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

Prepared by:

Harold Schock, Larry Brombolich, Eldon Case, Charles Cauchy, Tim Hogan, Mercouri Kanatzidis, James Novak, Fang Peng, Fei Ren, Jeff Sakamoto, Todd Sheridan, Tom Shih, Ed Timm

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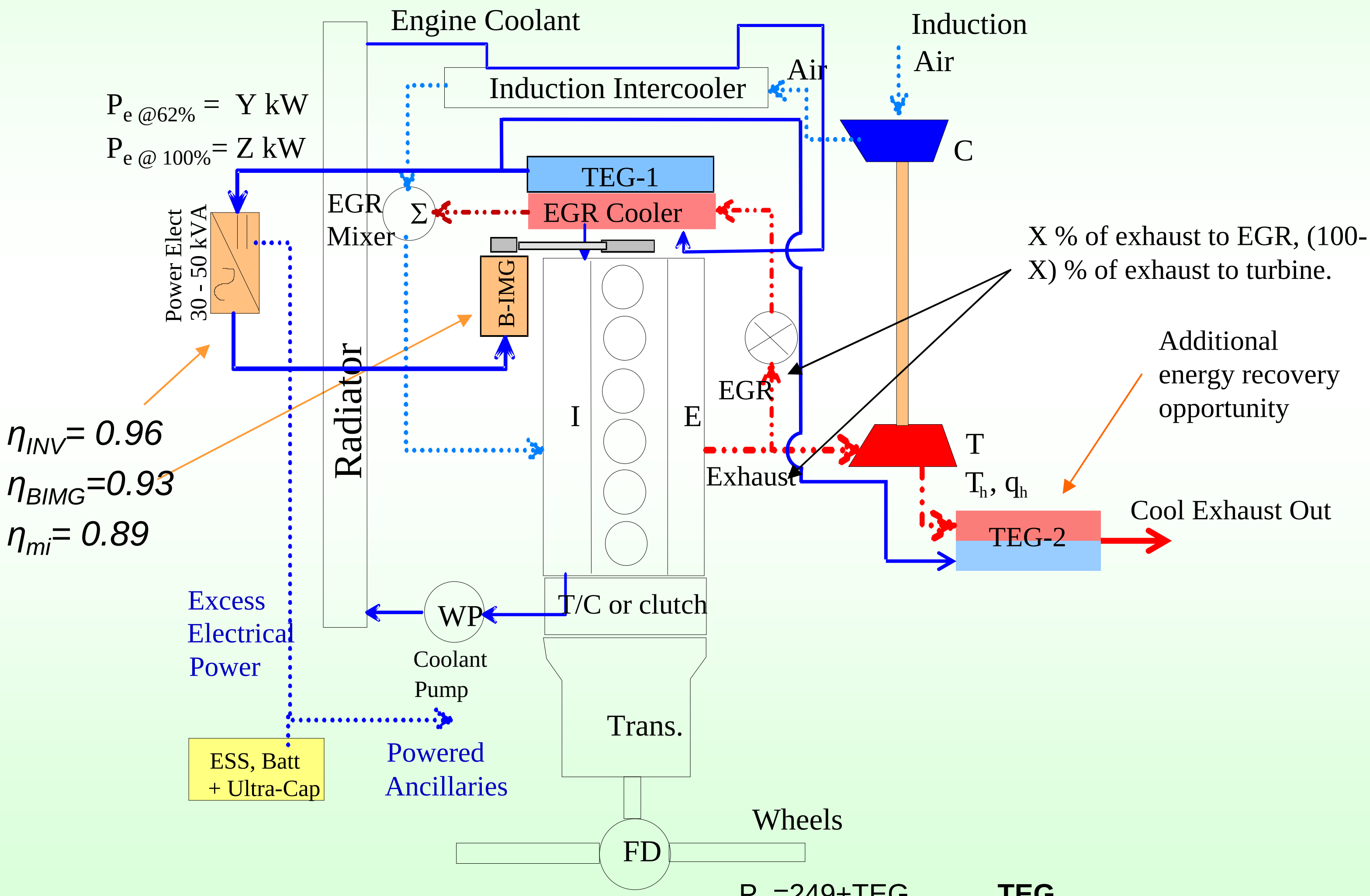
Application: Phase 2, Determine the Feasibility of Constructing a Thermal Power Split Hybrid Using the Electric Power Recovered from Waste Heat



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

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

Phase 3 - Single cylinder +TEG Demo
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/NU

- Generator design
- TEG materials selection
- Mechanical and TE material property characterization including Weibull analysis
- FEA analysis
- Leg and module fabrication methods
- 1 kW TEG demonstration in Phase 2

Previous Review Comments and Response

1# Relevance to Overall DOE Objectives:

b. One of the team's goals is to evaluate thermoelectric materials. Other than the LAST-m, there is no effort shown on alternative materials, and the original claimed properties of LAST-m were not realized.

The original claims of 1.7 at 700 K for LAST-18 were realized in small batches. The problem, however with this material, is its incredibly complex melt-crystallization chemistry, which is completely understood and results in repeatability problems. Another complication is its weak mechanical properties, which are also traced to the melt-crystallization chemistry.

The Northwestern group has been investigating two alternative materials systems as back up systems, which are not LAST-m based and have simpler chemistry. One is the PbTe-PbS system and the other is the PbTe-CdTe system. Both are n-type and have ZT~1.6 at 700 K (same as LAST-18). The reason for the high ZT in these systems is similar to that in LAST, i.e. good nanostructuring in the bulk material that gives rise to a very low thermal conductivity. There are several apparent advantages of these two materials systems compared to LAST.

- They are simpler in composition and they have more easily controlled chemistry than LAST.
- Repeatability of properties is significantly better.
- The chemical process required to prepare them is 50% shorter than that of LAST (allowing greater productivity of material).
- The cast ingots that are produced are stronger and have fewer mechanical problems that arise from micro-cracks.
- They appear to be scalable to 100-200gr batch preparations.

Previous Review Comments and Response, continued

MSU has substantial efforts underway to integrate and develop Skutterudite, TAGS, Bi_2Te_3 segmentation technology. A 16 leg, 40-watt module constructed at MSU, using Skutterudite, is shown in the presentation slides. Our partner, JPL, is also working on further improving Skutterudite ZT as well as metallization.

As for the original claimed properties of LAST-m not being realized, the ZTs in the smaller scale ingots are promising, but transitioning from small-scale ingots to larger-scale hot-pressed pucks requires further work. It seems that the smaller ingots have higher reproducible ZTs than the hot-pressed pucks, which are prepared from larger ingots. This transition can be rather involved and requires further development. Skutterudite, TAGS and Bi_2Te_3 are a bit further along in this regard, thus the ZTs of the larger-scale hot pressed pucks are in better agreement with the smaller experimental size batches.

Previous Review Comments and Response, continued

1# Relevance to Overall DOE Objectives:

c. The summary slide indicates the author's team will not meet the DOE 10 percent fuel economy improvement goal. The conclusion was it may be possible with a new thermoelectric material, but who will develop that? Isn't that what this research effort is all about?

Northwestern University is developing the alternative PbTe-PbS and PbTe-CdTe materials in small batches with scale up to occur at MSU and eventually Tellurex. ZT values of 1.8 at 800 K are expected in 2008 (small cast samples). The efforts using Skutterudite, TAGS, and Bi_2Te_3 segmented legs are also underway at MSU and JPL. Progress will be closer to incremental rather than a quantum leap. With respect to material issues, our plan is to ensure steady progress on current, mature systems while conducting a small effort on new systems. These new system efforts compliment work being funded by ONR and others.

On this Phase 2 project our group:

•Studies the physics and develops materials for new TE Systems

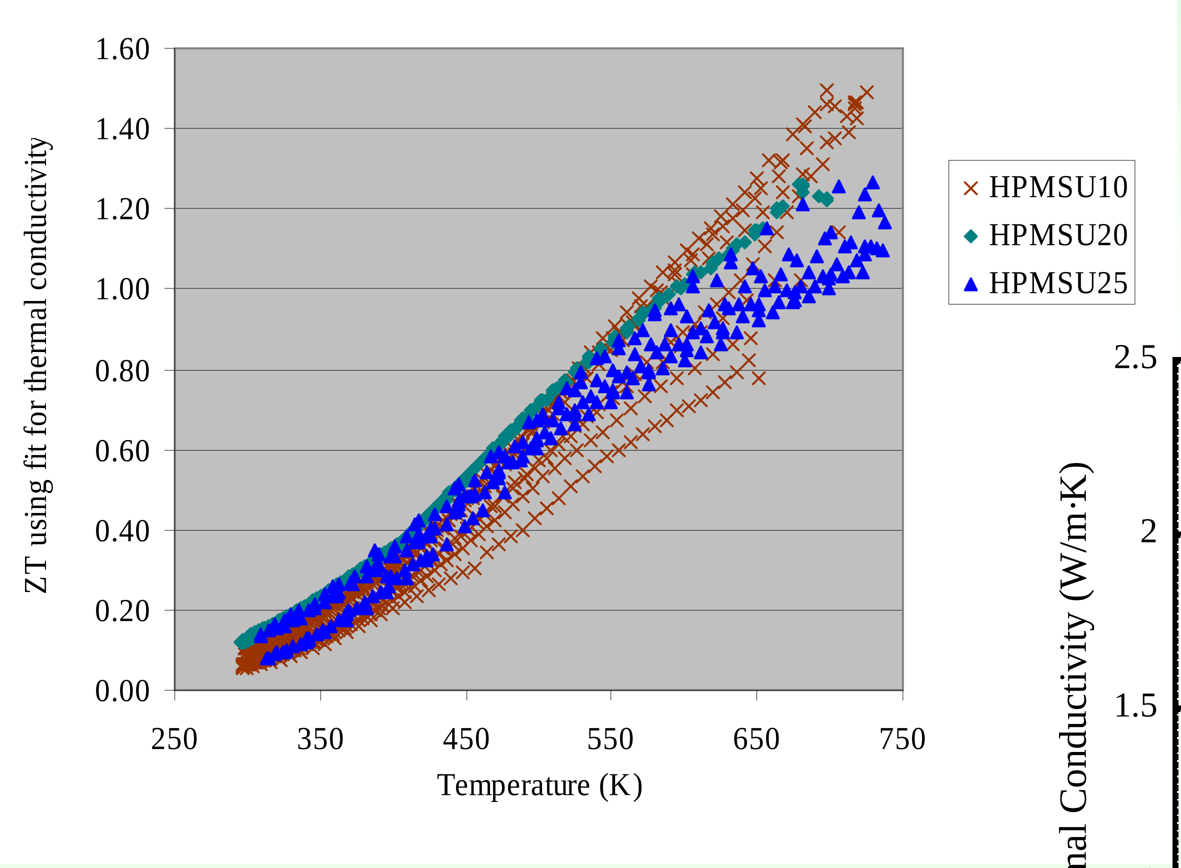
•Scales up the material synthesis, powder production and hot pressing

