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

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Mihal Gross, Project Monitor

IOWA STATE UNIVERSITY

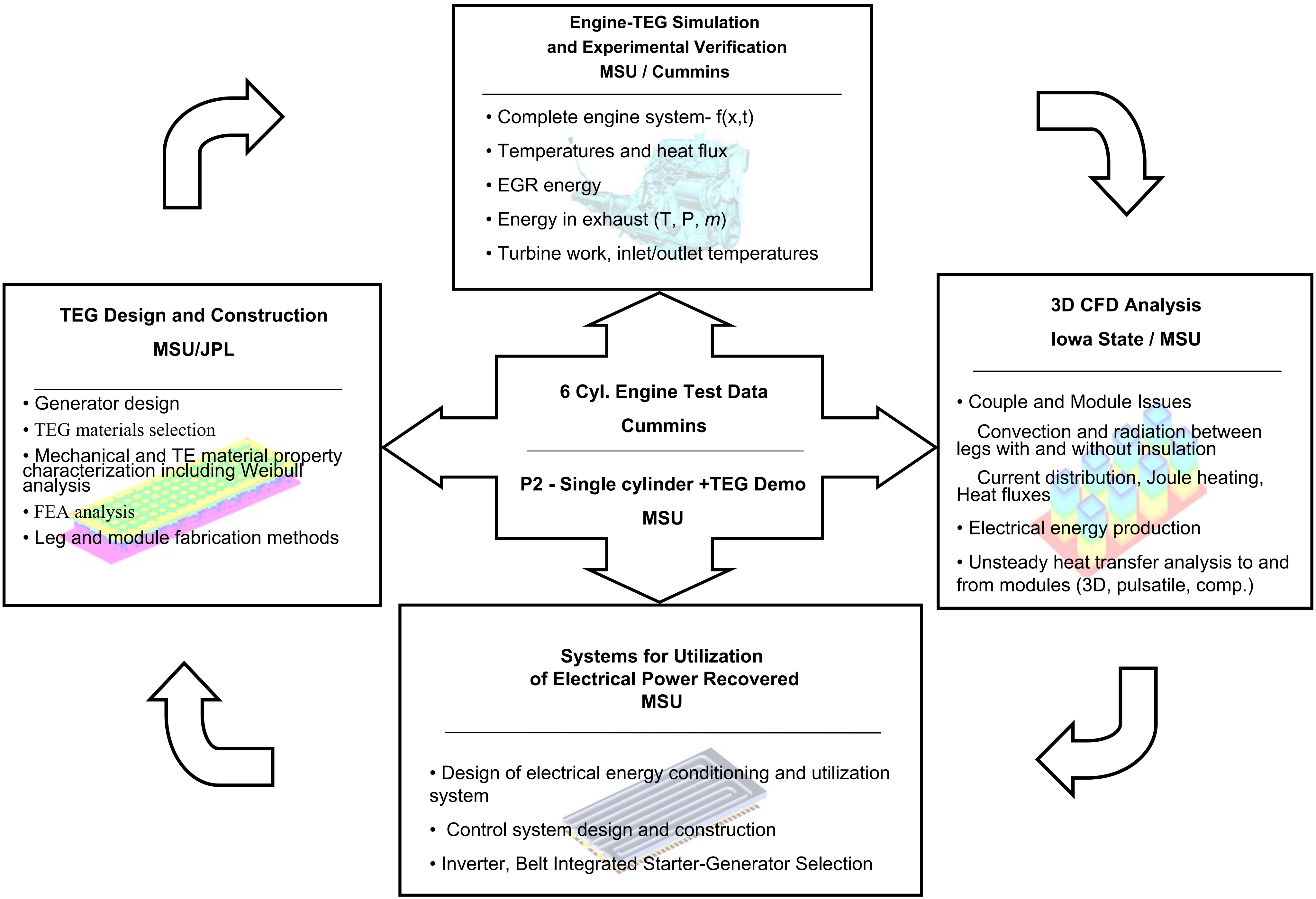
JPL

MICHIGAN STATE UNIVERSITY

Cummins

TELLUREX CORPORATION

Implementation of a Thermoelectric Generator with a Cummins ISX Over-the-Road Powerplant



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

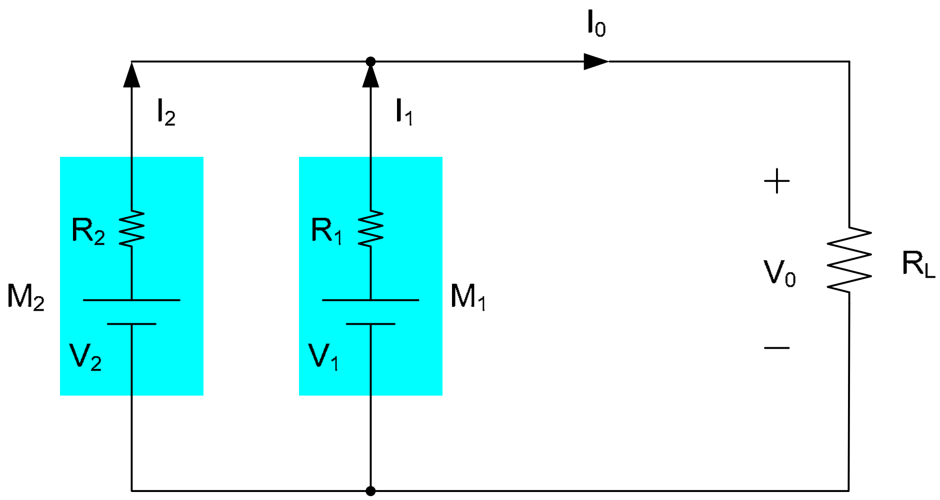
Important Barriers

- 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
- Material strength and thermoelectiric properties must meet life cycle performance criteria
- 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 last material are about 1.5 and need to be closer to 3.0 to reach the efficiency goals requested by DOE

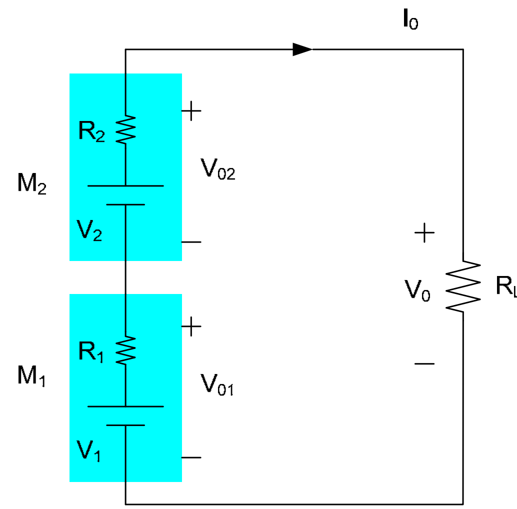
Accomplishment to date

- Systems for ingot synthesis and leg preparation demonstrated
  - March 07, 100 ton hot press operational at MSU (up to a 10 cm puck)
  - Tube furnaces and leg cutting equipment operational (500 grams/batch)
  - Segmented legs demonstrated by Sakamoto at JPL (now at MSU)
- Segmented leg - module fabrication methods being developed
  - Sakamoto at JPL demonstrated segmented p-leg with 14.5% efficiency
  - Hogan group fabricated and tested numerous LAST/LASTT modules
  - Diffusion bonding of stainless steel to LAST and BiTe demonstrated
- Power electronic module isolation methods designed and being tested at MSU
- Transport measurements conducted by MSU have been verified by Northwestern, JPL, Iowa State and the general literature
- Sublimation issues appear to be under control with aerogel coatings developed by Sakamoto at JPL and Fortifax at MSU
- Analytical studies performed for various operation modes and conditions
  - Geometries for high efficiency heat transfer rates evaluated
  - Efficiency improvements for various operational modes for the Cummins ISX engine evaluated for various geometries

