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

Prepared by:

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

May 22, 2009

Project ID# ace_46_schock

IOWA STATE UNIVERSITY

MICHIGAN STATE UNIVERSITY

TELLUREX CORPORATION

NORTHWESTERN UNIVERSITY

Outline of Presentation

- **Overview**
- Objectives
- 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 – November 2011
(est. based on rate of DOE funding)
56% Complete based on original funding

Budget

	DOE	Contractors
• Phase 1	215K	
• Phase 2	3,508K[1]	1,185K[2]
• Phase 3	1,078K[3]	
• Phase 4	1,029K[3]	
FY07	1,100K	
FY08	1,171K	

[1] Received 2,965K to date from DOE

[2] Note that 1,897K cost share required for Phases 1,2,3 and 4 per original contract

[3] Phase 3 and Phase 4 not yet funded involve a hardware demonstration on a diesel powered system

Barriers

- Utilize waste heat to reduce fuel consumption: DOE goal 10% reduction in bsfc
- Systematic accessory electrification to reduce fuel consumption (8-12% possible by EERC publication)
- Engine idle reduction reduces fuel consumption and emissions while lowering capital costs

A combination thermoelectric generator energy recovery system – auxiliary power unit (ERS-APU) addresses all of these barriers and is described later in the presentation.

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

Outline of Presentation

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

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

Outline of Presentation

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

Milestones
(Phase 2, 2008-2009)

- Identified new thermoelectric systems that have the potential for η>14% at 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 Generation-1 TEG has been designed and is under construction (est. based tests of MSU fabricated SKD modules, maximum theoretical output 1.3kW at a ΔT = 600C)
- Heat transfer issues for a Generation-2 TEG have been identified and solutions proposed

Outline of Presentation

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

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
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.)

6 Cyl. Engine Test Data
Cummins

ERS-APU Demonstration Phase 3-4
MSU

Systems for Utilization of Electrical Power Recovered
MSU

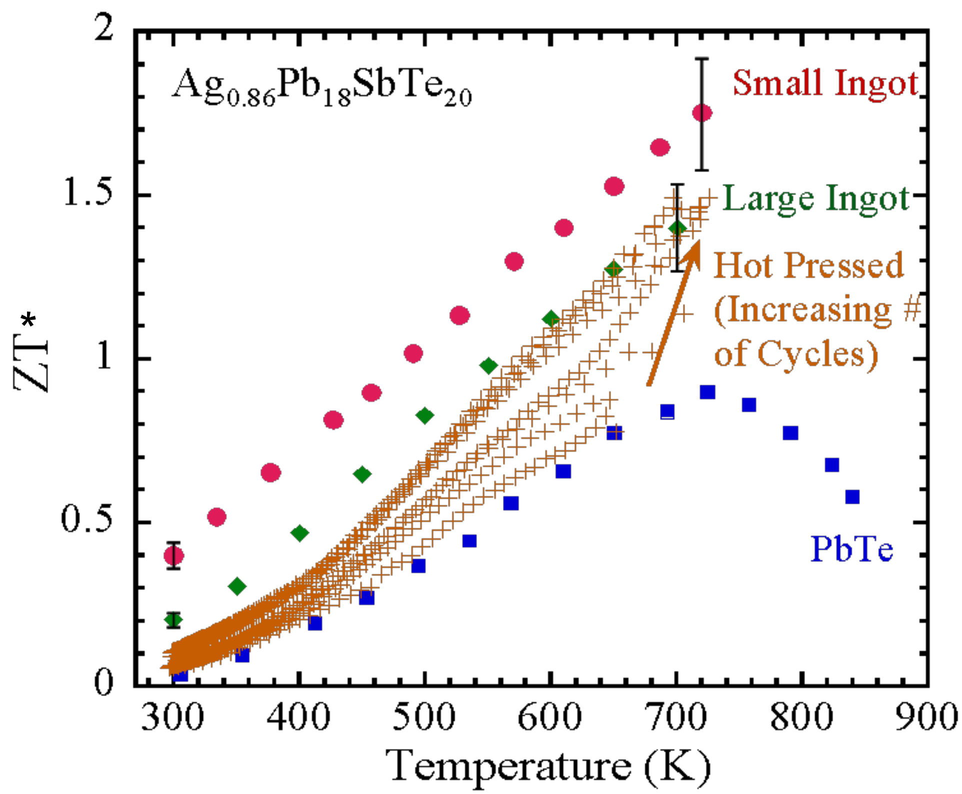
- Design of electrical energy conditioning and utilization system
- Control system design and construction
- Inverter, Belt Integrated Starter-Generator Selection

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

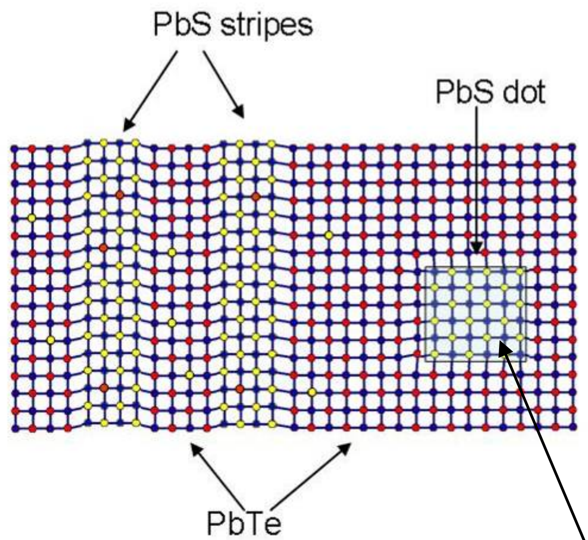
New Material and System Development: Best Hot Pressed LAST Samples

- 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.

New Material and System Development: PbTe – PbS System



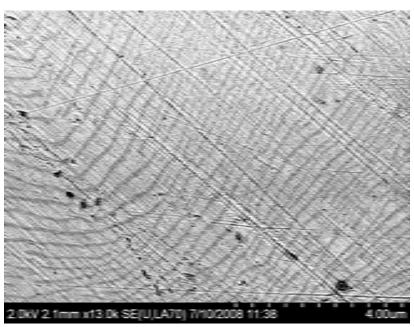
Background

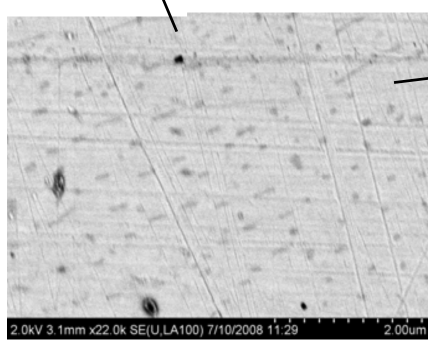
•The material PbTe – PbS 8% has been shown to exhibit at enhanced ZT ~1.4[1] 700 K.

•Reason for high ZT:

- •high power factor at 700 K (17-19 μW/cmK^2))
- •Very low total thermal conductivity (0.8 W/mK)

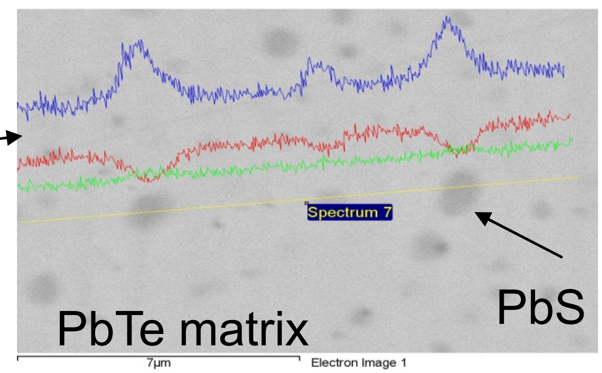
•Low lattice thermal conductivity is the result of nanostructures formed by the spinodal decomposition and nucleation and growth phenomena

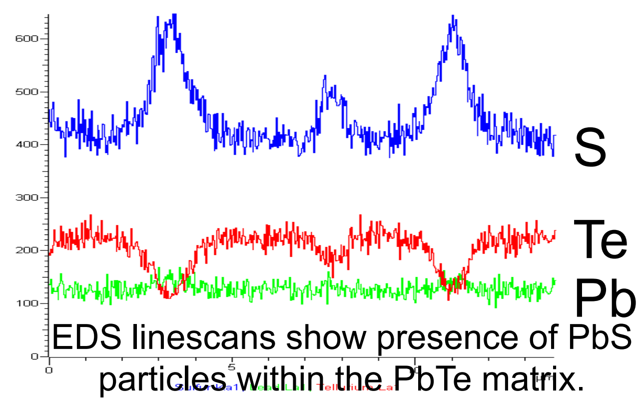




PbTe – PbS 8% nucleation and growth creates inhomogeneities on the micro and nanoscale

EDS analysis





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.