•Thermoelectrically and mechanically characterized cast and hot pressed materials

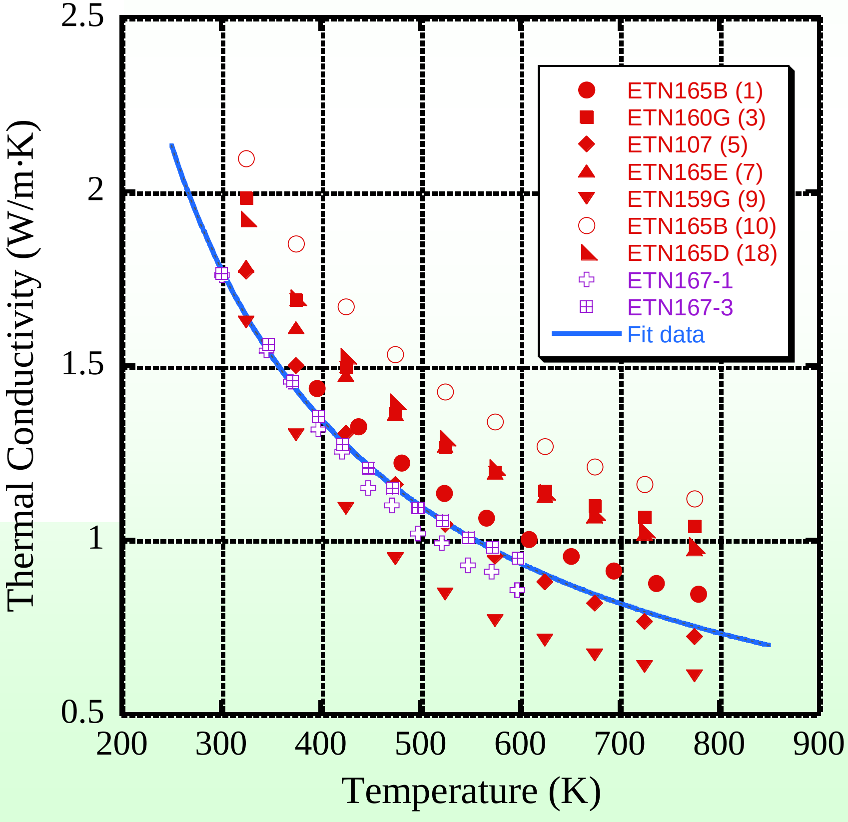
•Designs, fabricate modules, heat exchangers, power electronics and TEG systems

•Evaluates performance of TEG systems in a powertrain numerically in Phase 2 and in a scaled engine demonstration in Phase 3

ZT for Hot Pressed LAST Samples
(Thermal Conductivity Values from Cast Samples)



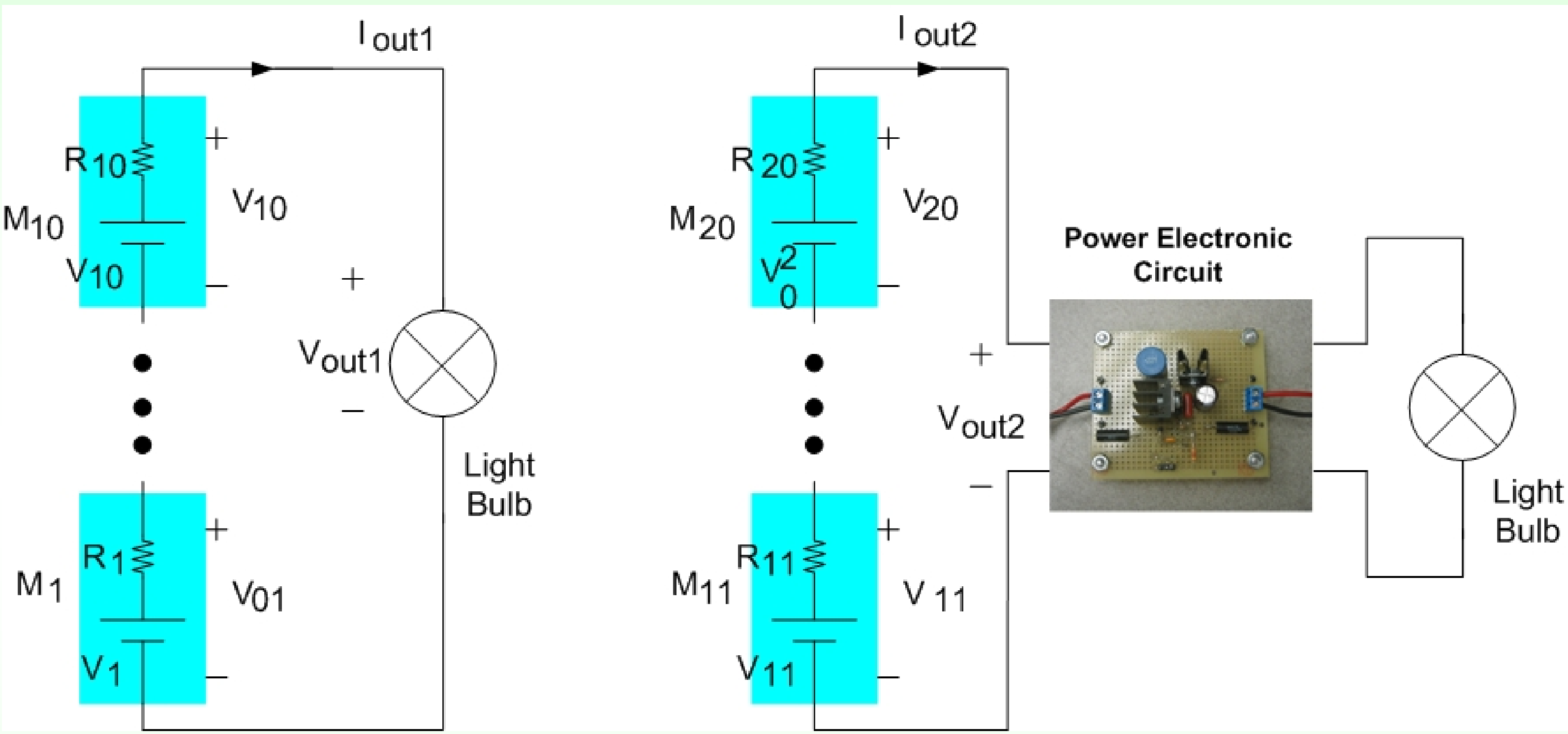
$$\kappa = 0.15283 + \frac{449.54}{T} + \frac{11337}{T^2}\left(\frac{\mathrm{W}}{\mathrm{m}\cdot\mathrm{K}}\right)$$



Performance Measures and Accomplishments: Some Specifics

- **Power Electronic Controls**
- Mechanical Strength Module Design and Fabrication
- Heat Transfer Issues
- Performance Calculations

Test Setup & Condition

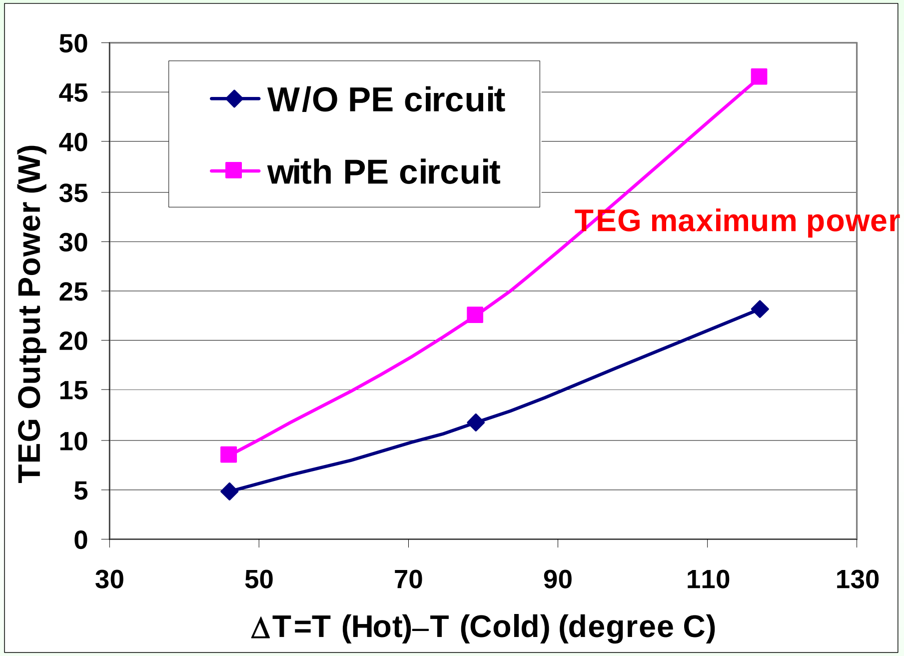


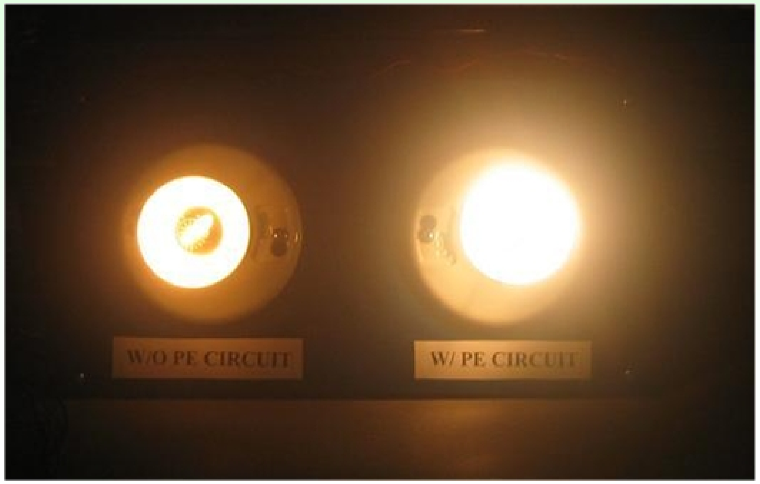
Set 1: Without PE Circuit **Set 2: With PE Circuit**

Set 1 is directly connected to a 50 W light bulb;
Set 2 is connected to a 50 W light bulb
via the power electronic circuit.