Problems of Traditional Connection Methods



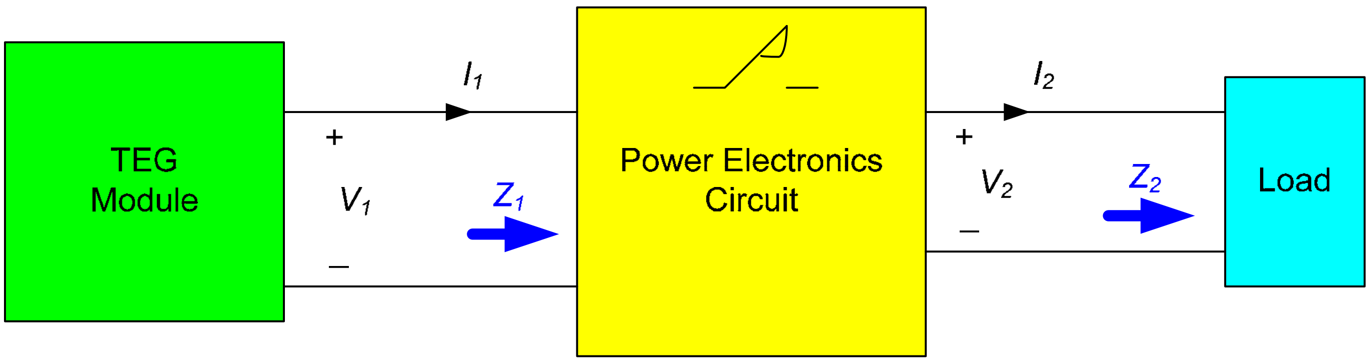
Parallel connection



Series connection

- **Different output characteristics of TEG modules cause problems when connect them with traditional methods;**
- **One TEG module can become the load of another and waste power;**
- **Can not guarantee maximum power output from each TEG module;**
- **Single failed module can cause power output interruption .**

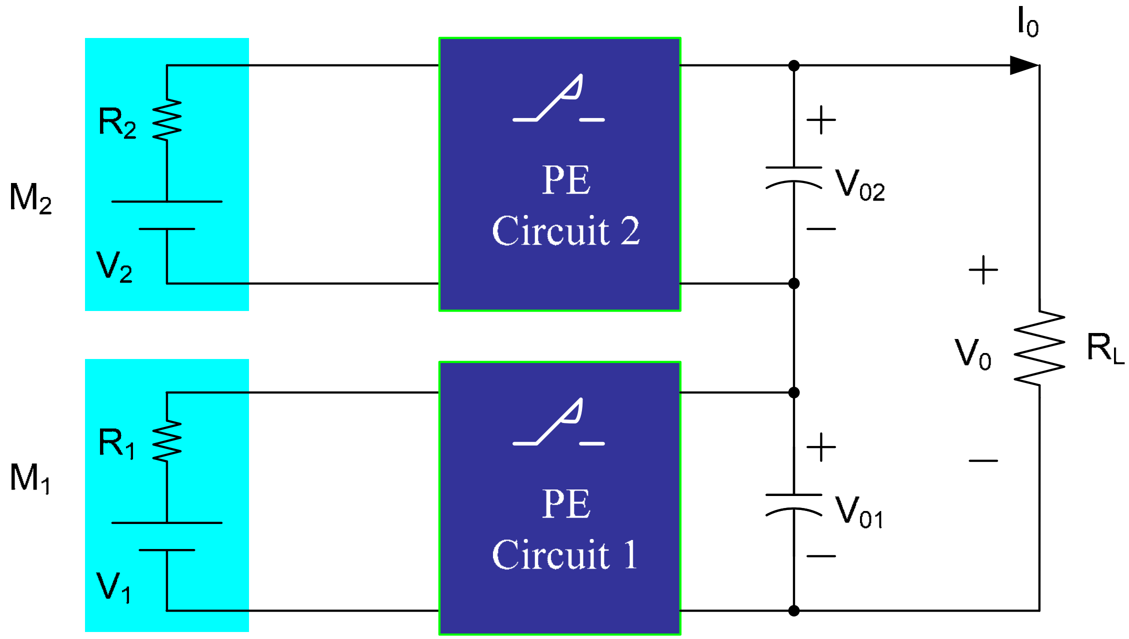
Power Electronics for TE Generation



Developing power electronic circuit as an interface between TEG module and load with the features of:

- Load matching;
- Power conditioning;
- Maximum power point tracking;
- Failed TEG module bypassing.

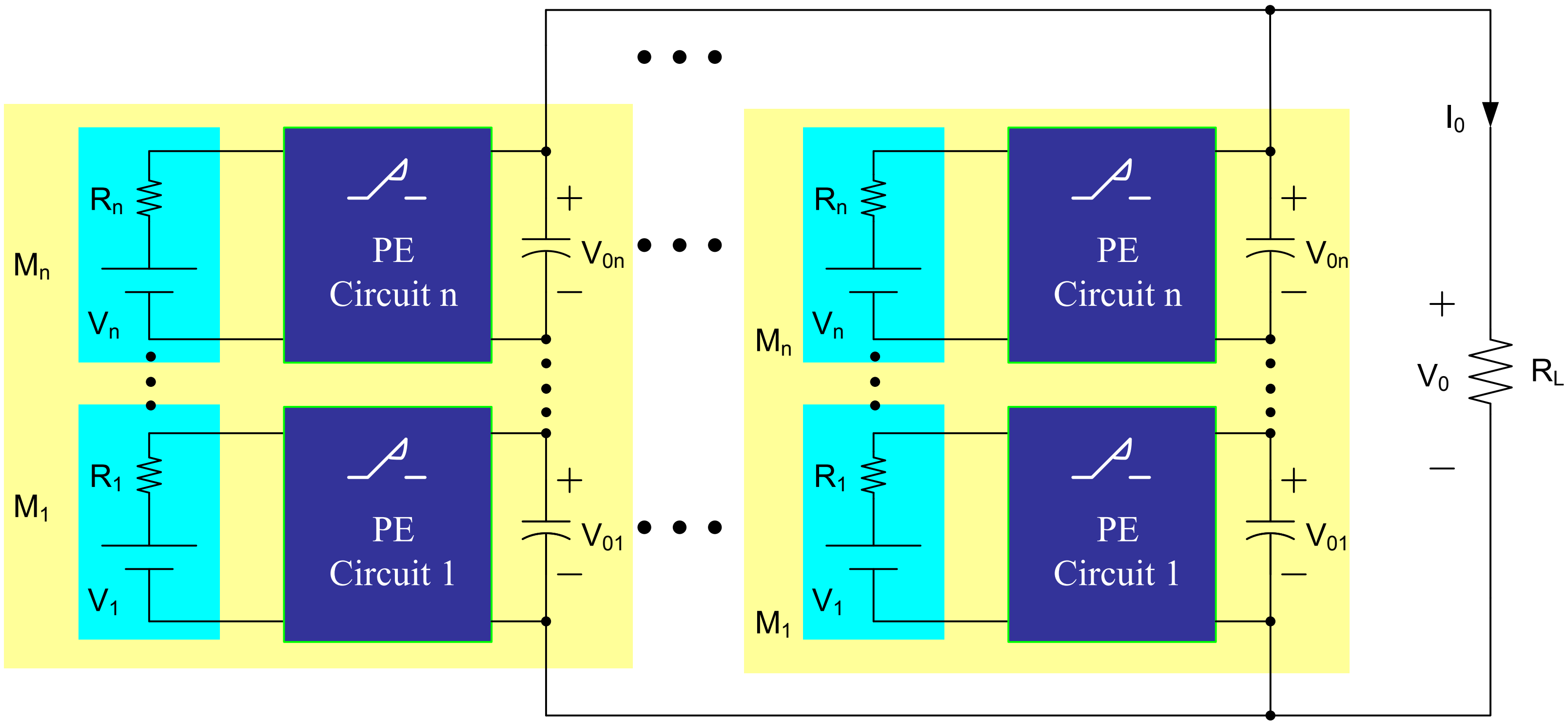
Power Electronics Solution



A power electronic circuit is designed for each TEG module and features functions of:

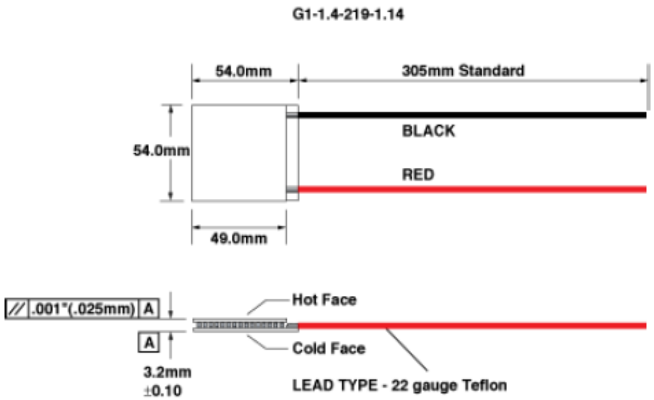
- Maximum power point tracking;
- Bypassing failed module;