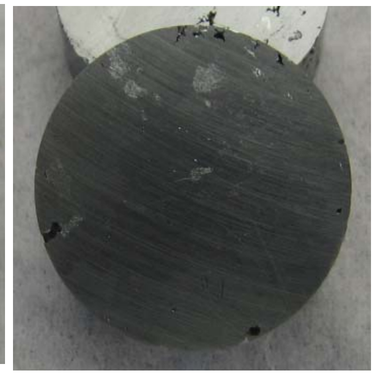
New Material and System Development: Optimization and Scale Up of the High ZT Material n-Type PbTe-PbS

•We have developed reproducible materials preparation procedures for 120 gr ingots of bubble-free PbTe-PbS

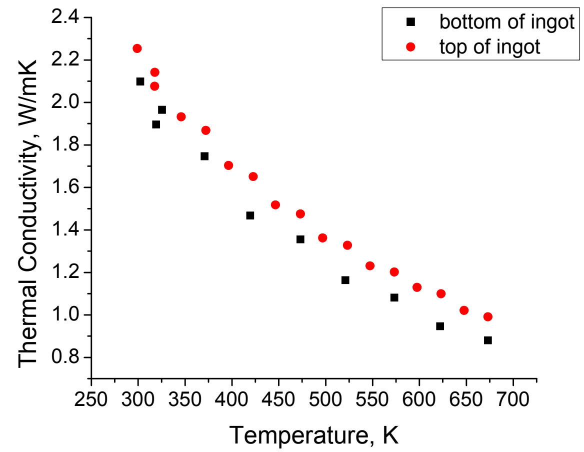
•Specimens exhibit high power factor (~17 μW/cmK^2) and very low thermal conductivity

120 gr ingot

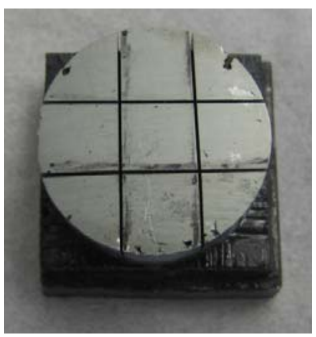
bottom coin

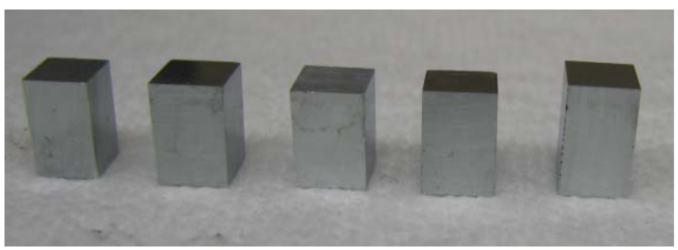


top coin



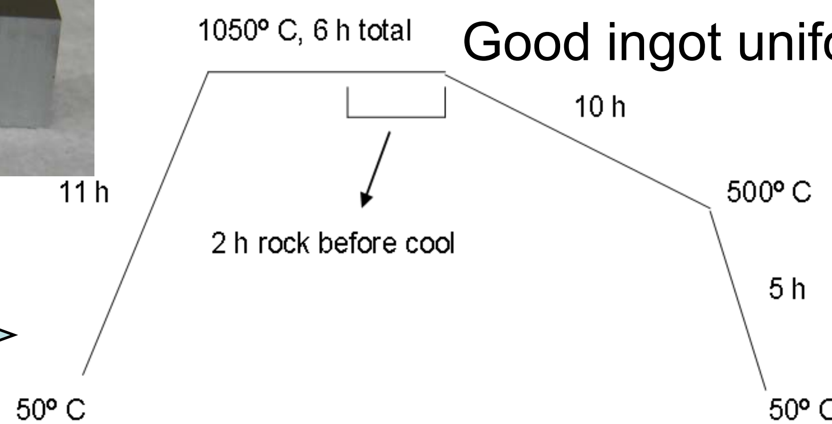
Good ingot uniformity



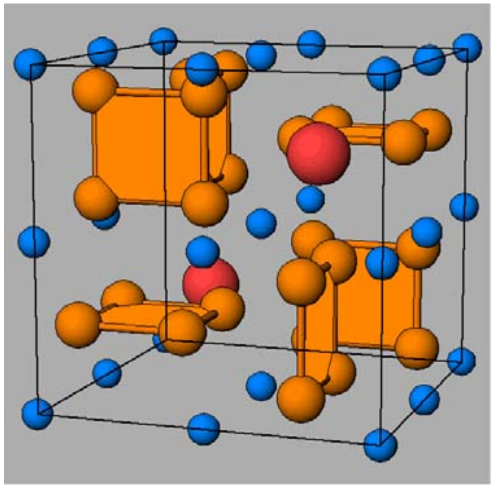


• The preparation procedure for n-type PbTe-PbS has been optimized.

ZT~1.4 at 725 K



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



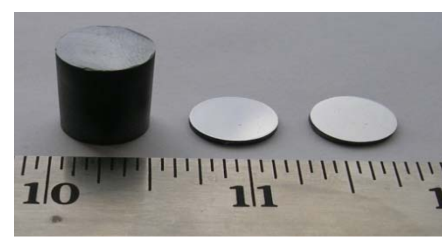
Skutterudite crystal structure

- 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

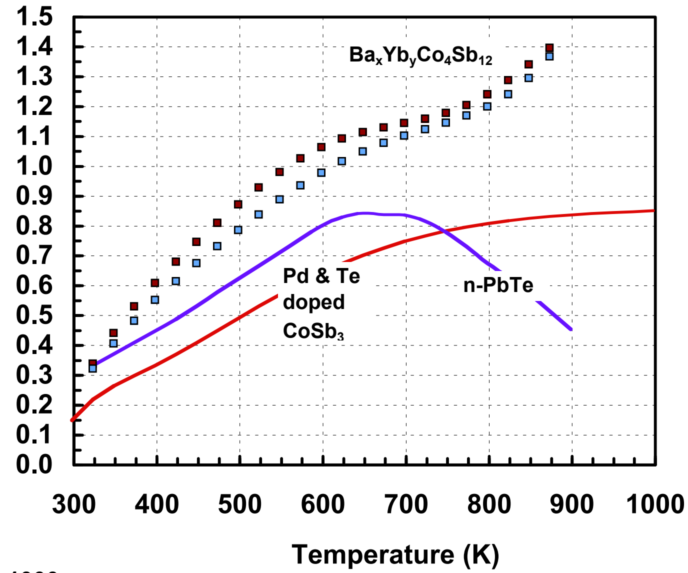


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

[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



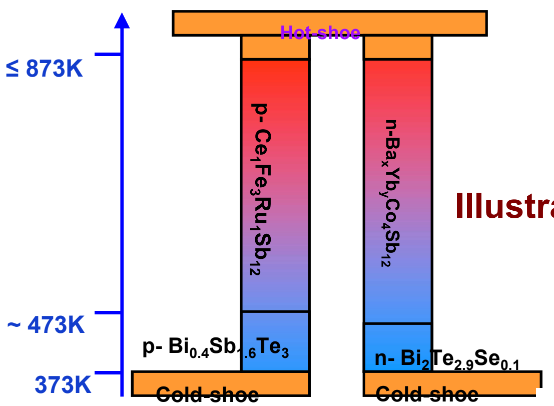
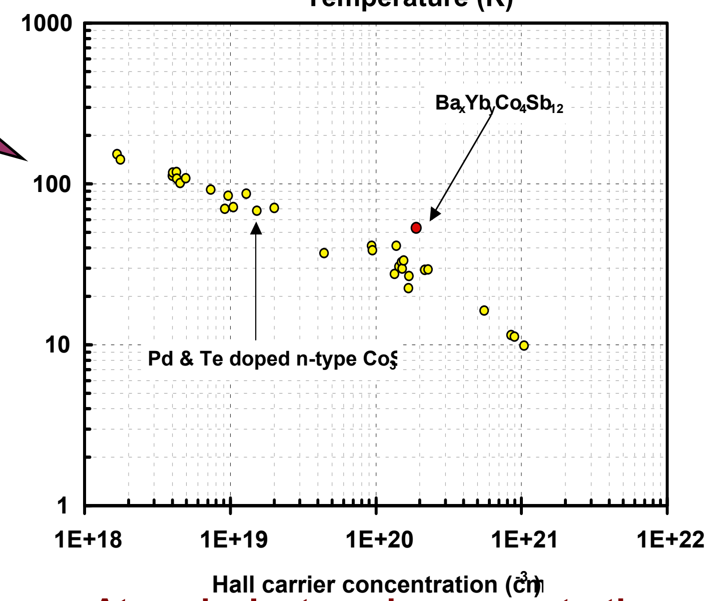


Illustration of skutterudite-Bi_2Te_3 couple

Couple efficiency (%)