Demo and Test Results of the PE Circuit for Maximum Power Point Tracking

TEG output electric power vs ΔT





W/O PE circuit   With PE circuit

The PE circuit can extract the maximum electrical power from the TE modules and feed any electric loads regardless of TE module's heat flux and load impedance/conditions. They can also isolate failed modules provide appropriate series / parallel connections.

Performance Measures and Accomplishments: Some Specifics

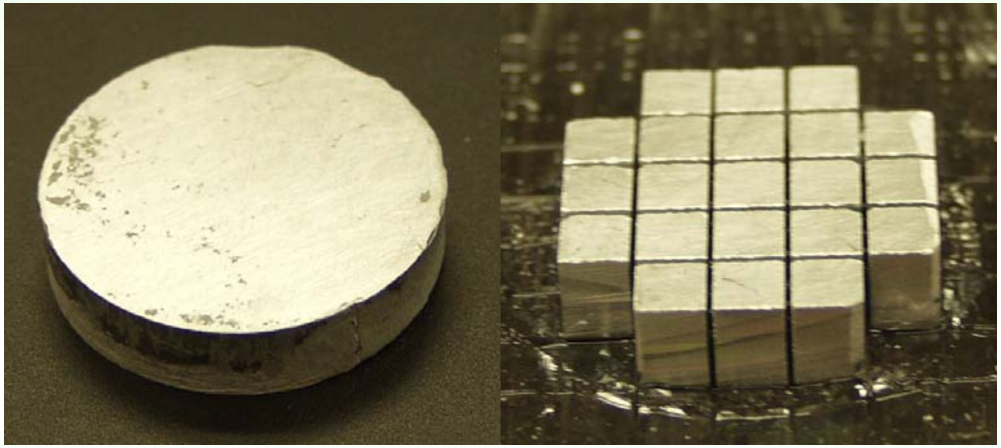
- Power Electronic Controls
- **Mechanical Strength Module Design and Fabrication**
- Heat Transfer Issues
- Performance Calculations

MSU Hot Press

- March 10th 2006:
  press ordered
- January 4th 2007:
  press arrived at MSU
- January 23rd 2007:
  press up righted and moved into location
- January 24th – February 2nd:
  electrical and water installed
- February 5th – 9th:
  TTI technician assists with final installation of components
- March 7th:
  Initial hot press run

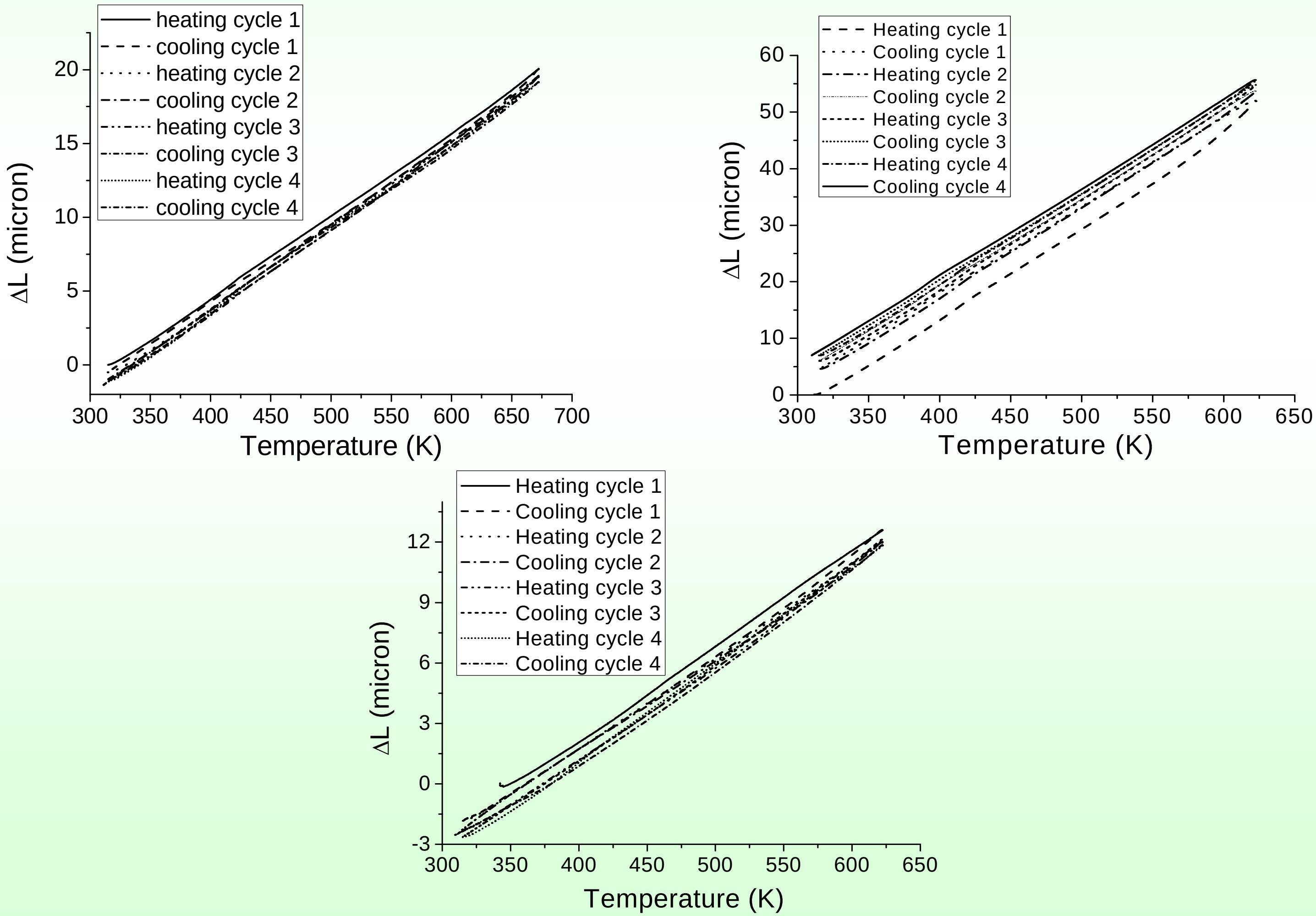
Ingot Synthesis and Hot Pressing at MSU

HPMSU-01



Since HPMSU-01, 10Kgs of TE Material Synthesized During Past Year (50 ingots, up to 10 days per ingot) and 40 Hot Press Runs

Dimensional Change as a Function of Temperature as Determined by TMA for (A) the Ingot LAST Specimen N155 (Ag0.86Pb19Sb1.0Te20), (B) the Hot Pressed LAST Specimen MSUHP20 (Ag0.86Pb19Sb1.0Te20), and (C) the Hot Pressed LAST Specimen MSUHP6 (Ag0.43Pb18Sb1.2Te20)



Room Temperature Values of Hardness, H, Young's Modulus, E, and Poisson's Ratio, ν, from the Literature and from Work Done at MSU for Selected Thermoelectric (Wide Band Semiconductor) Materials and Common Narrow Band Semiconducting Materials

Material	H (GPa)	E (GPa)	ν
Si	9 [1]	163 [2]	0.22 [2]
Ge	9.2 [3]	128 [3]	0.21 [4]
GaAs	6.52 [5]	117 [3]	0.24 [3]
PbTe	0.34 [6] - 0.45 [7]	58 [8]	0.26 [9]
LAST, LAST-T	0.53 - 0.96 [10]	24.6-71.2 [11]	0.24-0.28 [28]
ZnSe	1 [12]	76.1 [13]	0.29 [13]
Zn_4Sb_3	2.24 [14]	57.9-76.3 [15]	
Bi_2Te_3	0.25-0.68 [16]	40.4-46.8 [17]	0.21-0.37