To Achieve High Power Output

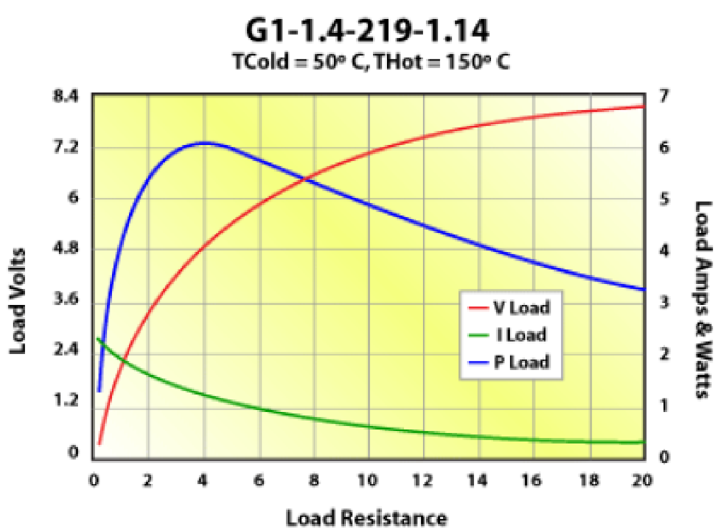


- High power output can be achieved by series-parallel connection of TEG modules;
- Power electronic circuits guarantee each TEG module output its maximum power;
- Failed modules will not effect the operation of other modules.

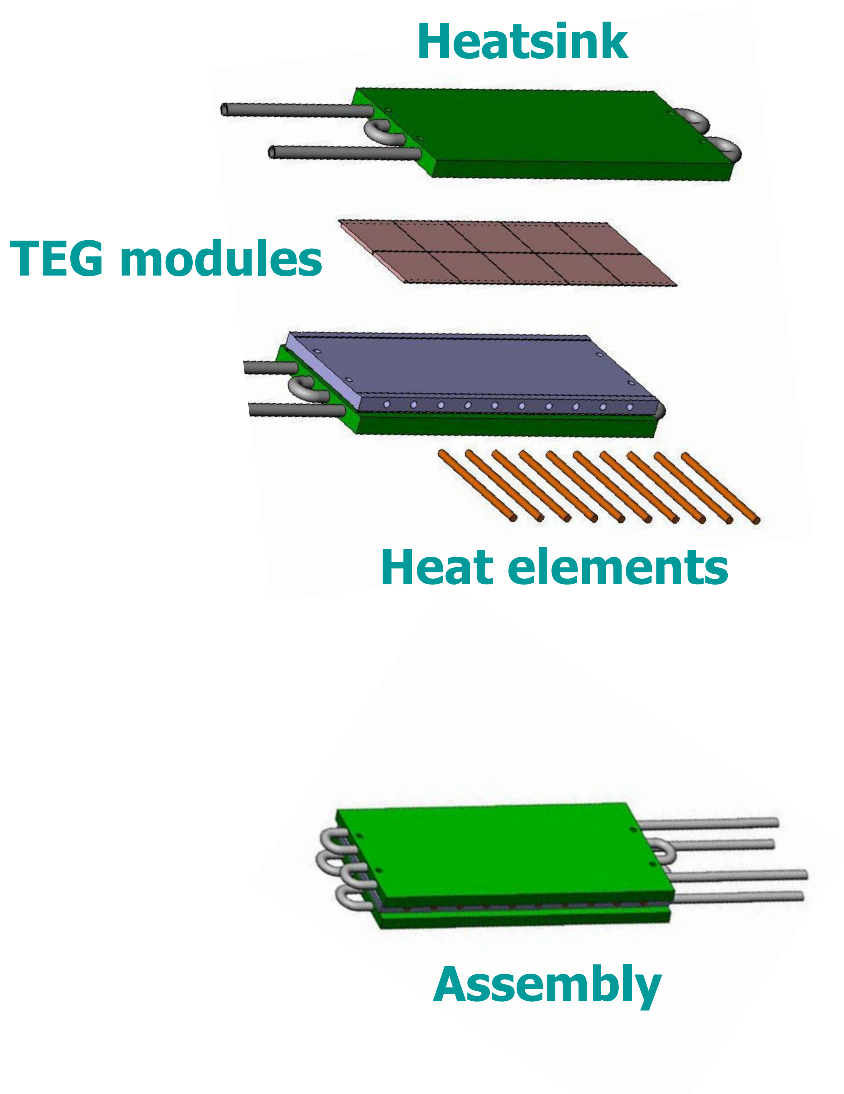
TEG module and Heat Exchanger



TEG module from Tellurex®

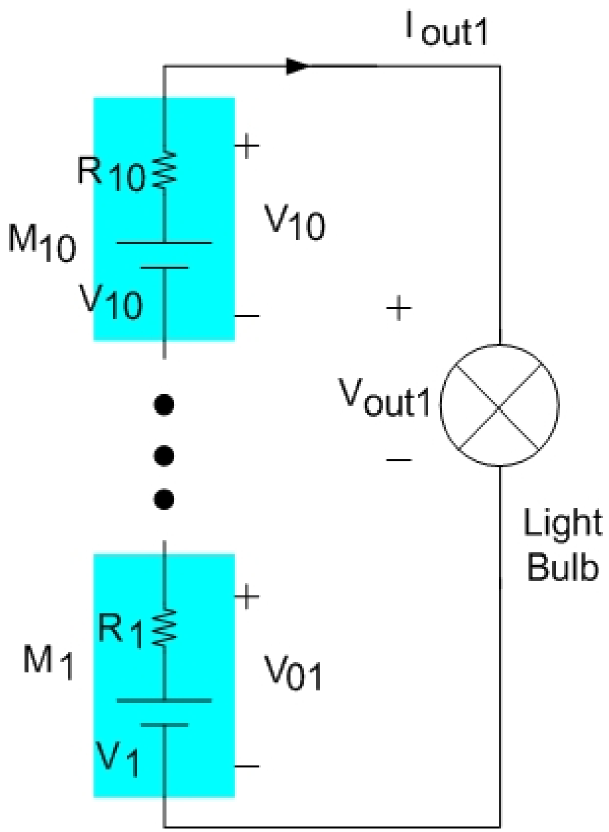


Output characteristics (Tellurex®)

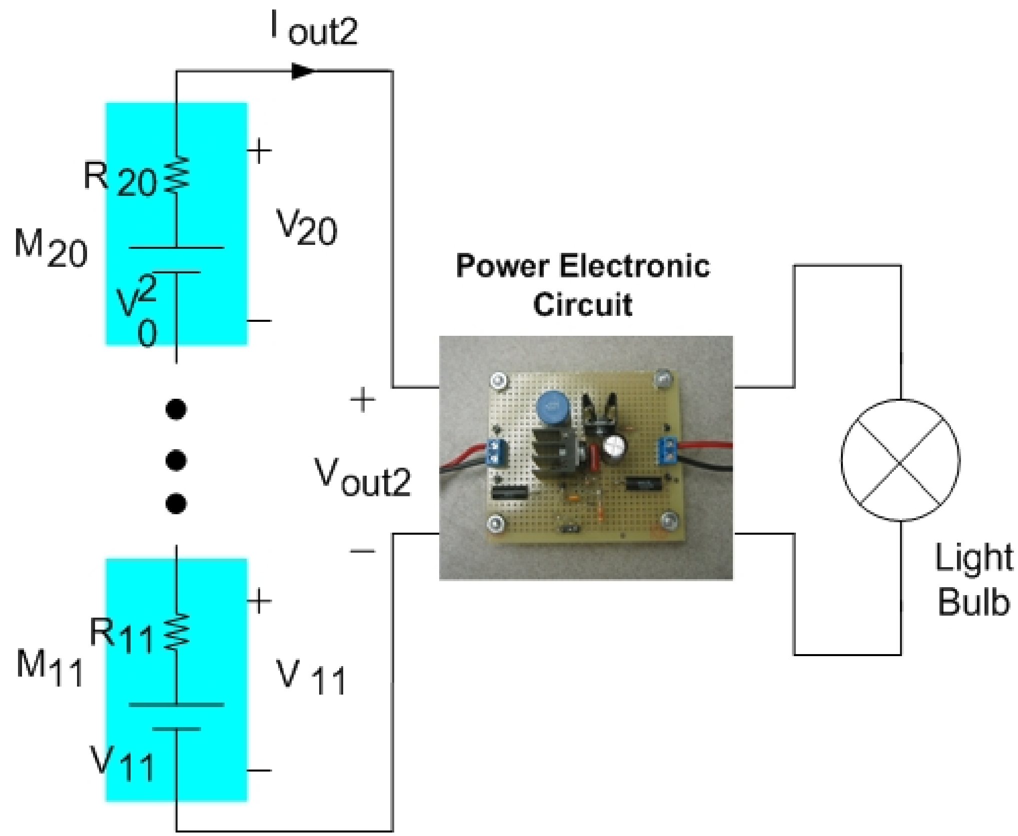


➢ **A heat exchanger capable of 100 W electrical power output has been fabricated and Tested.**