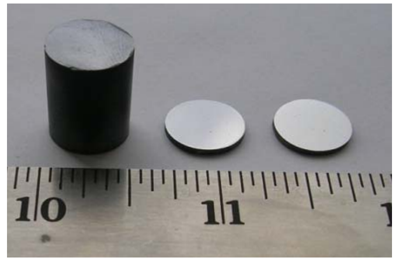
	T_H= 873K - T_C=373K	T_H= 773K - T_C=373K	T_H= 773K - T_C=373K
With Bi_2Te_3 segments	11.8	10.0	7.9
Without Bi_2Te_3 segments	10.7	8.8	6.75



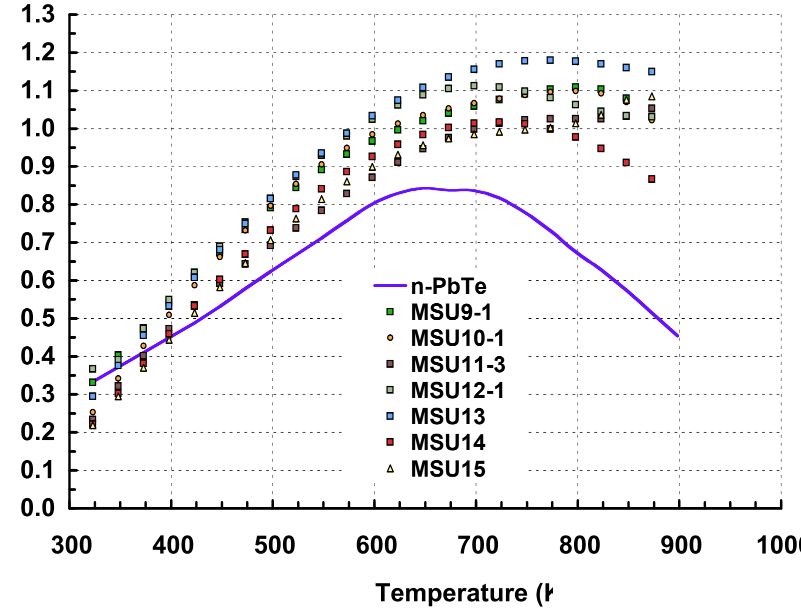
At equivalent carrier concentration, the Hall mobility for $Ba_xYb_yCo_4Sb_{12}$ is higher than that for doped $CoSb_3$

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

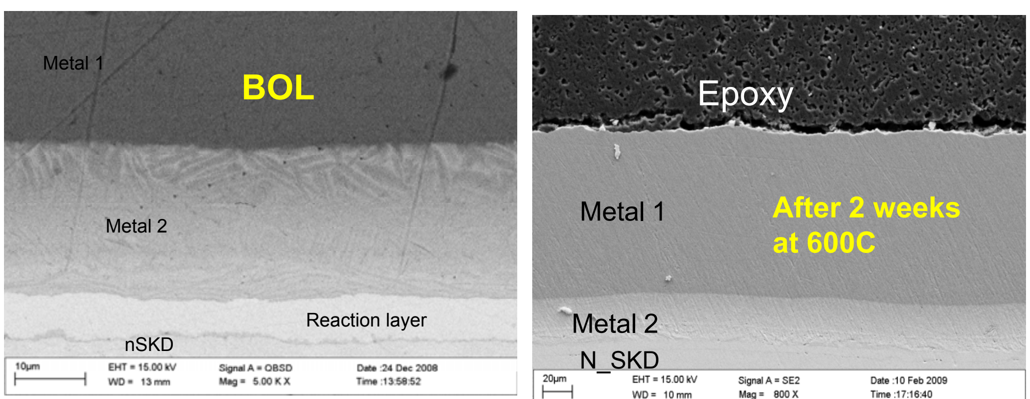


Hot-pressed pucks and disks of $Ba_xYb_yCo_4Sb_{12}$

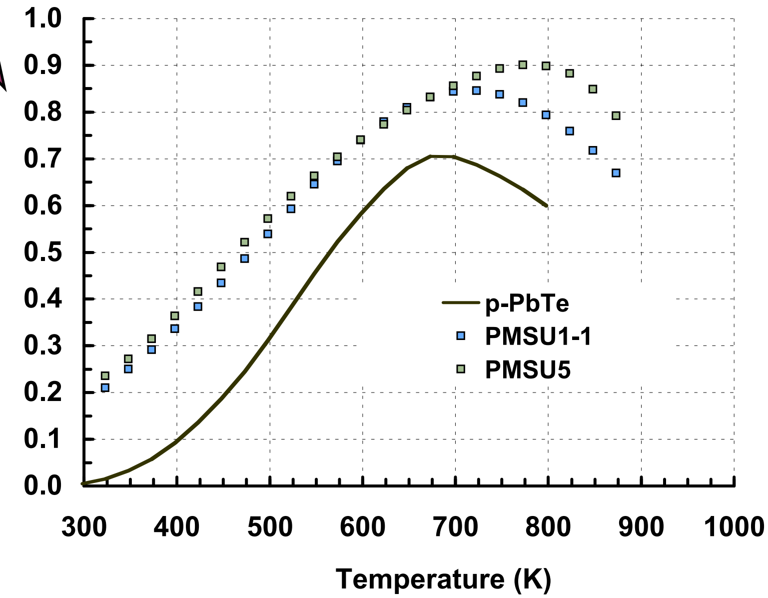


ZT values for n-type $Ba_xYb_yCo_4Sb_{12}$ ball milled materials. Each set of data corresponds to a separate 100 g batch.

- 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

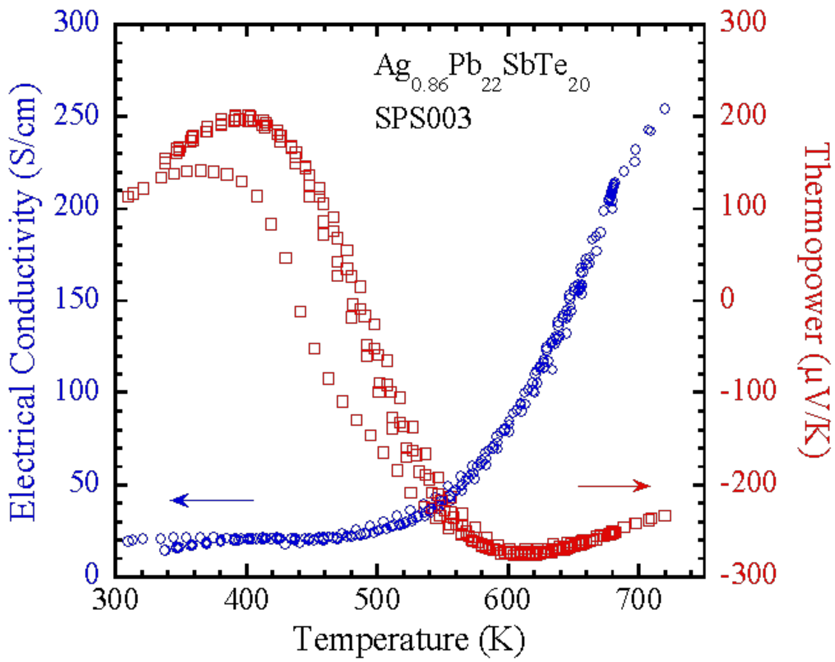


SEM images showing the SKD/metallization interface at beginning of life (BOL) and after 2 weeks aging at 600C. After aging, no degradation of the interface and no significant metal/SKD diffusion is observed.