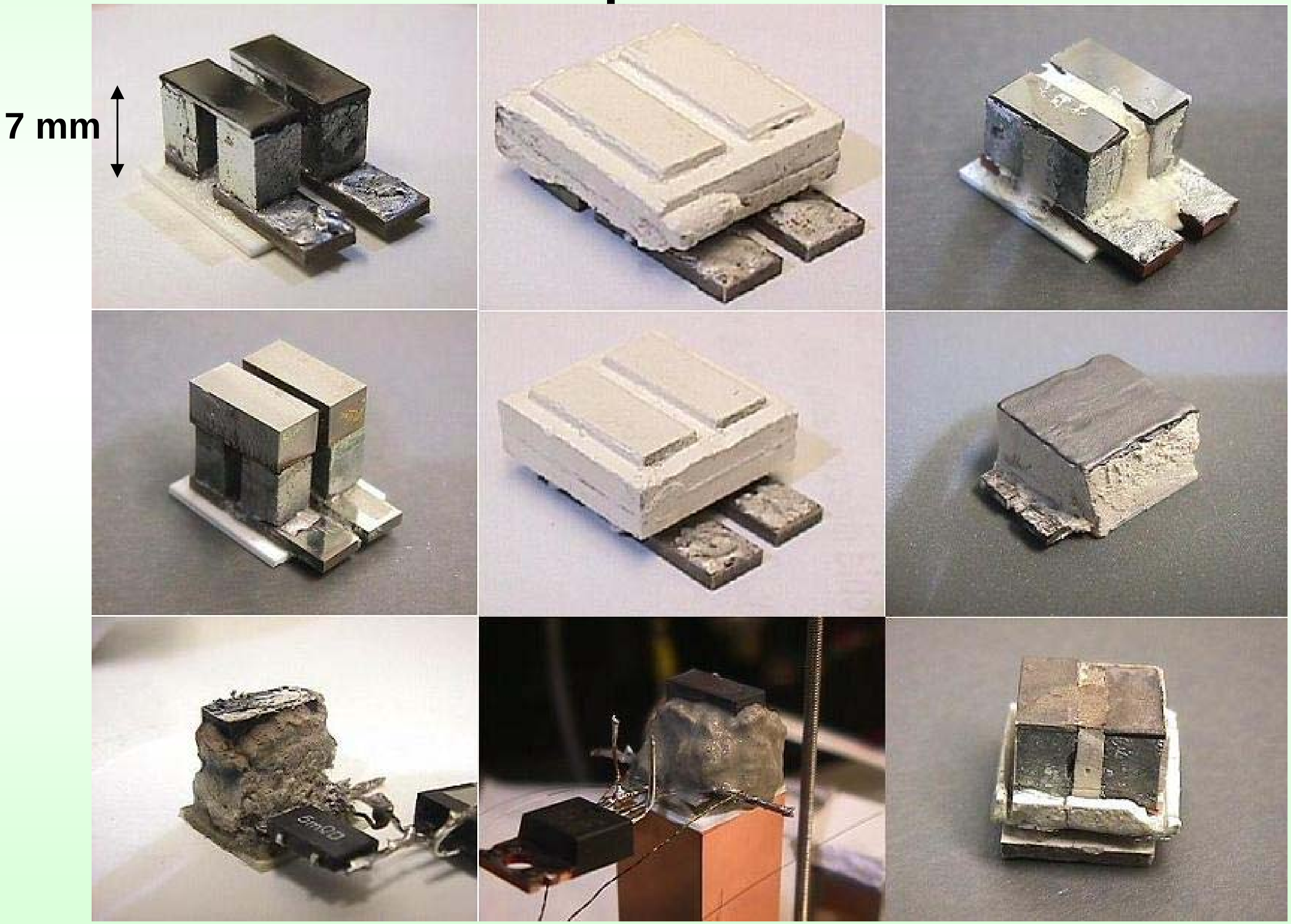
Room Temperature Values of Fracture Toughness, K_c, Fracture Strength, σ_f, and Linear Coefficient of Thermal Expansion, CTE, from the Literature and from Work Done at MSU for Selected Thermoelectric (Wide Band Semiconductor) Materials and Common Narrow Band Semiconducting Materials

Material	K_c (MPa-$m^{0.5}$)	σ_f (MPa)	CTE (10^{-6}/K)
Si	0.7 [1]	247 [9]	2.7 [29]
Ge	0.6 [3]	231-392 [4]	6 [30]
GaAs	0.46 [5]	66 [18]	6.86 [19]
PbTe			19.8 - 20.4 [20]
LAST, LAST-T		15.3 [21] - 51.6	20.4 [28]
ZnSe	0.9 [22]	~60 [23]	8.5 (293-573 K) [24]
Zn_4Sb_3	0.64 [15]-1.49 [14]	56.5 [15] - 83.4 [25]	
Bi_2Te_3		8 [26]-166 [27]	14.4 (⊥)*, 21.3 (∥) [20]

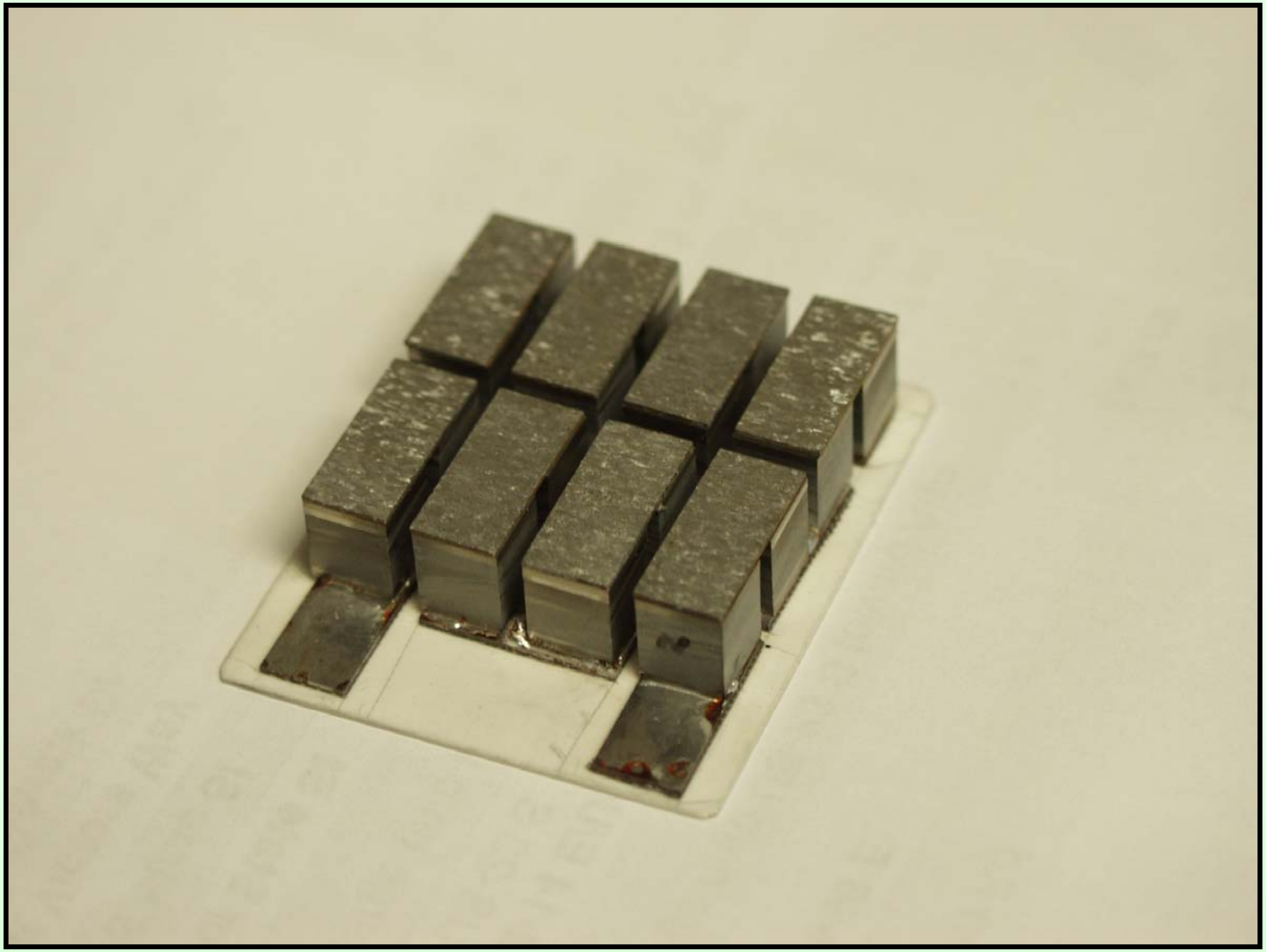
•The symbols ⊥ and ∥indicate directions that are perpendicular and parallel, respectively, to the c axis of Bi_2Te_3.