Test Setup & Condition



Set 1: Without PE Circuit

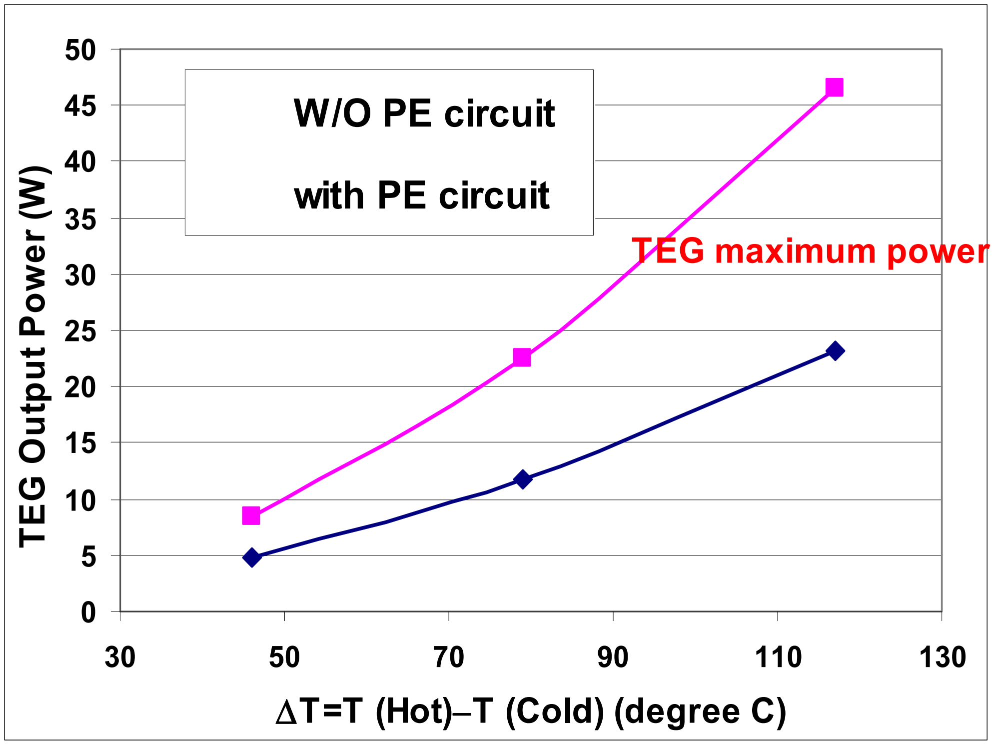


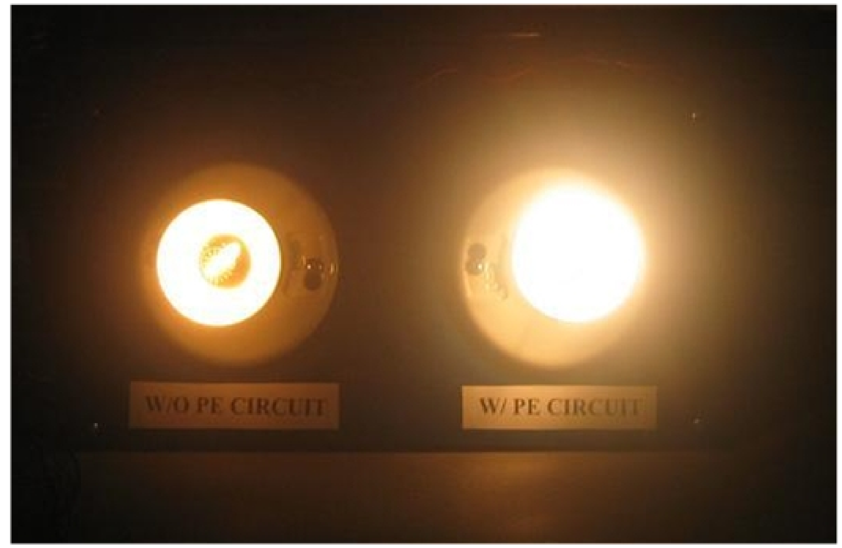
Set 2: With PE Circuit

- 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



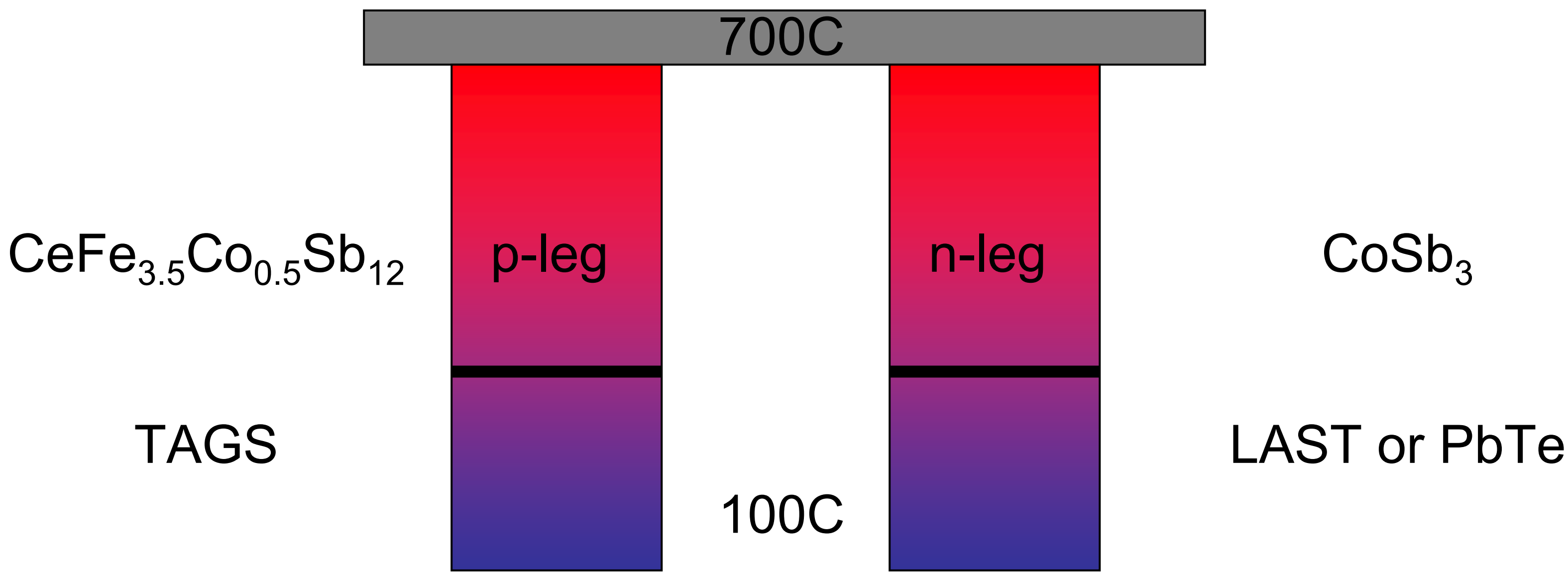


W/O PE circuit With PE circuit

➢ **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.**

Device level efficiency projections:

