, F., Case, E.D., Timm, E.J., and Schock, H.J., (2007). "Hardness as a Function of Composition for N-Type Last Thermoelectric Material," Applied Physics Letters.
- Ren, F., Case, E.D., Timm, E.J., Jacobs, M.D., Schock, H.J., (2007). "Weibull Analysis of the Biaxial Fracture Strength of a Cast P-Type Last-T Thermoelectric Material," Philosophical Magazine Letters.
- Case, E.J., Ren, F., Schock, H.J., and Timm, E.J., (2006). "Weibull Analysis of Biaxial Fracture Strength of Cast P-Type LAST-T Thermoelectric Material," Philos. Mag. Lett. 86 [10]: pp. 673-682.

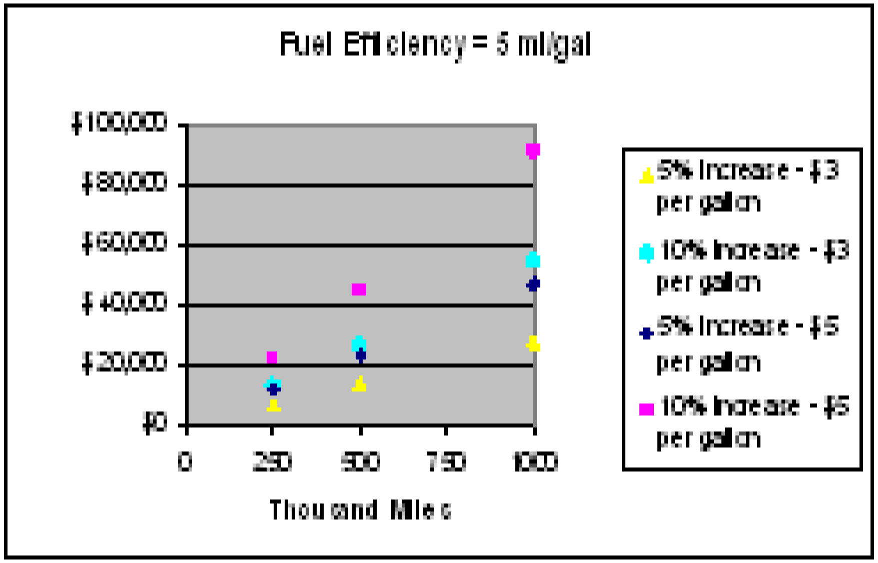
Major Plans for Remainder of Phase 2 Effort

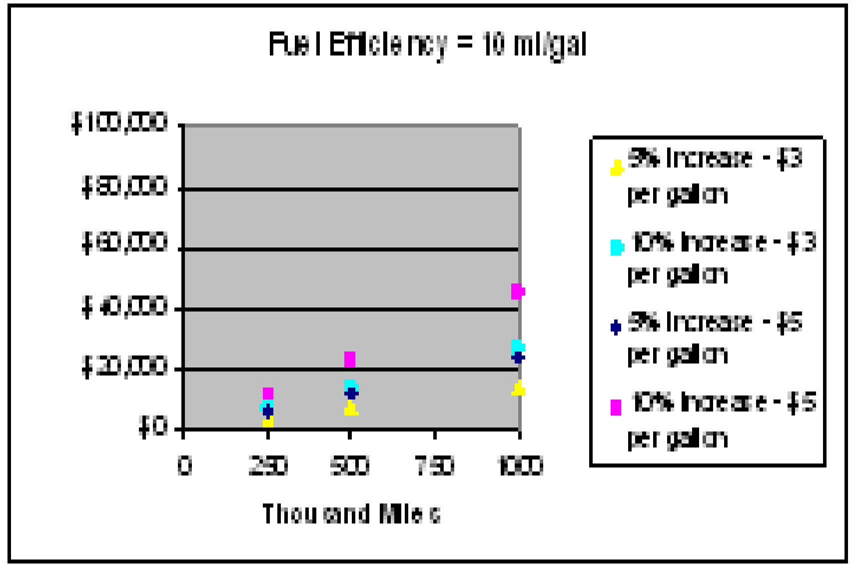
- July ~ Aug, 2008: 2,4,8 and 16 leg modules being fabricated, segmented concepts evaluated and powder processing method development ongoing
- Aug ~ Nov, 2008: Module construction and performance testing
- Sept ~ Nov, 2008: Advanced heat exchanger design and numerical simulation of expected system performance
- Dec, 2008: Choose a thermoelectric system to demonstrate a 500 watt generator
- January 2009: Complete 500 watt generator design
- Feb-June 2009: Construct the 500 watt generator
- July-Nov. 2009: Generator testing
- December 2009: Complete report on generator performance

Summary

- Systems for material synthesis, powder processing, hot pressing, leg and module fabrication are operational at MSU
- Performance testing of legs and modules at MSU is in agreement with others doing similar measurements
- Can produce materials required for a 500 watt module in one month
- Power conditioning electronics for being designed and tested
- Improved head exchanger designs are critical to success of TE effort for waste heat recovery
- Using TEG technology, a 5% improvement in bsfc for and OTR truck is a reasonable 5 year goal …10% improvement possible with new TE materials

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	$13636	$11,905	$22,727
1M miles	$14,286	$27,273	$23,810	$45,455