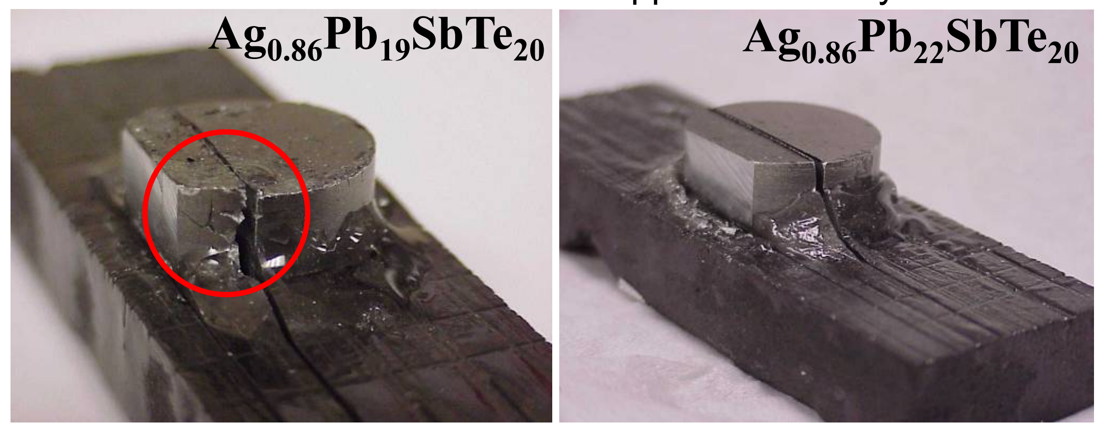


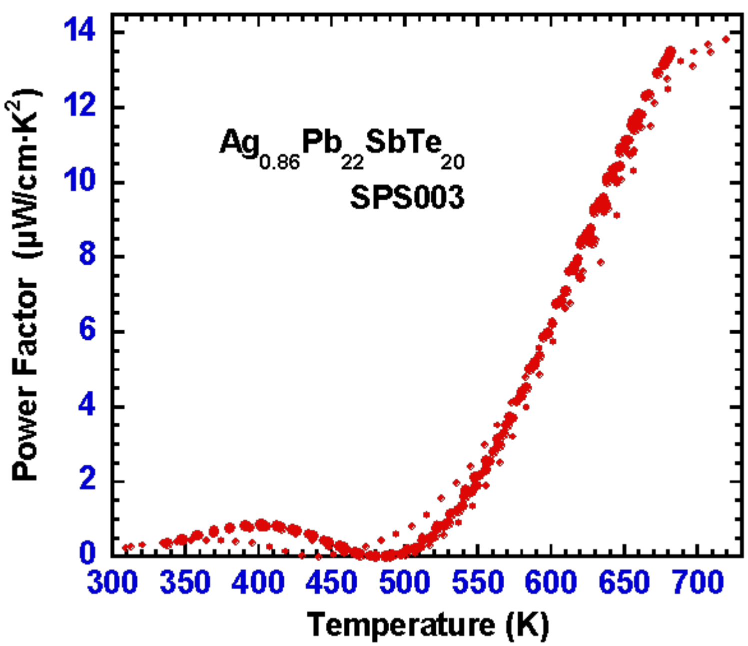
ZT values for p-type $Ce_xFe_{4-y}Co_ySb_{12}$ ball milled materials. Each set of data corresponds to a separate 50 g batch.

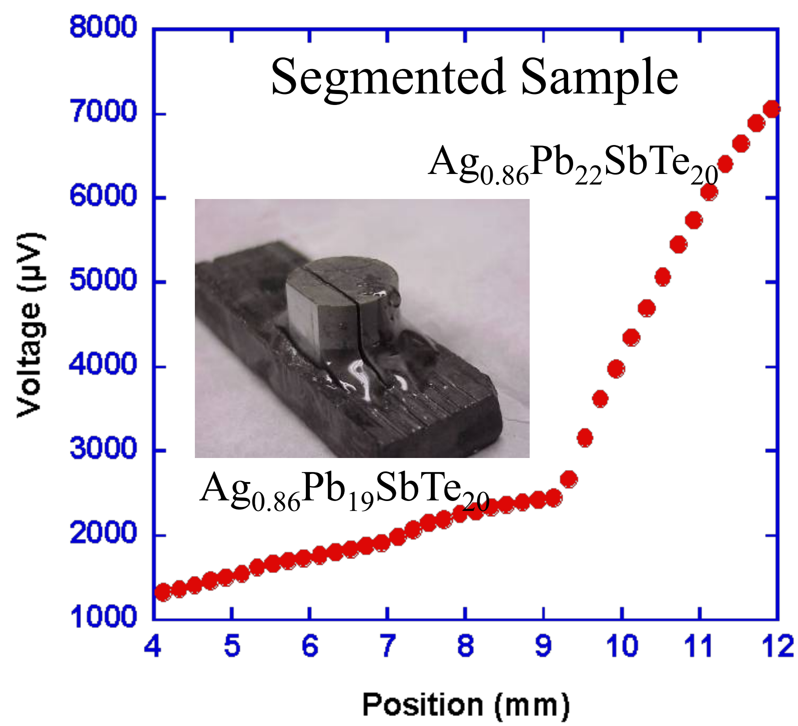
NMSD: Spark Plasma Sintering (SPS) of LAST Samples



Materials and Manufacturing Directorate
Air Force Research Laboratory, WPAFB
Michael Cinibulk, Civ USAF AFMC AFRL/RXLN
Office of Naval Research Supported SPS System







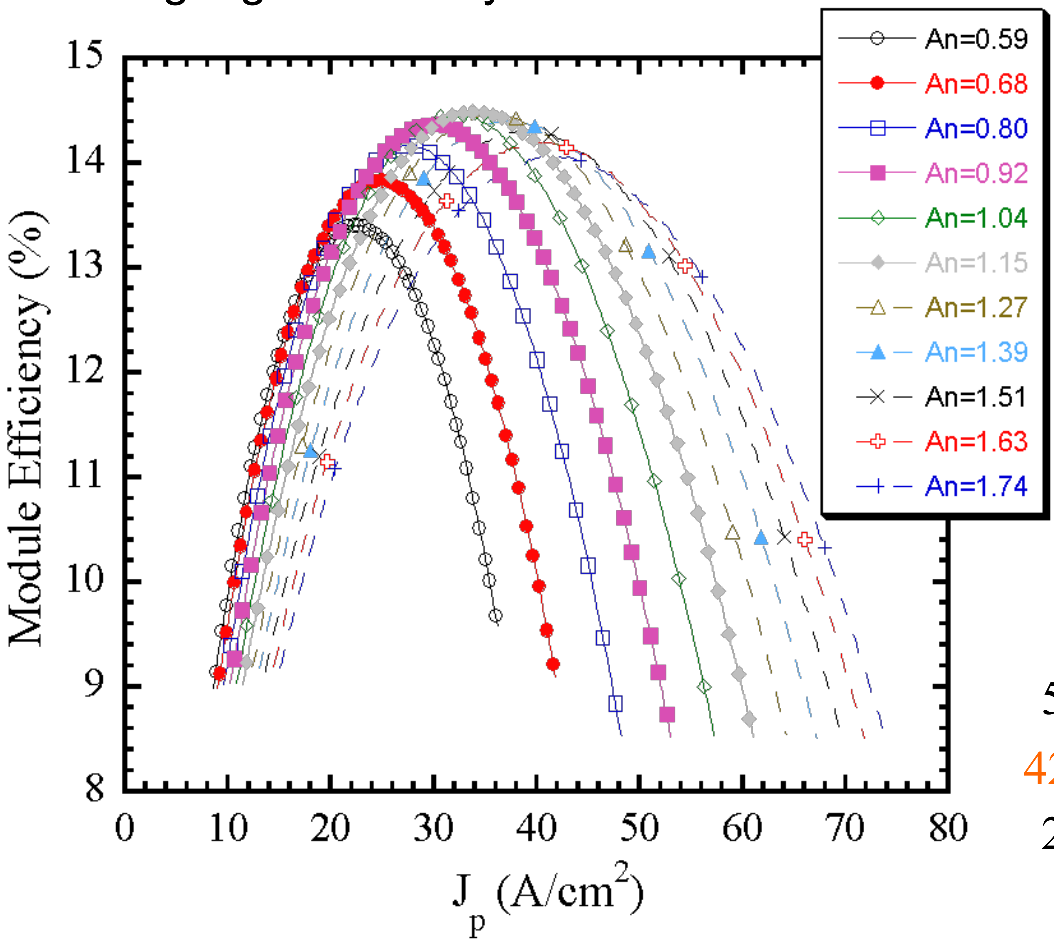
0.75” diameter
7mm thick

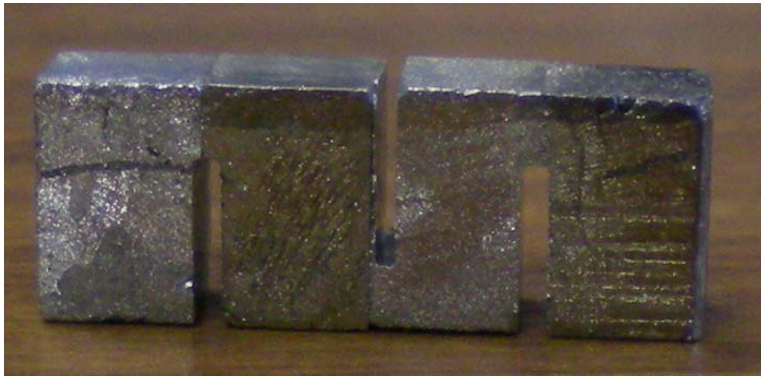
Ground
50µm sieve
Reground
Ball milled
(110rpm,
3hrs)

50MPa
400ºC
10 minutes

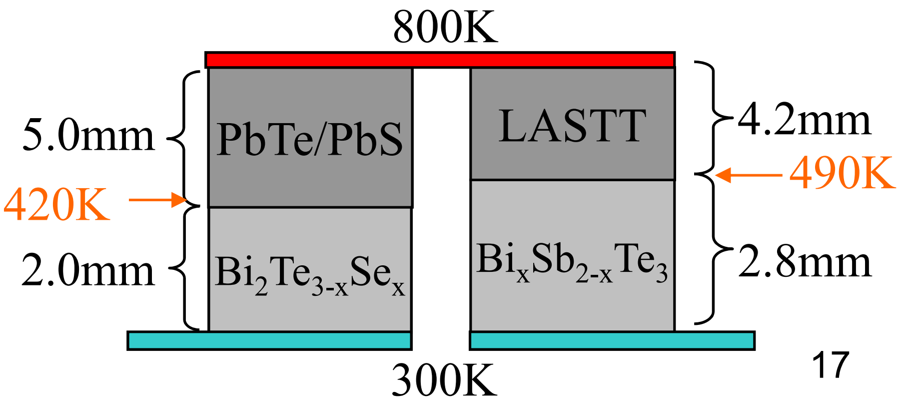
NMSD: Continuing and Future Work

- We will utilize ONR supported SPS system for the fabrication of functionally graded and segmented leg modules.
- We will investigate SnTe, Fe-LAST and direct diffusion bonded contacts for module fabrication.
- Work toward the expected ideal module efficiency > 14% for T_c = 300K, T_h = 800K using high efficiency materials shown below.