Skutterudite+heritage materials



Option 1: LAST for cold stage of n-leg (525C interface) = 14.80% efficiency

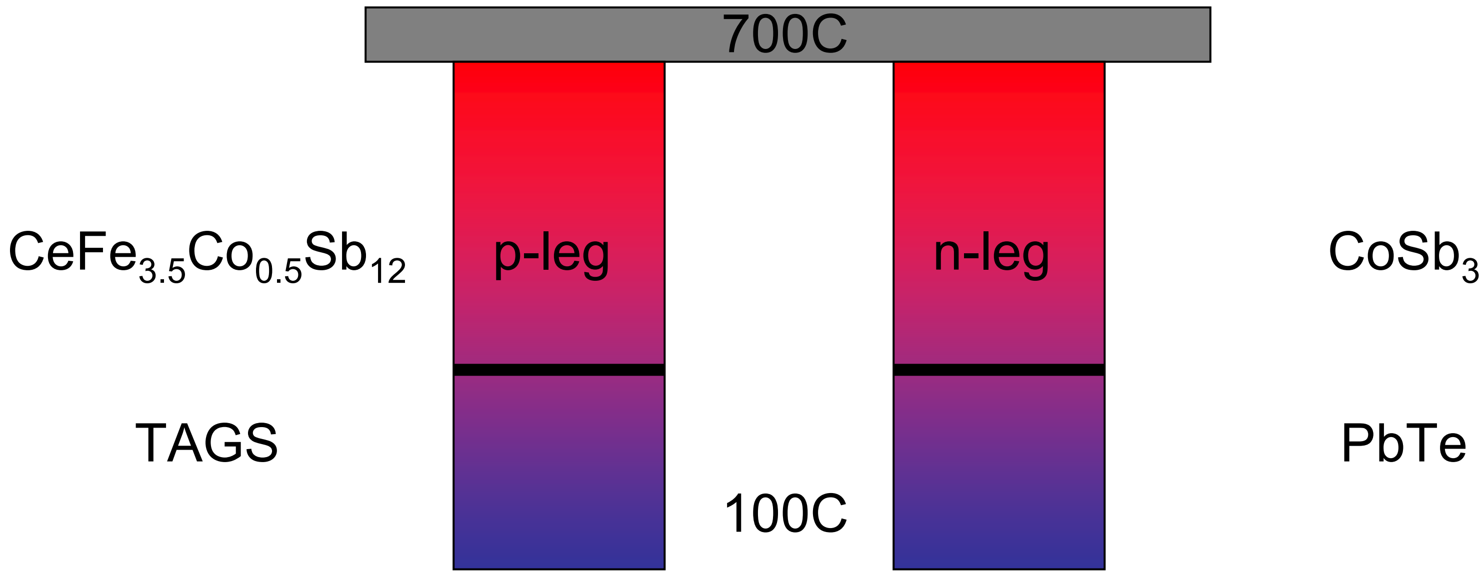
Option 2: PbTe for cold stage of n-leg (438C interface) = ~12.4% efficiency

Option 3: PbTe for cold stage of n-leg (525C interface + TAGS at 500C) = 13.0% efficiency

SOA: Heritage TAGS & PbTe 450C-100C = 8% efficiency

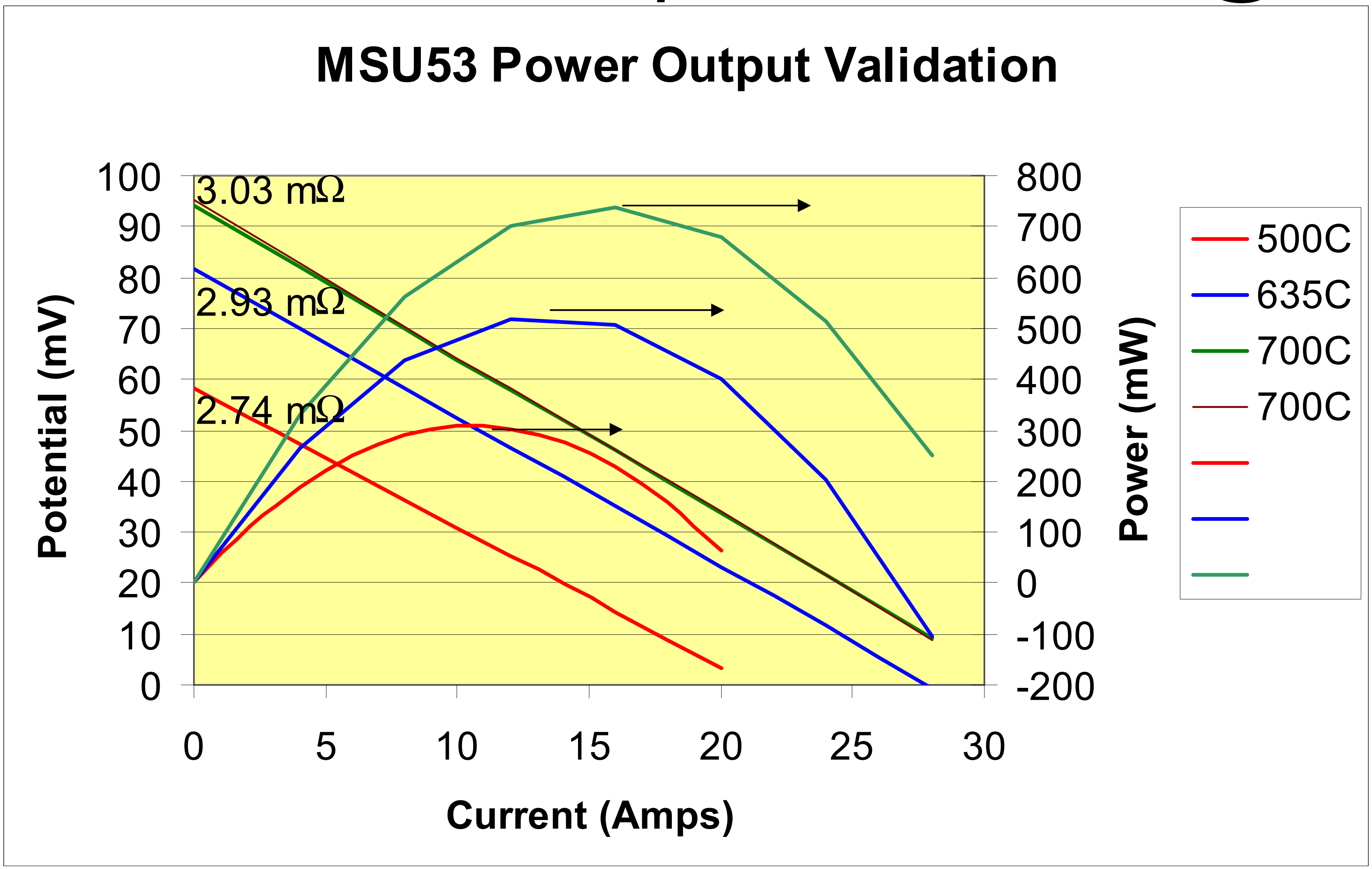
Device details & power output

Option 3: PbTe for cold stage of n-leg (525C interface + TAGS at 500C) = 13.0% efficiency



- 0.5cm long legs 0.5cm^2 each leg
- 1 gram (total) for each couple
- 2.2 mOhm per couple
- 0.127 mV at peak load
- 41 amps
- 5.2W output
- Assumes 40W/cm^2
- **200 couples in series at 25V (6” by 6” footprint including gaps) = 1040W**