LAST/T Module Fabrication

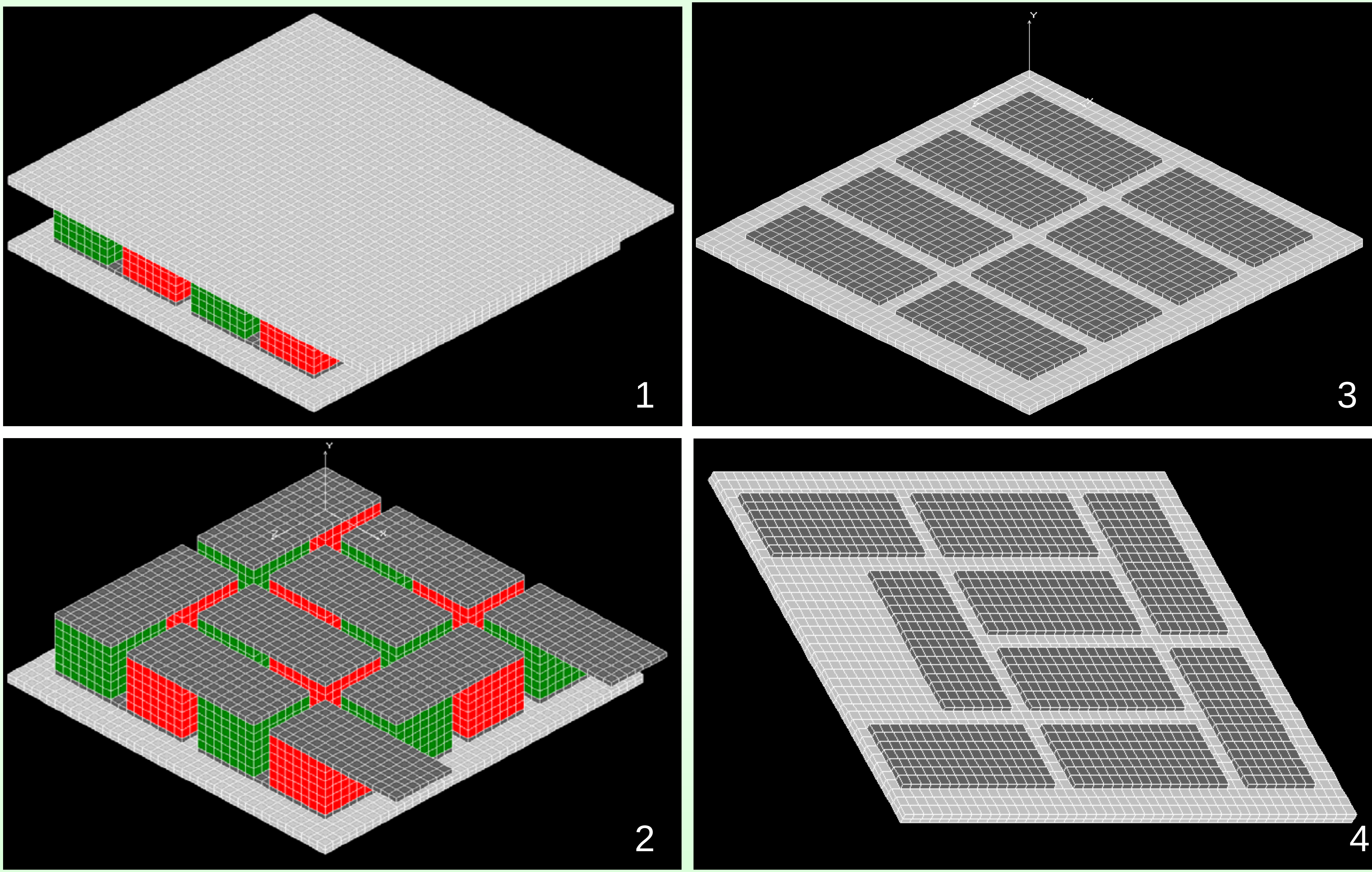
Example Modules



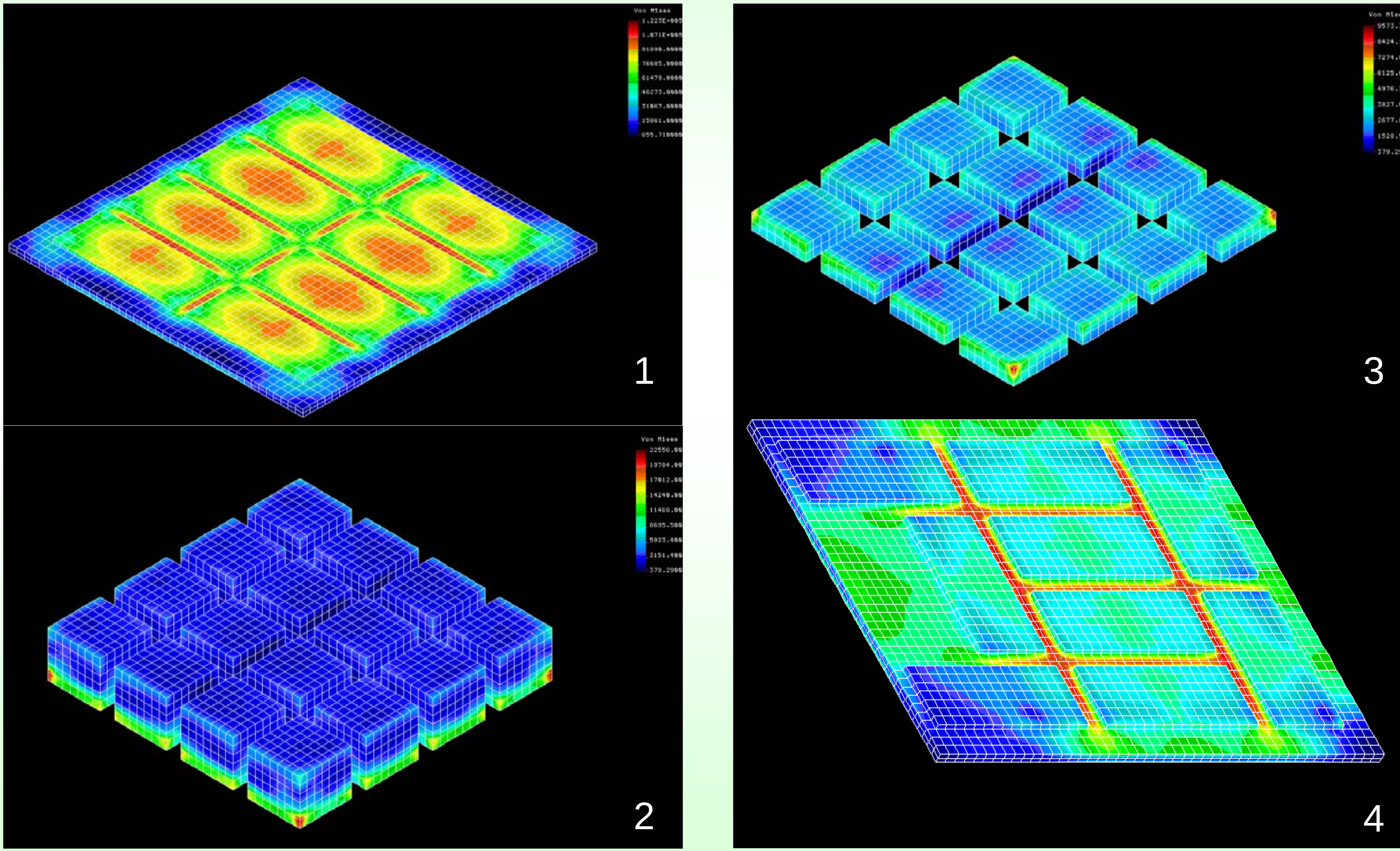
16 Leg Skutterudite Module Fabricated at MSU
(40 Watts @ Δ T = 700C)



FEA Model of 16 Leg Module



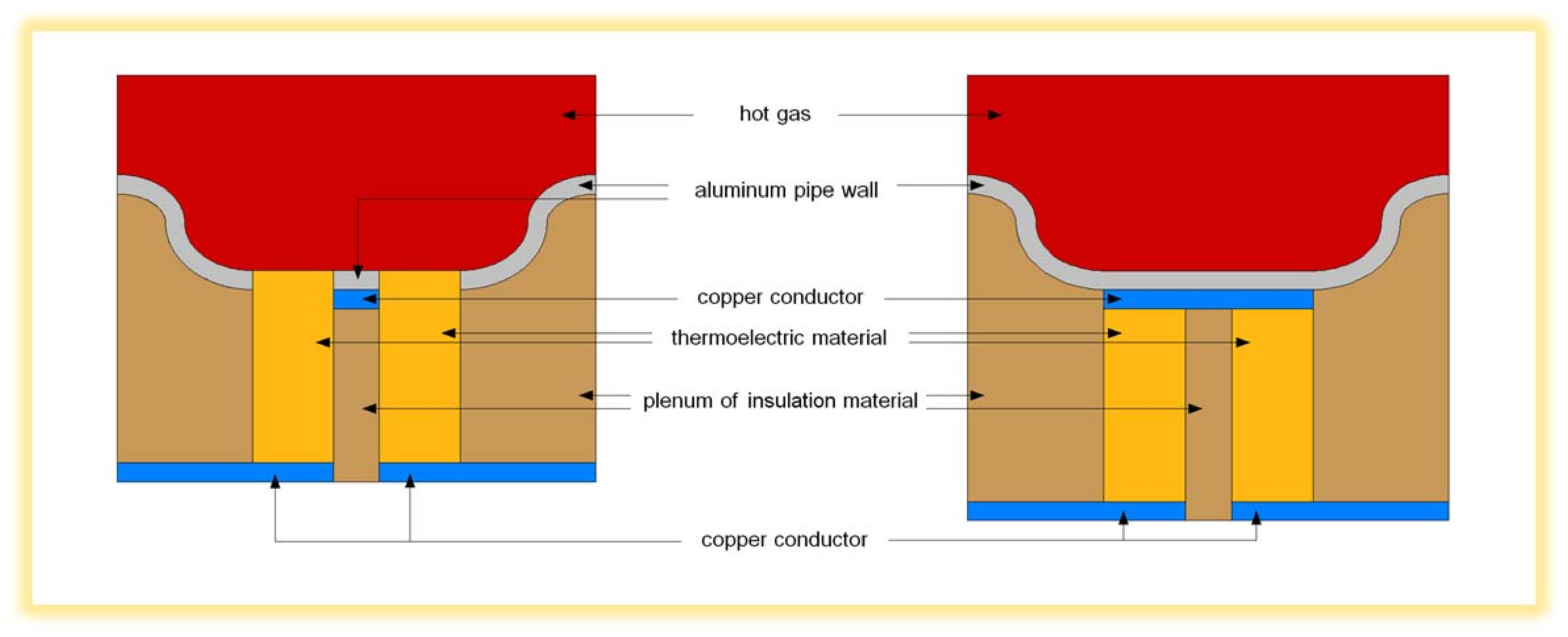
Example of Stress Distribution in 16 Leg Module (300K - 800K)