Direct bonded LAST-LASTT

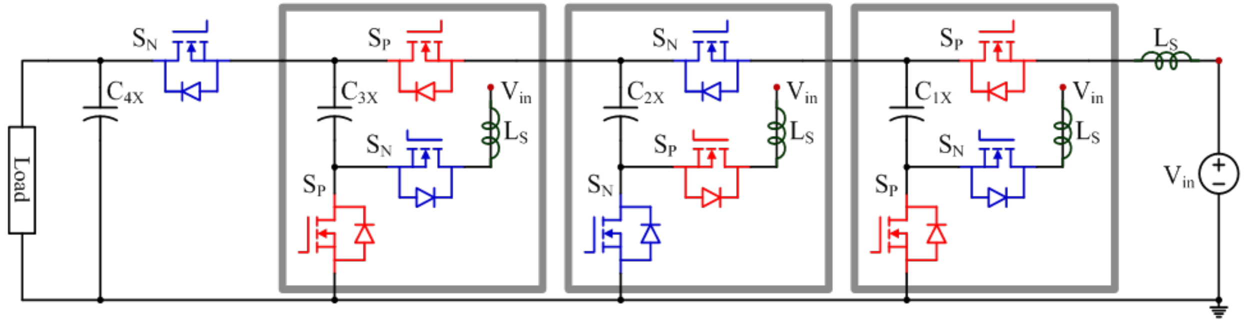


Power Electronics: Accomplishments of Current Year

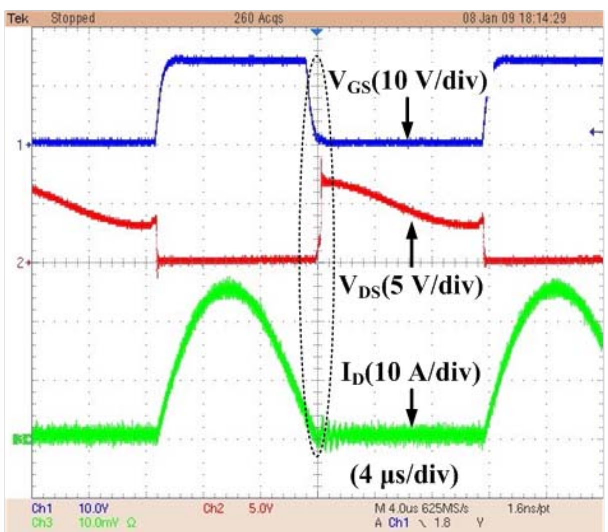
- A novel low input voltage high gain dc-dc converter has been proposed and built.
- Faulty-module bypass and voltage balance circuits have been investigated and simulated.

Specifications & Characteristics of the novel DC-DC Converter prototype:

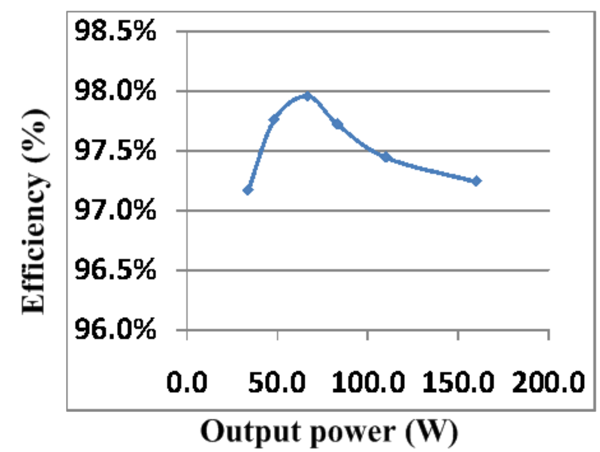
- Input voltage: 5 Vdc;
- Output voltage: 50 Vdc;
- Rated Power output: 1 kW;
- Switching device rating: 24 V, 160 A;
- Switching frequency: 42 kHz;
- Efficiency: ~98%;
- Shared water cooling with TEG module;
- Lower EMI;
- Higher efficiency than the state-of-the-art; 97% vs 90%
- Lower cost;
- Higher reliability;
- Suited for higher power rating;
- Modular structure;
- Simpler control strategy.



Proposed low input voltage high voltage gain high efficiency dc-dc converter

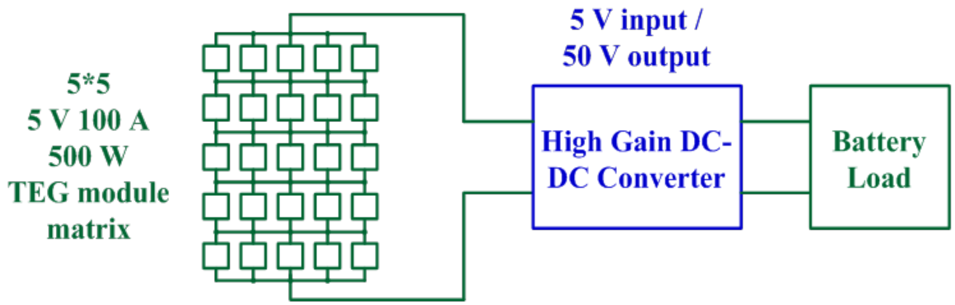


Switch voltage and current waveforms with soft switching characteristics of proposed converter prototype

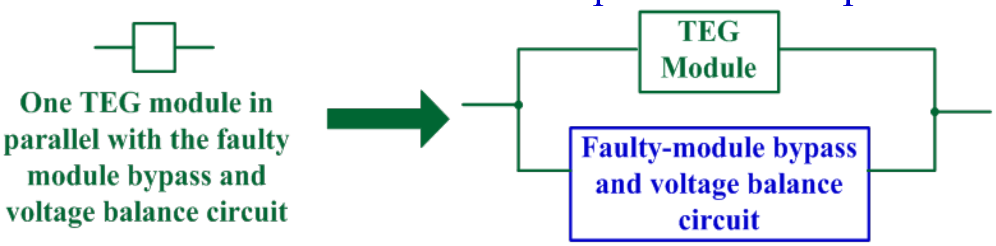


Measured efficiency of proposed high-gain dc-dc converter prototype

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

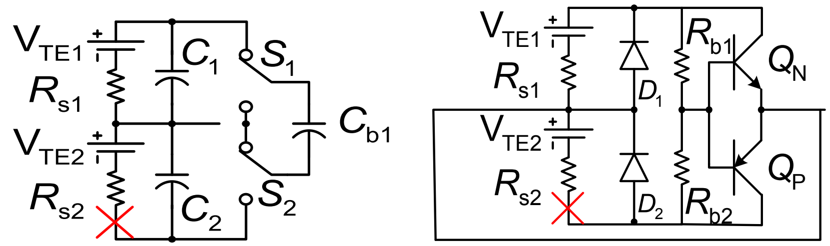


➢ A high efficiency low voltage input high gain dc-dc converter is needed for TEG module matrix to output maximum power.