MSU53 Power Output Validation @ JPL



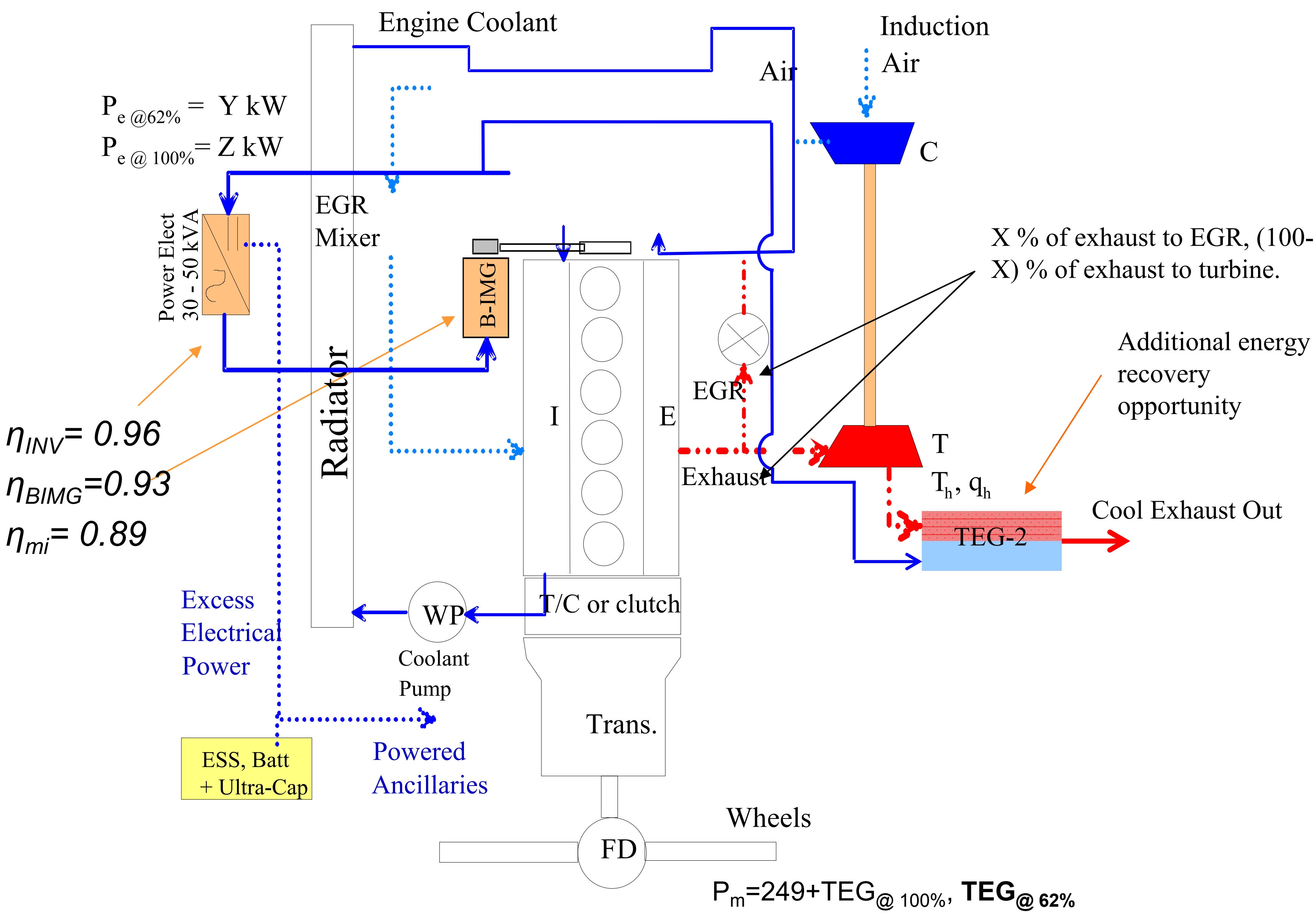
•Resistance is within ~1% of predicted value

•14.57% conversion efficiency!

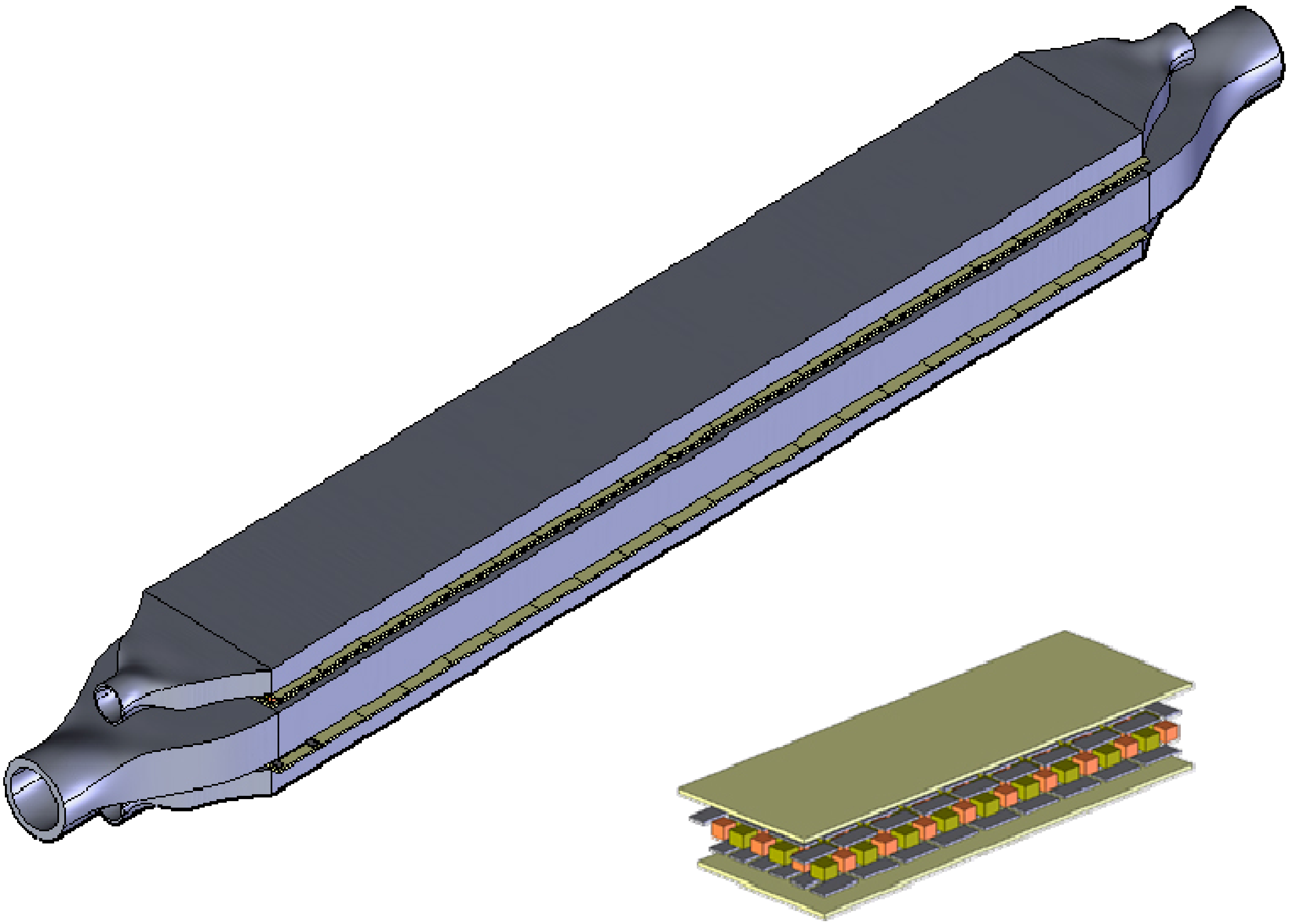
Cummins ISX 6 cylinder diesel engine

Thermal Power Split Hybrid – Options

Using the electric power recovered from waste heat



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

Issues:

Heat Exchanger (HX)

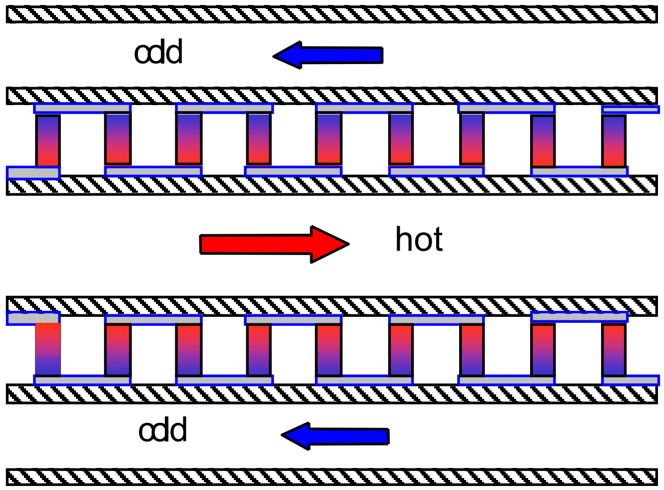
- How to fully utilize the hot & cold temperature sources as efficiently and compactly as possible.