Performance Measures and Accomplishments: Some Specifics

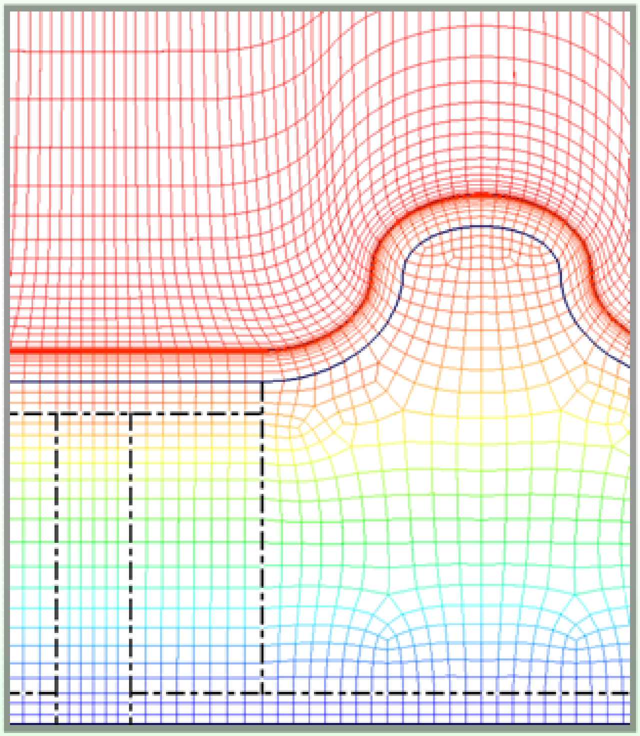
- Power Electronic Controls
- Mechanical Strength and Module Design and Fabrication
- **Heat Transfer Issues**
- Performance Calculations

Right - Traditional Design (TE Couple Sandwiched by the Hot and Cold Surfaces). Left - New Design (TE Couple Structurally Disconnected from the Hot Side but Connected Thermally)

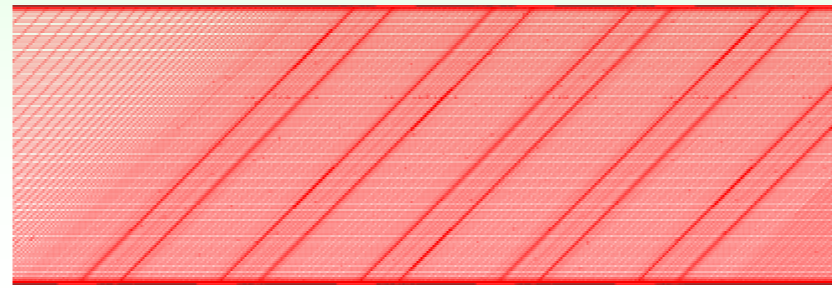


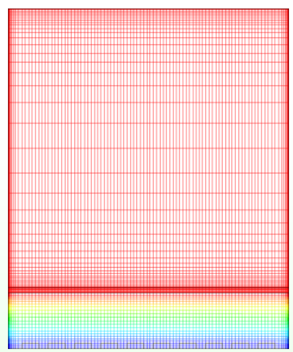
Grid System: Design 1

Side view

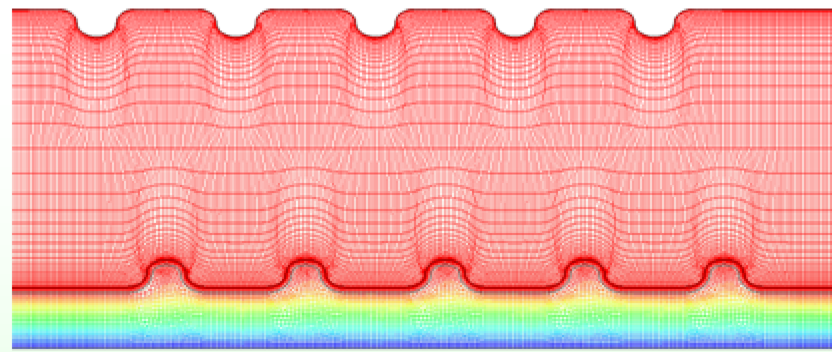


Top view





Front view



Side view

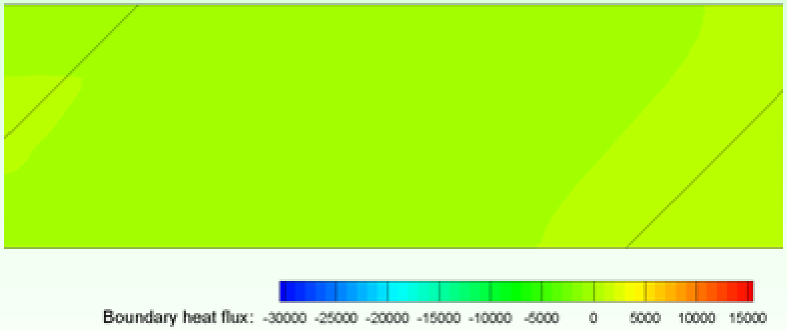
3.63M cells, y^+ of 1st grid < 1 (0.02 mm)

Results: Summary of Cases

Case	TE Design	Smooth/Ribs	Contact between pipe and conductor	Grid Points
1	Design 1	Smooth	N/A	2,826,428
2	Design 2	Smooth	Fully contact	2,738,534
3	Design 2	Smooth	Isolated	2,738,534
4	Design 1	Ribs	N/A	3,628,902
5	Design 2	Ribs	Fully contact	3,829,882
6	Design 2	Ribs	Isolated	3,829,882

Surface Heat Flux on Hot-Gas Side

1



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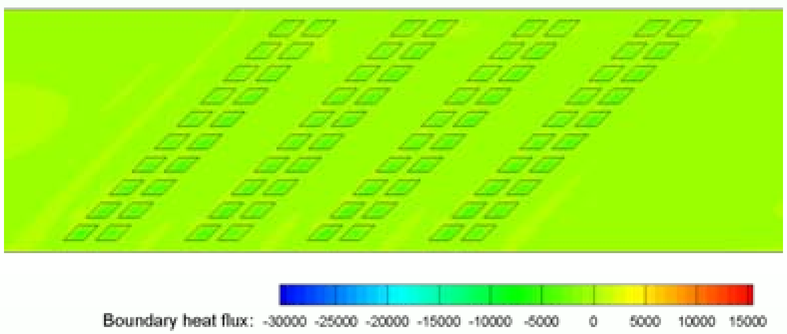

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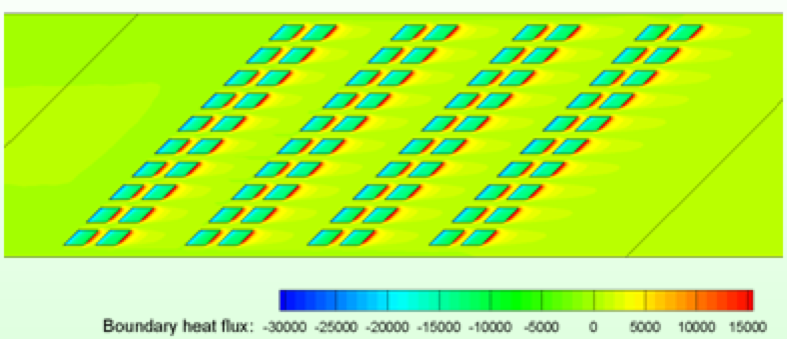

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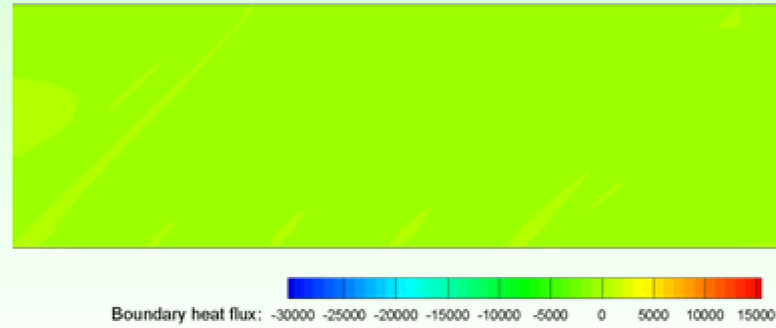

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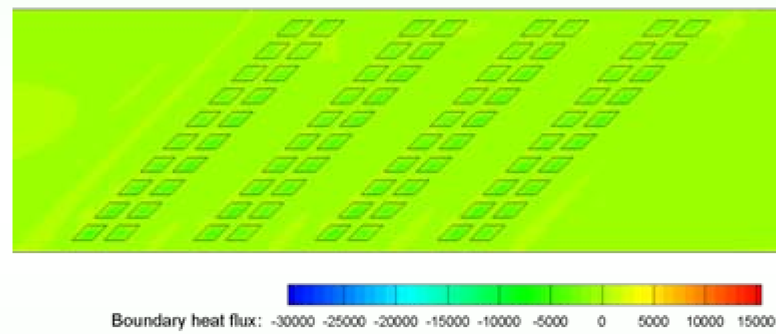