➢ 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.**

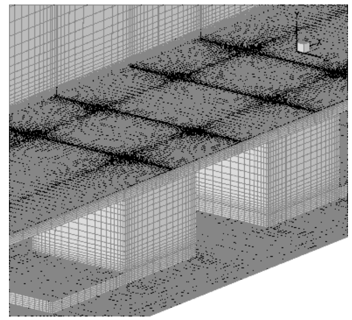
Future Plan:

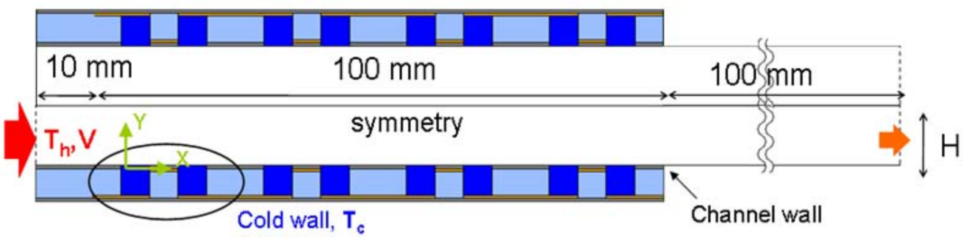
- ➢ **Full power (1 kW) operation of proposed dc-dc converter prototype will be tested.**
- ➢ **Low cost faulty-module bypass and voltage balance circuit will be proposed and proved of concept.**
- ➢ **Power electronics circuits will be built and tested for the integration and demonstration in the 500W TEG beign constructed at MSU.**

Heat Transfer Studies: Accomplishments in 2008-09

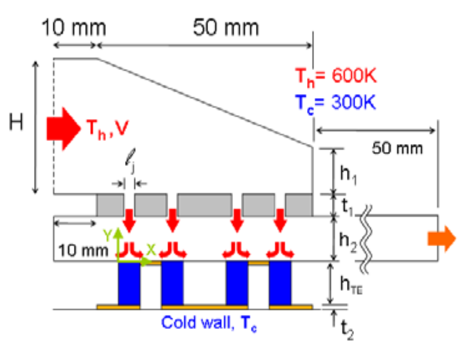
Developed and evaluated two HX concepts:

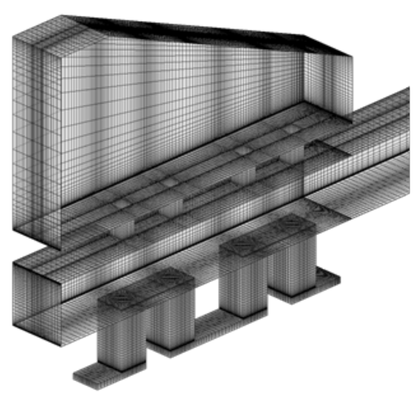
- starting boundary layer: can yield up to 1 W/cm²