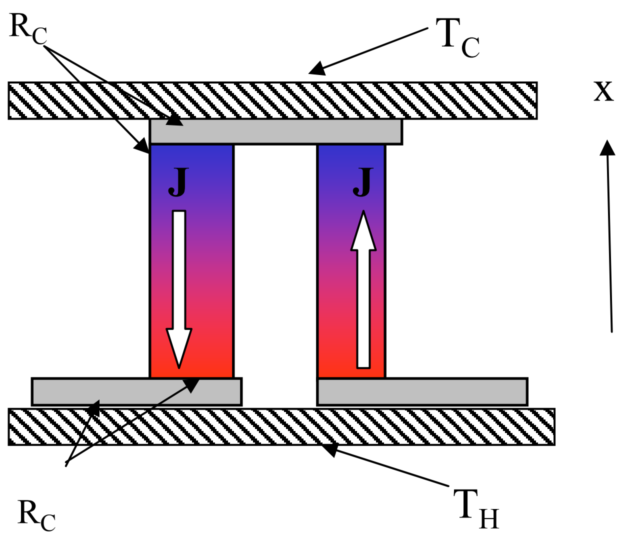
Heat Transfer in the TE Couple

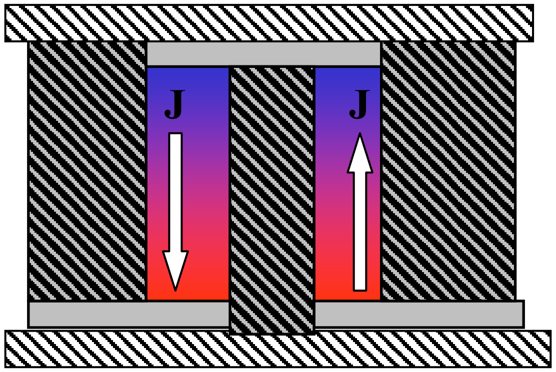
- TE cavity: inert gas/insulation
- TE legs

Durability and Life

- thermal stress considerations





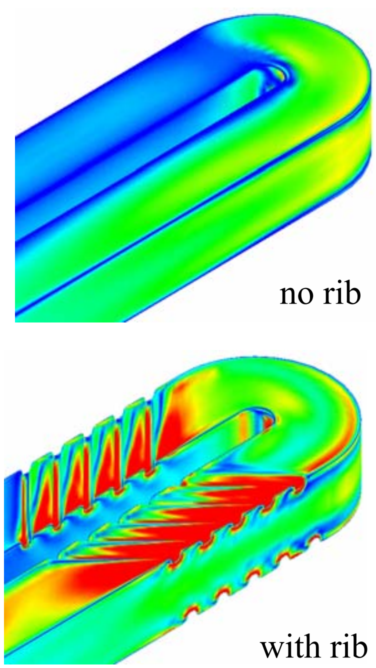


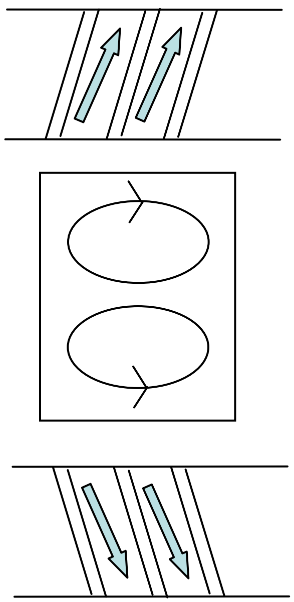
HX: Heat Transfer Enhancement

Goal:

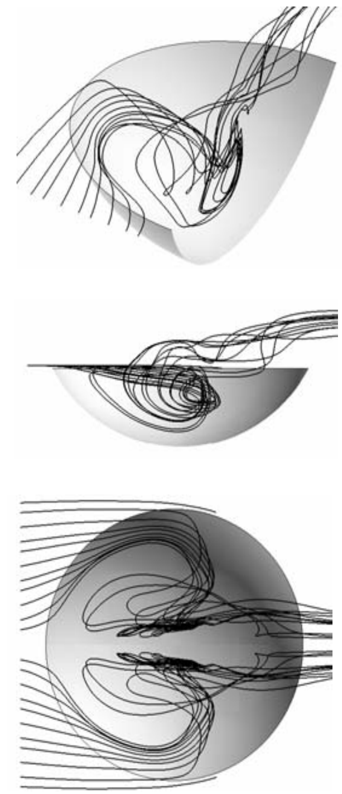
- ➢ high heat transfer rate
- ➢ low pressure drop

How to get high heat-transfer rate?





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



Guiding Principle for HT Enhancement

- Increase streamwise vorticity / recirculating flow to increases surface heat transfer

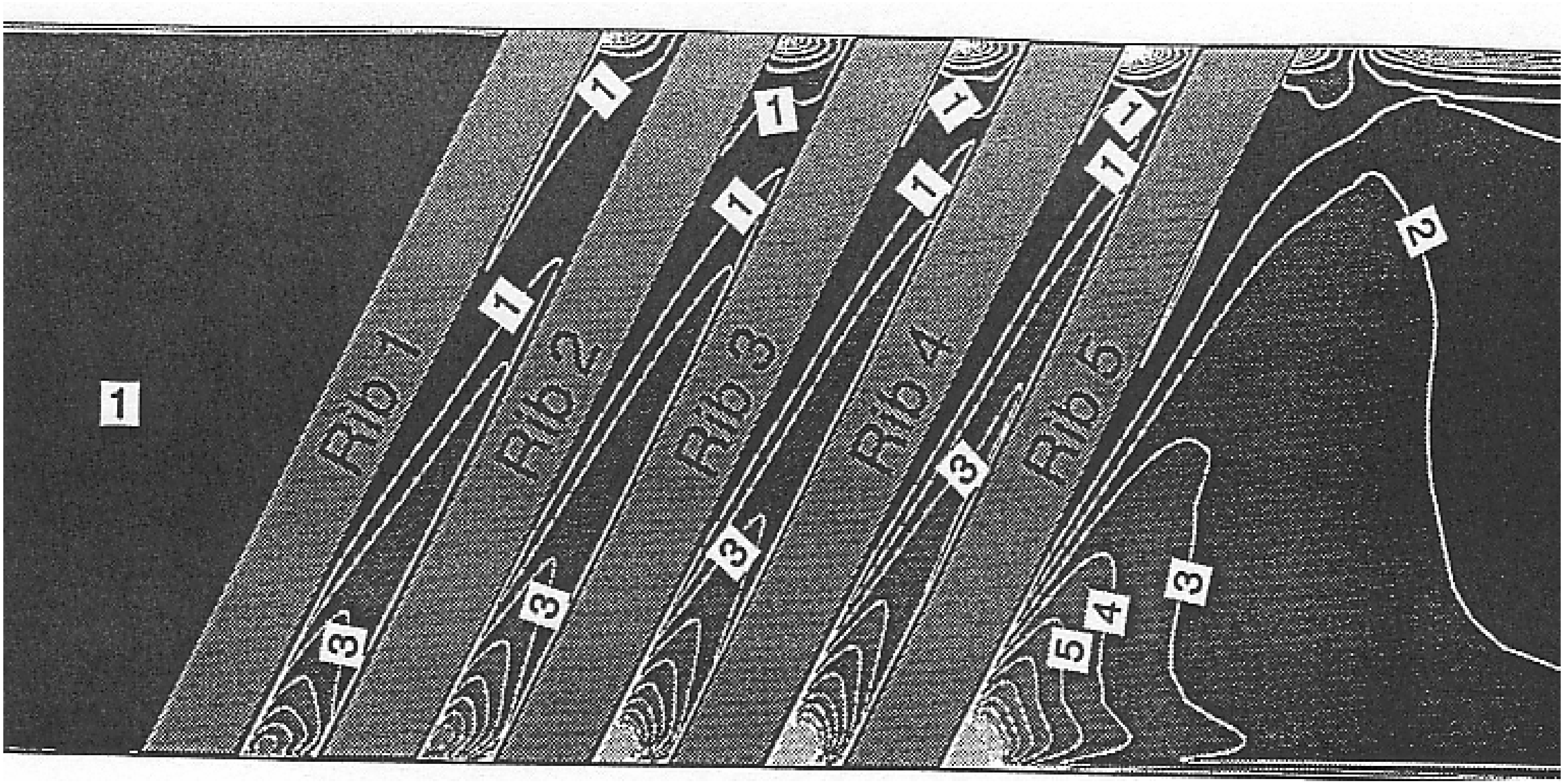
  Why?
  Brings hotter & higher momentum fluid in the "core" to the surface.