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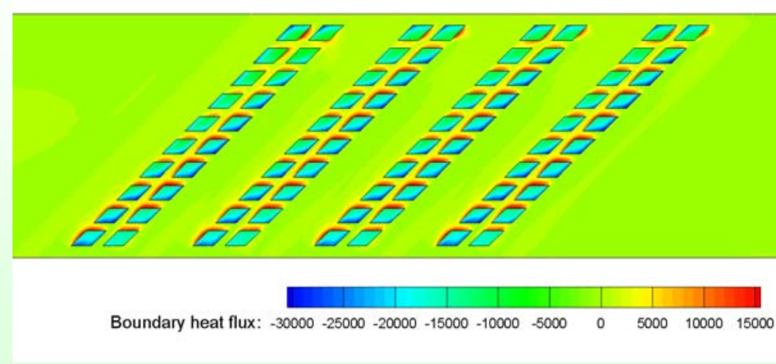
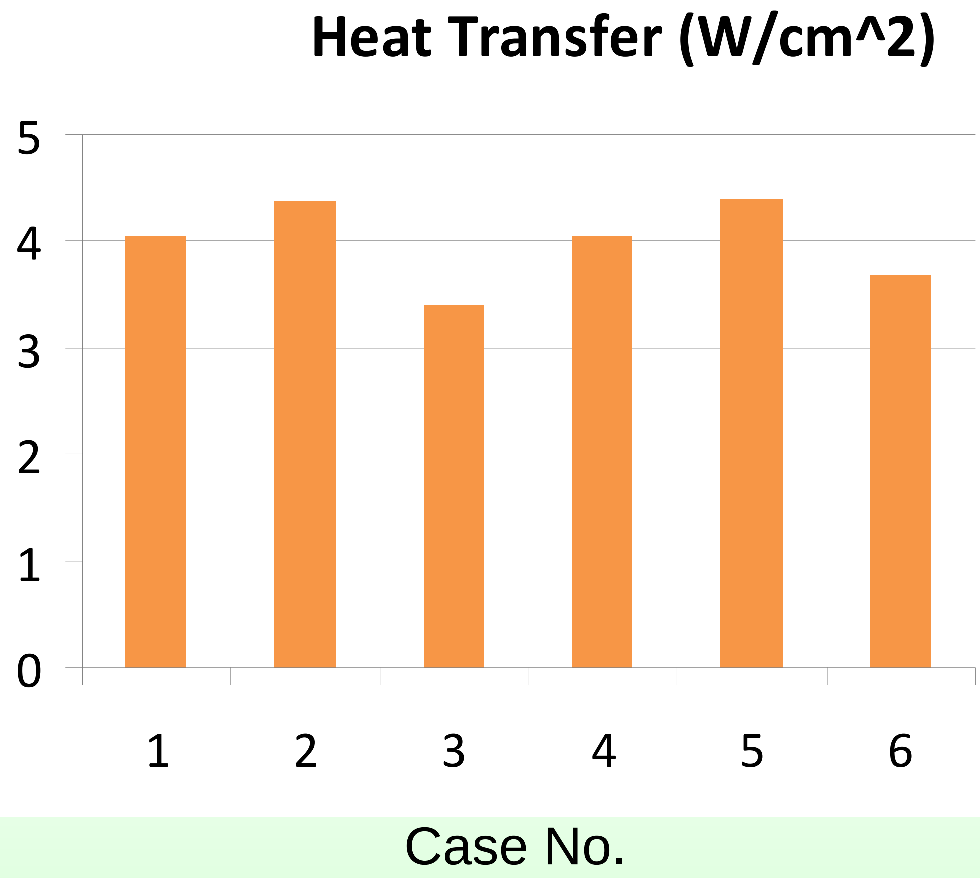


Average Heat Transfer Rate Per Unit Area Through TE Legs



Design 1: cases 1 (no rib), 4 (rib) Design 2: cases 2,3 & 5, 6

Rib did not help much because thermal boundary layer is very thin for the smooth wall. But, for fully developed thermal boundary layer, the enhancement can be up to 4.

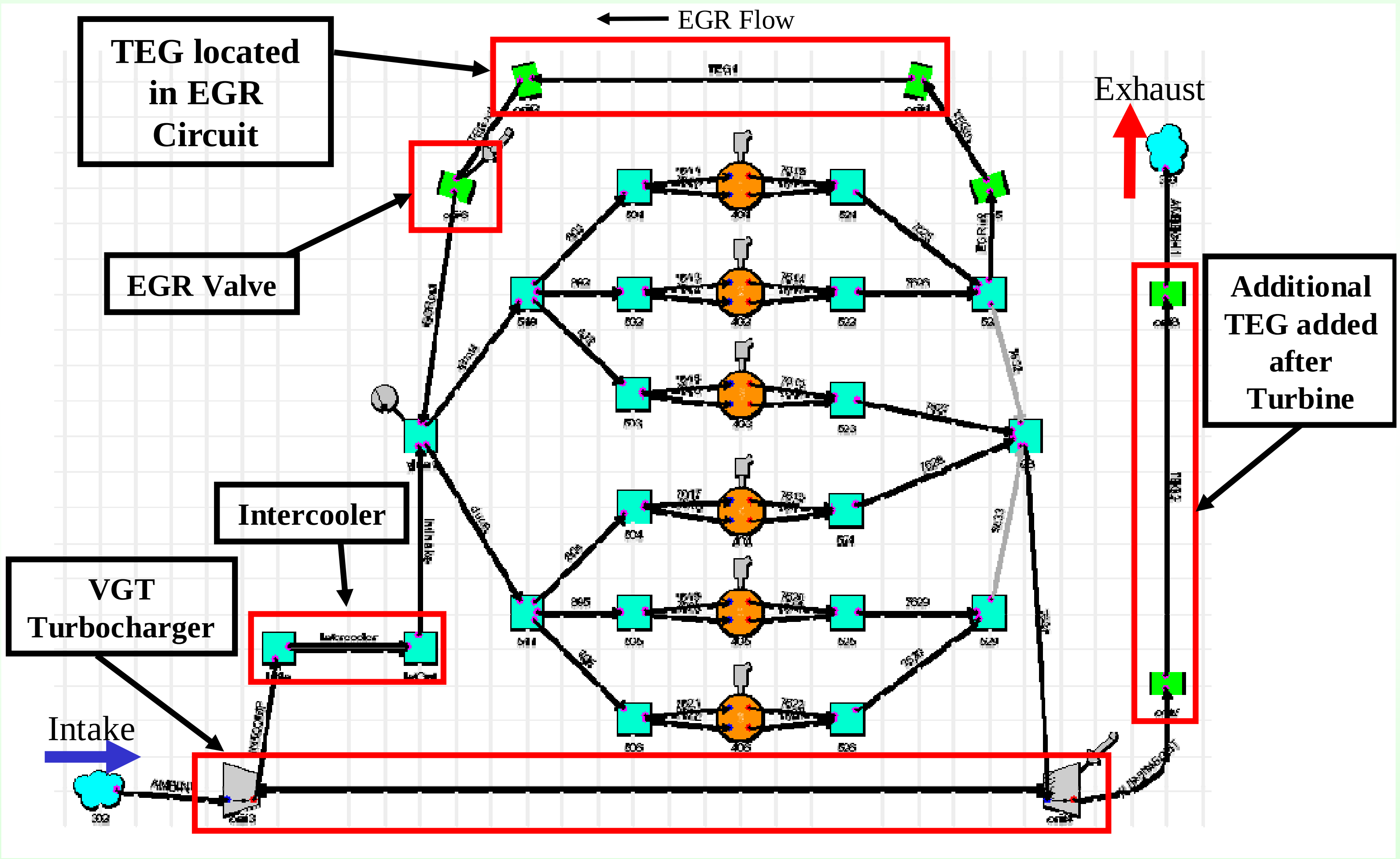
Future Plan: jet impingement

Tight fit (cases 2 & 5) produced the highest heat transfer rate.

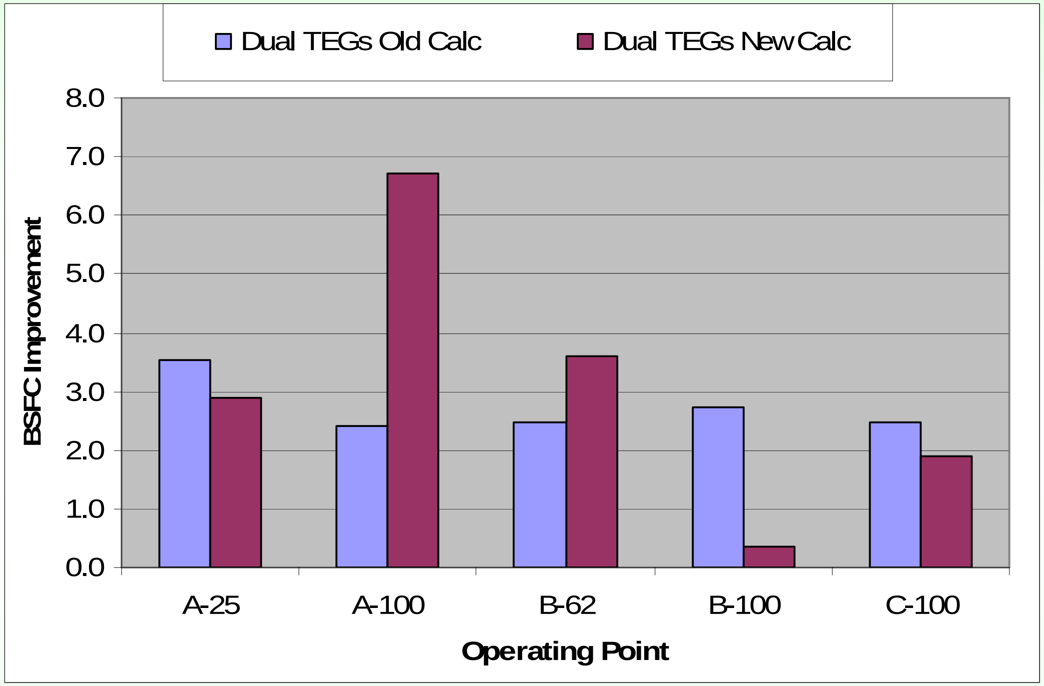
Performance Measures and Accomplishments: Some Specifics

- Power Electronic Controls
- Mechanical Strength and Module Design and Fabrication
- Heat Transfer Issues
- **Performance Calculations**

WAVE Diagram of the Dual TEG Model



% Improvement in BSFC
New Calculation More Accurately Represents an Improvement in BSFC



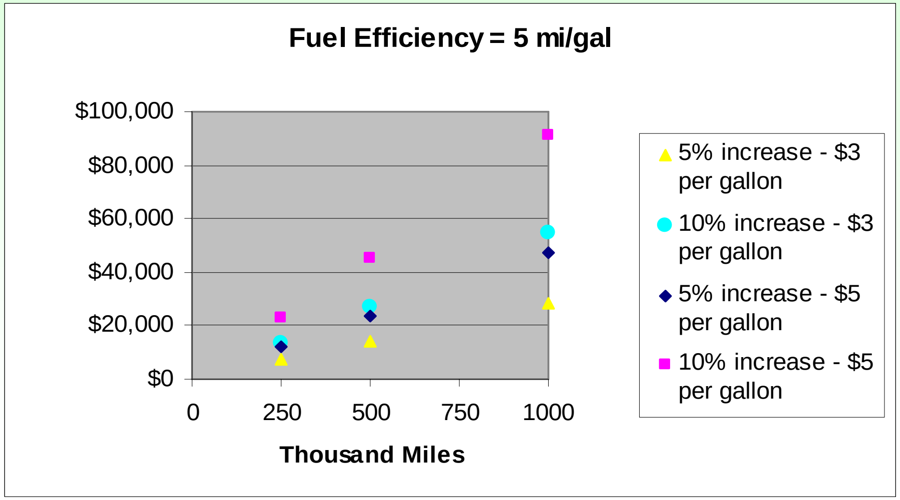
$$BSFC\ \ IMP.(\%) = \frac{Q_{TEG} \times \eta_{TEG} \times \eta_{BSIG} \times \eta_{INV}}{Power_{WAVE}} \times 100$$