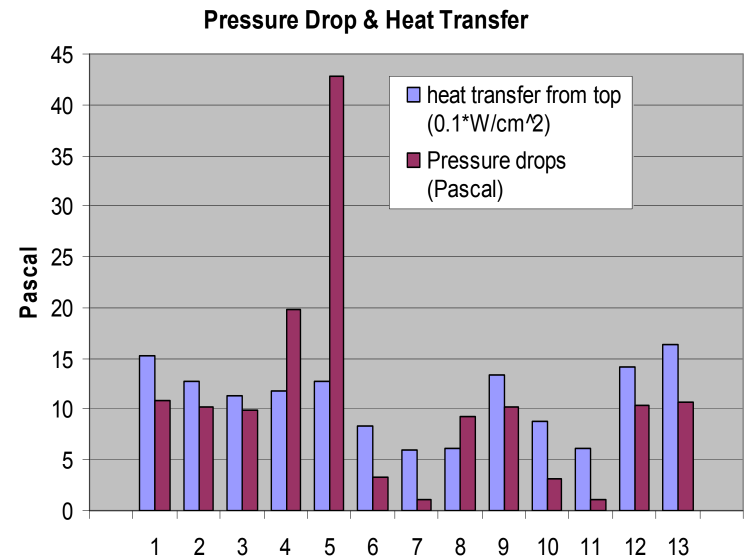


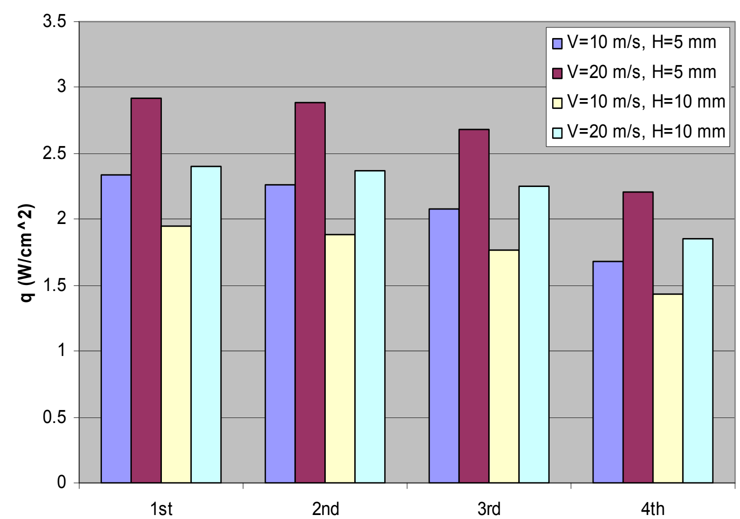


- jet impingement: can yield up to 3 W/cm²

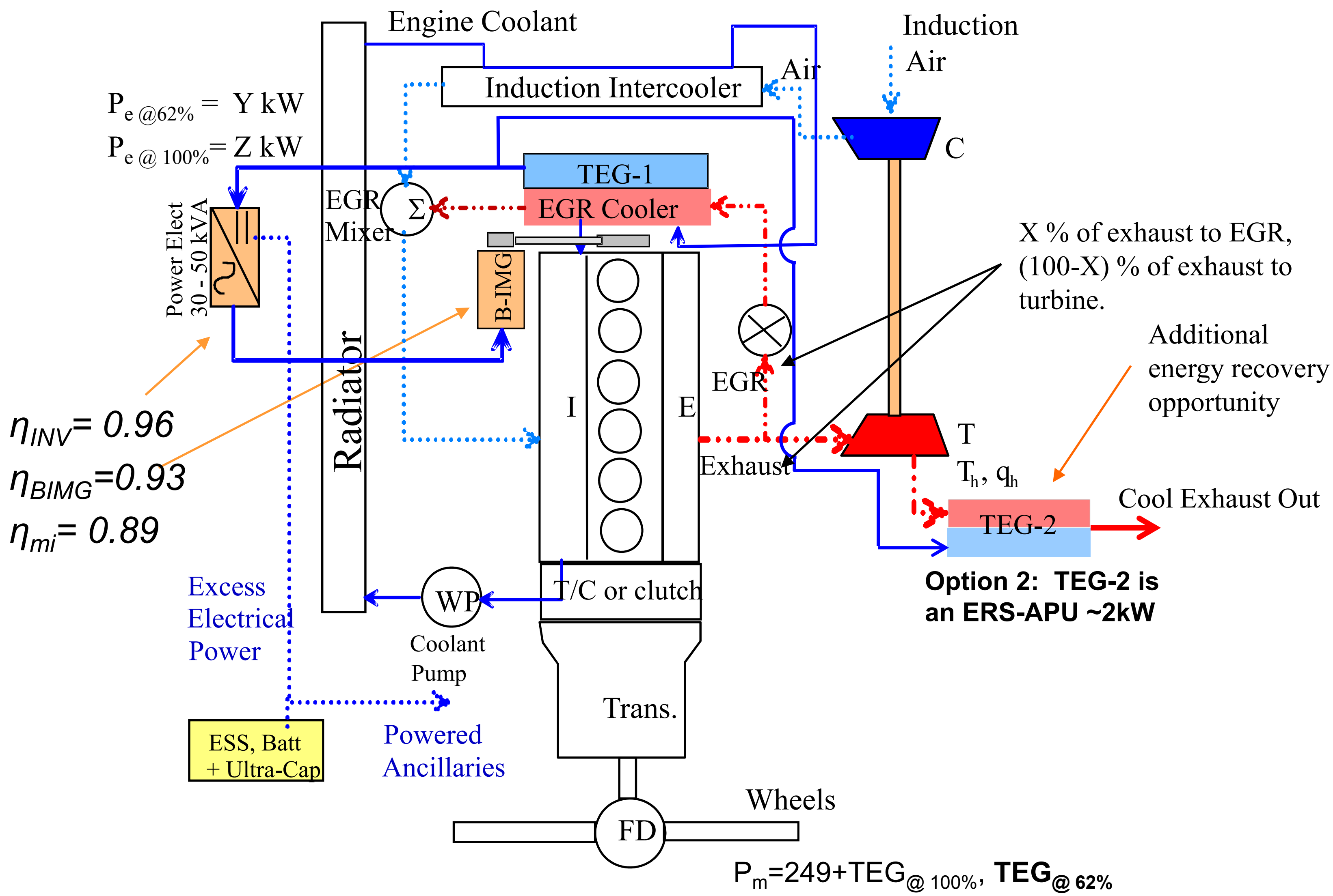






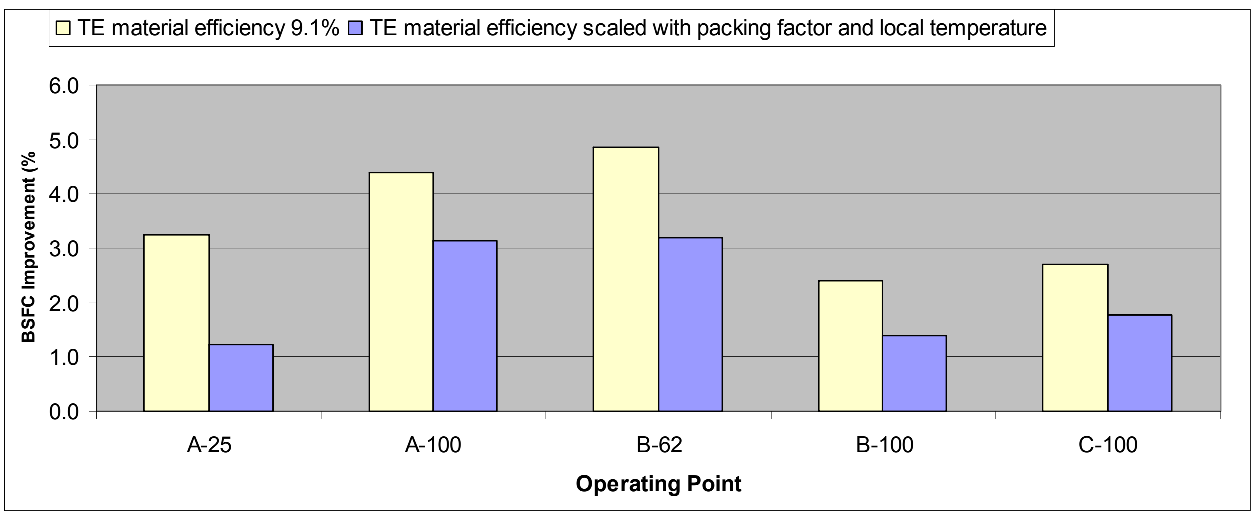


Efficiency Improvements: Option 1: Thermal Power Split Hybrid, Option 2: Energy Recovery System-Auxiliary Power Unit (ERS-APU)



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



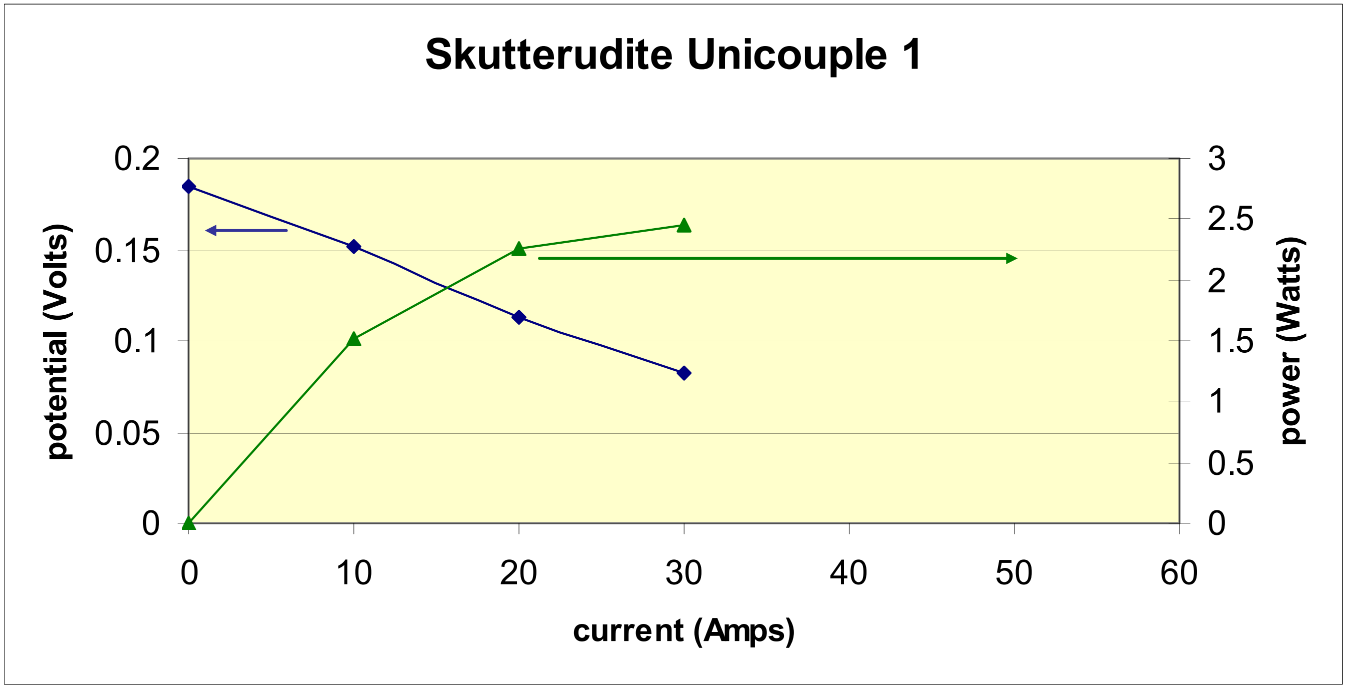
Analysis of Implementing Option 2: ERS-APU for Waste Heat Recovery and Idle Reduction for a Class 8 OTR Truck

- **Assumptions**
  - 2kWe APU operating on diesel fuel $4/gal, 5MPG base fuel economy, 5% energy recovery efficiency engine exhaust energy recovery with belt integrated motor-generator, 10% electrical energy conversion efficiency when operating as an APU (high temp, 0.492 gal/hr.), operates 300 days per year (14 hours on road and 8 hours with APU in operation, 250K miles per year)
- **Savings Calculation**
  - From Waste Exhaust Heat: (250000 mi. per yr./5 mi per gal)-(250000mi./(5 + 5(.05))mi per gal))=397 gal/yr fuel savings
  - From Idle Reduction: (0.829[1] gal per hr engine – 0.492 gal per hr for TE APU)(8hrs. Idle per day)(300 days per year)=808 gallons per year fuel savings
- **Total Savings**
  - (397 + 808 gal/year) ($4/gal)=$4828 per year or $19280 over 1 M mile life of engine
- **Other 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

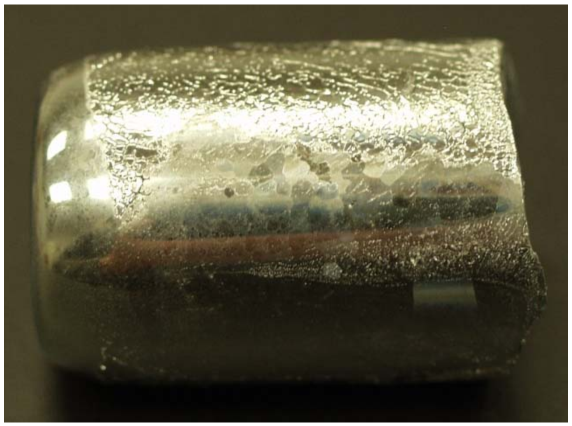
[2] Roadmap and Technical White Papers, USDOE-EERE, 21CTP-0003, Dec. 06

Material Down Selection, Couple and Module Scale-up Progress



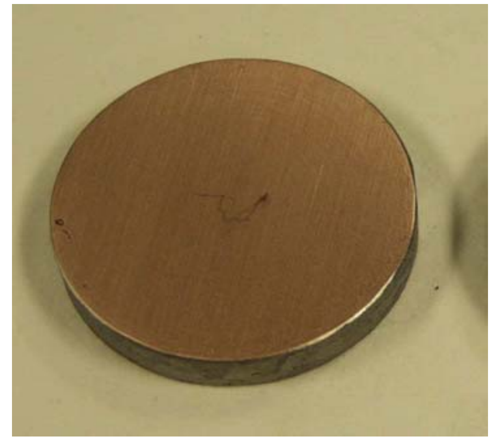
- Unicouple power output ~ 2.5 Watts per 0.67cc of material at ΔT = 600C
- Peak power at ~30 Amps, test limited by power supply current limitations
- Routinely produce hot pressed legs with uniform power characteristics
- As of 3/20/09 Approximately 300 skd. unicouples have been fabricated at MSU

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

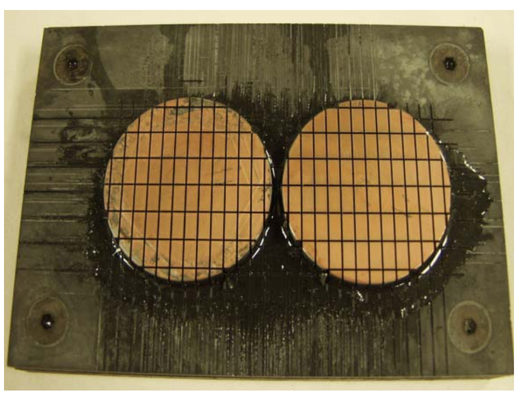


INGOT

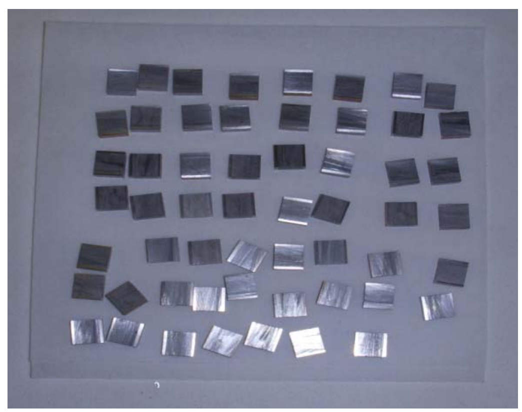
POWDER



HOT PRESSED PUCK



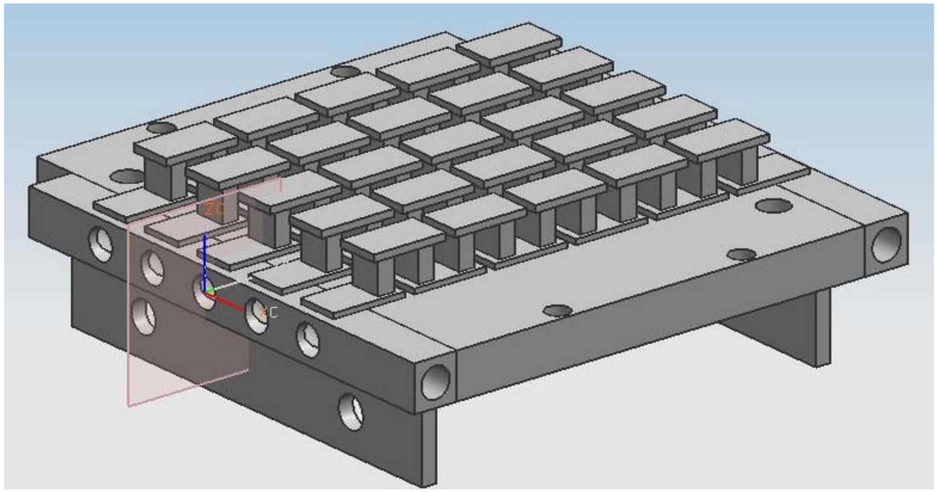
CUT HOT
PRESSED PUCK



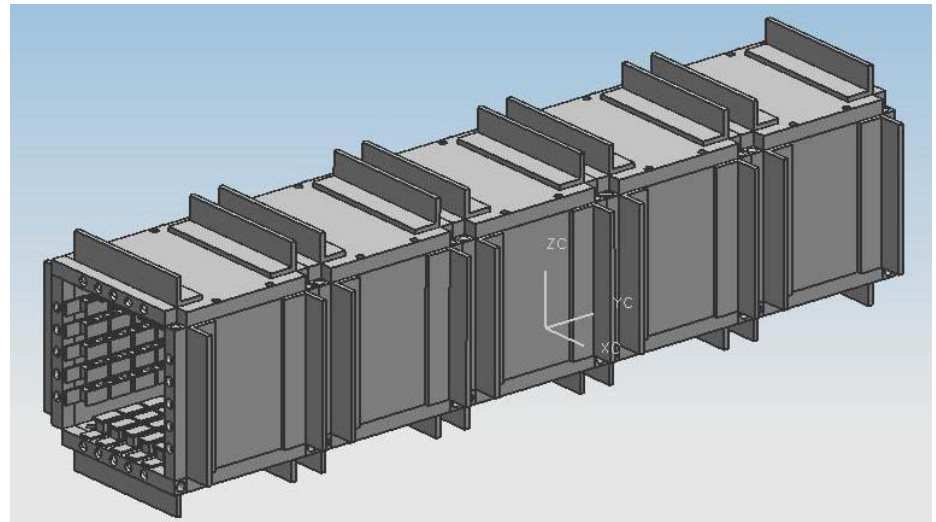
LEGS FROM PUCK
> 95% YIELD

5 COUPLE, 13W -
THEOR. SKD MODULES

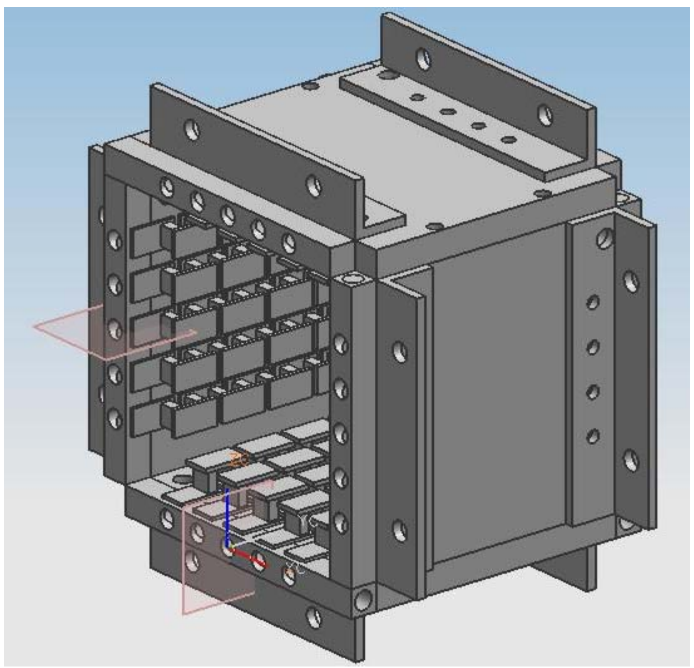
MSU Generation-1 TEG (SKD) Design



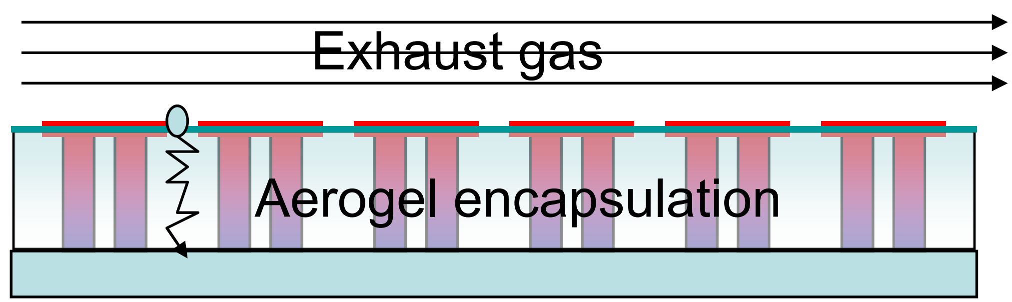
65W (theoretical) section of TEG



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



Section of Generator



Outline of Presentation

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

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 an efficiencies from 11-14 % from 300-830K
  - Routine synthesis of skutterudite legs and modules demonstrated (114 couples every four days possible, 95% throughput efficiency)
- **MSU has reached lab-scale mass production of TE couples**
  - Fabrication of dozens of 2, 4 and 8 leg LAST/LASTT modules
  - Fabricated more than 300 skutterudite couples and numerous modules
- **Skutterudite technology has been selected for the Generation-1 TEG due to efficiency, ability to operate at high temperature and reproducible mechanical and thermoelectric properties**
- **Power electronic modules for voltage boost (η>97%) and fault bypass have been designed and tested at MSU**
- **Temperature dependent elastic moduli and thermal expansion coefficients have been measured for 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 5% improvement in bsfc has been estimated.
  - A new concept, the thermoelectric energy recovery system-auxiliary power unit (ERS-APU) has been proposed.
- **A Generation-1 thermoelectric generator has been designed and is under construction**

Outline of Presentation

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

Future Work: Major Plans for Remainder of Phase 2 Effort

- Feb-June 2009: Construction and testing of first skutterudite based 500 watt thermoelectric generator including power electronic controls
- March-June 2008: Complete scale-up and metallization of advanced skutterudite formulations which have been demonstrated
- March-August 2009: Construct and evaluate performance of PbTe-PbS, LAST/T and segmented systems using spark plasma sintering and other methods
- August 2009: Demonstrate second iteration of Gen-1 system with advanced skutterudite materials
- April-August 2009: Develop with Cummins the design and plans for a powertrain demonstration (Phase 3 and 4) of an advanced material Gen-2 waste heat energy recovery system-auxiliary power unit (ERS-APU). System to be tested at MSU's Heavy Duty Vehicle Laboratory
- May-September 2009: Complete design of Generation-2 ERS-APU

Outline of Presentation

- Overview
- Objectives
- 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 materials required for a 500 watt TEG in one month (1.3 W per unicouple @ ΔT=600C, 114 unicouples per 4 working days)
- Power conditioning electronics have been designed, tested and are being prepared for the Gen-1 TEG demonstration
- High heat flux head exchanger designs critical to success of practical TE waste heat recovery systems are being designed
- Using TEG technology, a 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
- Plans for Phase 3 and 4 proof-of-prototype ERS-APU testing on a diesel powertrain will be finalized by Aug. 09