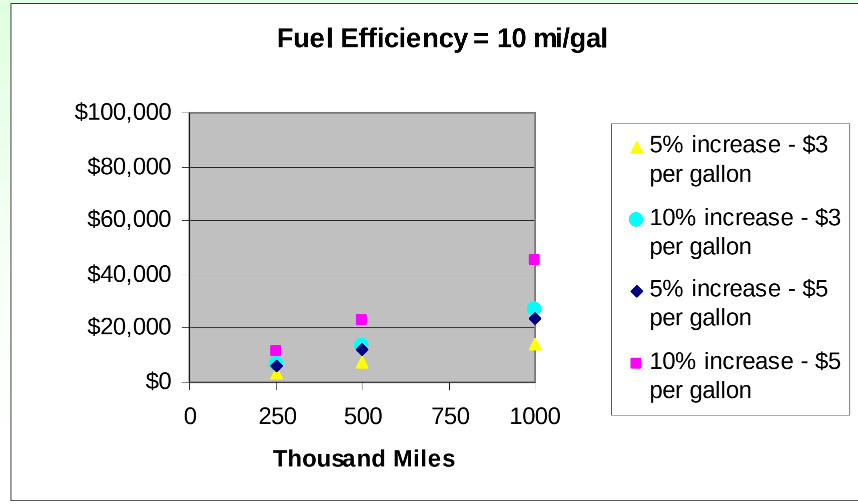
$$BSFC\ \ IMP.(\%) = \frac{(Q_{TEG} \times \eta_{TEG} \times \eta_{BSIG} \times \eta_{INV} + Power_{WAVE}) - Power_{Baseline}}{Power_{Baseline}} \times 100$$

Barriers

- **Major Barriers**
  - Improving the efficiency of thermoelectric materials for the temperature range of interest by segmentation and the introduction of advanced materials
  - Design heat exchangers that will permit heat transfer coefficients of about 5 W/cm^2 to the thermoelectric modules while managing thermal stresses
- **Other Barriers**
  - Develop power processing methods which will yield the material strength and high efficiency required for this application
  - Develop module fabrication methods
  - Develop power electronics to manage electrical loads and module efficiency

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

Summary

Our group has found the following with respect to thermoelectric generation systems for exhaust heat recovery:

- New thermoelectric material systems consisting of **PbTe-PbS** systems show a **ZT of ~1.7 in the temperature range of 650-700K**. Future work is aimed at increasing the power factor of these materials to 30 uW/cm^2 K and a thermal conductivity of 0.8W/m K at 700K could give a **ZT ~2.6**. This is a technology stretching goal and likely to take a few years to achieve, but would clearly make thermoelectrics practical for the diesel applications being evaluated.

- LAST/LASTT modules have been fabricated from the hot pressed materials prepared at MSU. In the next year we plan to continue to produce these modules, measure their performance and evaluate segmentation alternatives. Initial efforts will be directed toward LAST-Bi_2Te_3 segmented legs.

Summary, continued

- Skutterudite and segmented-Skutterudite module fabrication has been ongoing in parallel with the Pb based systems. As previously described, **the JPL group has demonstrated a couple with a 15% efficiency over the temperature range of 700 C to 50 C.** Fabrication of a **40 watt skutterudite module was the primary focus of the latter half of 2007 at MSU** for Sakamoto. We expect this module to be operational by the end of March, 2008.

- We have brought a supercritical autoclave to operational status, which will permit our modules to be insulated using aerogel in carbon dioxide at room temperature and 1500 psi and in supercritical methanol, ethanol, or acetone at 250C and 2500 psi. This insulation will also be used for sublimation suppression.

Summary, continued

- Mechanical property characterization of the LAST materials has been conducted to a temperature of 673K in conjunction with researchers at the Oak Ridge National Laboratory and at MSU. This includes high temperature elastic modulus measurements, thermal fatigue measurements and coefficient of thermal expansion measurements to 650K. Results were repeatable and in agreement with those of other brittle materials. Finite element analysis for modules and thermoelectric generators has been initiated based on the availability of mechanical property data.

- A power electronic circuit capable of extracting the maximum power from a TE module for various load conditions has been demonstrated. Power conditioning circuits to interface to the TEG modules for various vehicle accessory loads are being evaluated along with solutions for module failure identification and bypass selection.

Summary, continued

- Detailed heat transfer studies have shown that special designs will be needed to permit average heat transfer rates to be **greater than 5 W/cm^2.** Alternative flow configurations are being investigated during the first half of 2008.

- Recent calculations have shown that when two TEGs are employed, a **3-6% improvement** in brake specific fuel consumption can be realized. The variation in improvement depends upon the engines mode of operation. We expect that with material improvements a 5% goal is reasonable prediction for the end of Phase 2.

Technology Transfer/Market Transformation

- **Tellurex is making preproduction prototype LAST/LASTT modules for performance and cost assessment.**
- **Near the end of 2008, upon providing Cummins with preliminary performance and geometrical designs, they will provide input on the economic viability of this concept for an over-the-road truck application.**

Publications and Presentations (partial list)

- “Natural Convection and Radiation Heat Transfer in High Temperature Thermoelectric Couples,” Zhu, B., Schock, H.J., Hogan, T., Shih, T., Michigan State University, AIAA Paper 2006-0574, Aerospace Sciences Meeting, Reno, Nevada, January 2006.

- “Heat Transfer and Electric Current Flow in a Thermoelectric Couple,” Harris, R., Schock, H.J., Hogan, T., Shih, T., Michigan State University, AIAA Paper 2006-0575, Aerospace Sciences Meeting, Reno, Nevada, January 2006.

- “Weibull Analysis of the Biaxial Fracture Strength of a Cast P-type Last-T Thermoelectric Material,” Ren, F., Case, E.D., Timm, E.J., Jacobs, M.D., Schock, H.J., Michigan State University. Philosophical Magazine Letters, 2006.

- “Hardness as a Function of Composition for N-type Last Thermoelectric Material,” Ren, F., Case, E.D., Timm, E.J., Schock, H.J., Michigan State University. Journal of Alloys and Compounds, published on-line 2007.

- Young’s modulus as a function of composition for an n-type lead-antimony-silver-telluride (LAST) thermoelectric material,” Ren, F., Case, E.D., Hall, B.D., Timm, E.J., Schock, H.J., Michigan State University. Philosophical Magazine, 2007.

- “The Effect of Milling Time and Grinding Media Upon the Particle Size Distribution for Last (Lead-antimony-silver-telliurm) Powders,” Pilchak, A.L., Ren, F., Case, E.D., Timm, E.J., Schock, H.J., Michigan State University. Philosophical Magazine, 2007.

MSU Led Thermoelectics Group Plans for 2008

- **Continue to evaluate alternative thermoelectric systems including LAST/T, PbTe-PbS and PbTe-CdTe, skutturudites, TAGS and Bi_2Te_3 legs for segmentation ease and efficiency …this work continues from 2007.**
  - **Demonstrate scalability of PbTe-PbS material system (next 2 months)**
  - **Demonstrate repeatability of good TE properties (ZT~1.5) of PbTe-PbS material system (next 2 months)**
  - **Demonstrate scalability of PbTe-CdTe system (next 5 months)**
  - **Evaluate ingots of PbTe-PbS for n-type leg production**
  - **Evaluate mechanical properties of PbTe-PbS and assess need for powder processing.**
  - **Independently validate thermoelectric properties at JPL.**
  - **Segmented modules, prepare n and p Skutterudite, TAGS (p-type) and both n and p Bi_2Te_3. Segment these and prepare legs for segmented modules.**
  - **Integrate aerogel-based thermal insulation to enable realistic couple and module efficiency measurements.**

- **Down select materials for leg segmentation and demonstration of a 1kW module in 2009.**

MSU Led Thermoelectics Group Plans for 2008, continued

- Fabricate 8, 16 and 32 couple 40W modules. The increase in the number of couples will increase the voltage and decrease the current requirement, thus making electrical integration easier.
- Build a test station for measuring module efficiency.
- Build test stations to measure key/possible degradation mechanisms, e.g. stability of metallization and sublimation.
- Preliminary design of the power electronic system needed for operation of a 10 kW TEG for an over-the-road truck application.
- Continue to develop mechanical property data for new thermoelectric material classification and for input to finite element analysis (FEA).
- Heat transfer studies will focus on jet impingement to increase surface heat transfer for both tight fit and isolated TE legs.

MSU Led Thermoelectics Group Plans for 2008, continued

- Establish a protocol for synthesizing large quantities of TE materials, which will include detailed quality assurance from batch to batch.
- Try to establish feasible designs first, then integrate mechanical properties FEA and characterize influence of mechanical properties on a particular module design.
- Develop a preliminary design of a 1kW TEG (Phase 3 demo with engine) for an over-the-road truck with input from WAVE, FEA (stresses) and CFD (heat transfer) analysis and efficiency. This 1kW unit will be scalable to a 10kW unit for OTR truck applications. In Phase 2 complete a 1 kW demo without engine.
- Phase 2 funding as requested, a 2009 completion anticipated
- Provide Cummins and Tellurex with sufficient details of system design and performance so that reasonable cost estimates of the TEG can be developed.

Thanks for your attention!