- Interrupting the streamwise recirculating flow periodically is needed (i.e., restart boundary layer).

- Induce unsteadiness as another mechanism to restart boundary layer.

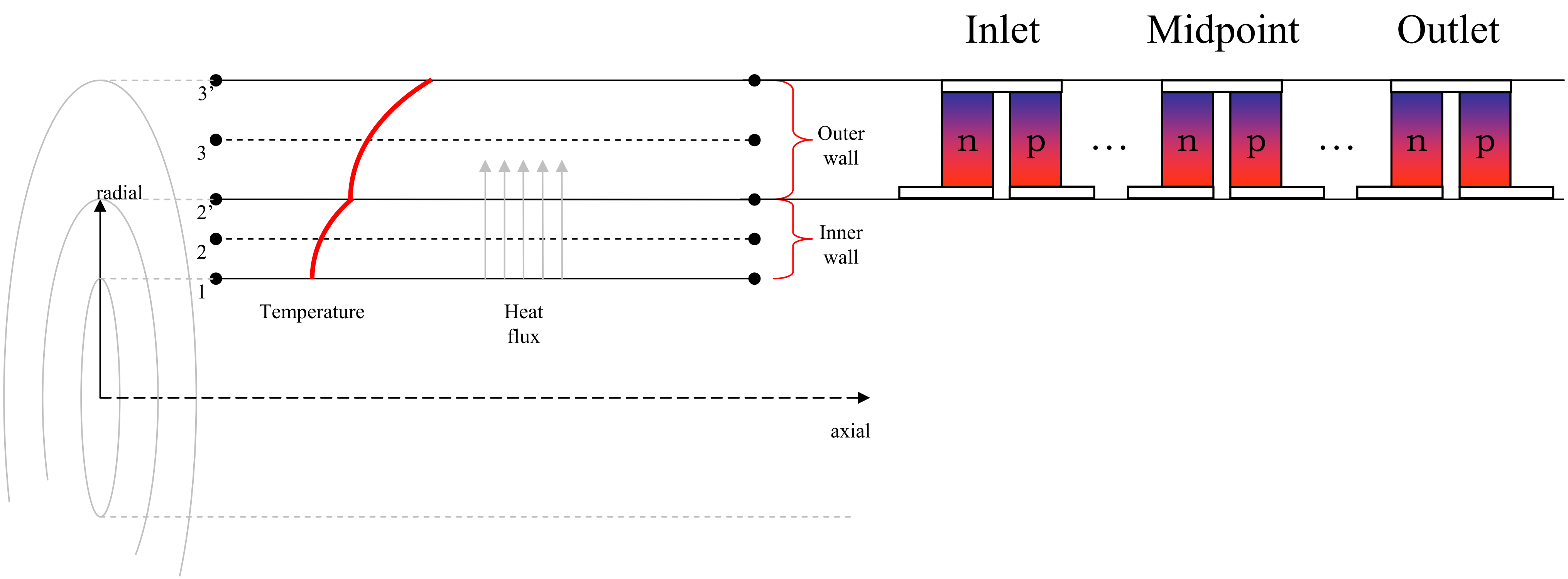
New Concept

$h_{\text{with rib}} / h_{\text{no rib}}$



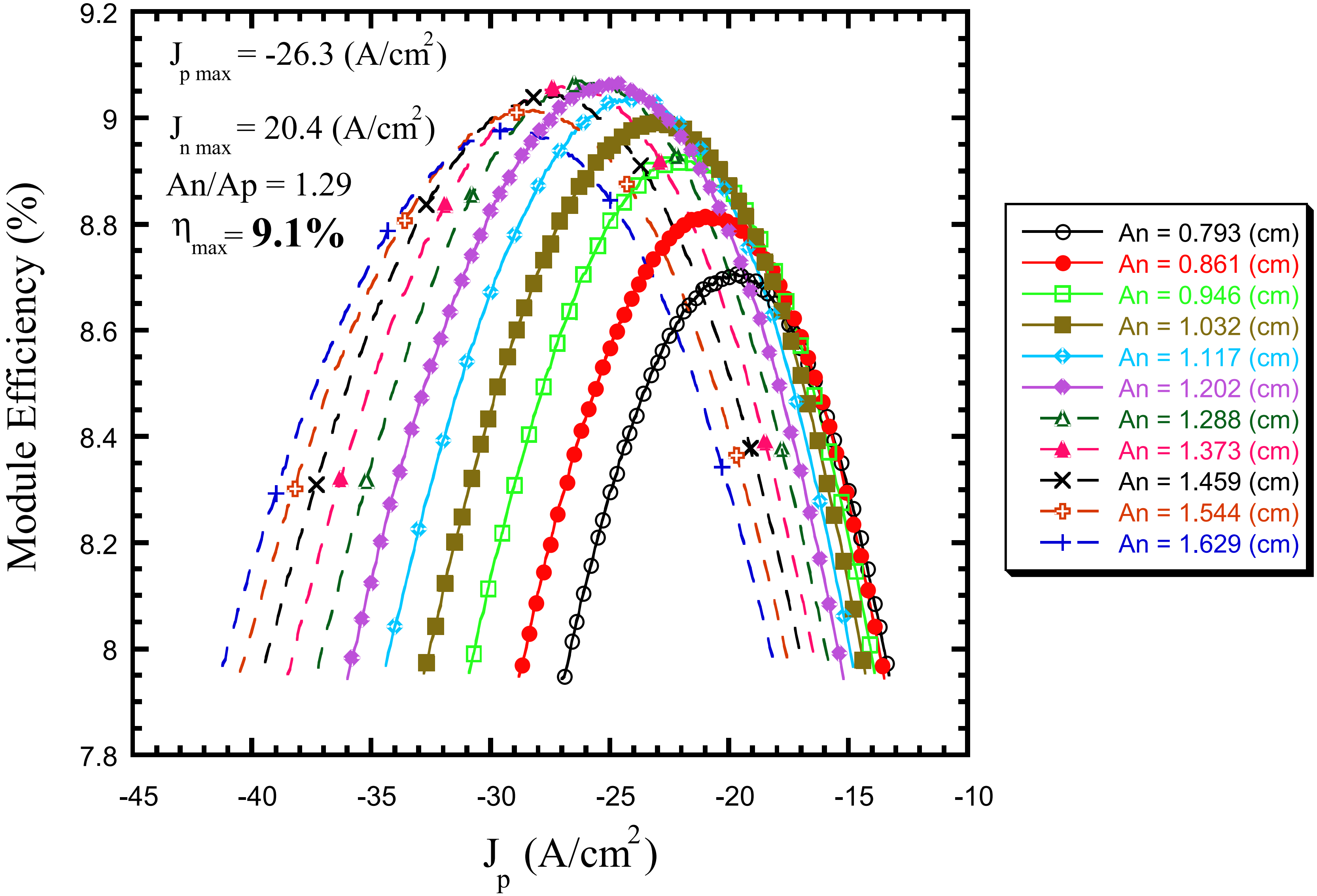
TEG for Waste Heat from IC Engines

TEG Configuration		T2	T2'	T3	T3'
Outlet	6-1	731	**727**	524	**342**
Midpoint	6-1	781	**777**	546	**338**
Inlet	6-1	831	**826**	567	**334**
Outlet	EGR Cooler	495	**493**	408	**331**
Midpoint	EGR Cooler	636	**633**	474	**331**
Inlet	EGR Cooler	834	**829**	568	**334**



1 Cylinder per TEG MP Module Efficiency

(LAST, BiTe (470K)), T2` = 644K, T3` = 338K



Fuel economy of ISX Engine Operating at Cruise (B62 Point) – Phase I Work TEG Placed at Head in Exhaust Port

$$\% \text{ Imp. In BSFC * } = \frac{Q_{TEG} \cdot N_{TEG} \cdot \eta_{TEG} \cdot \eta_{BISG} \cdot \eta_{INV}}{BHP \cdot 0.746}$$

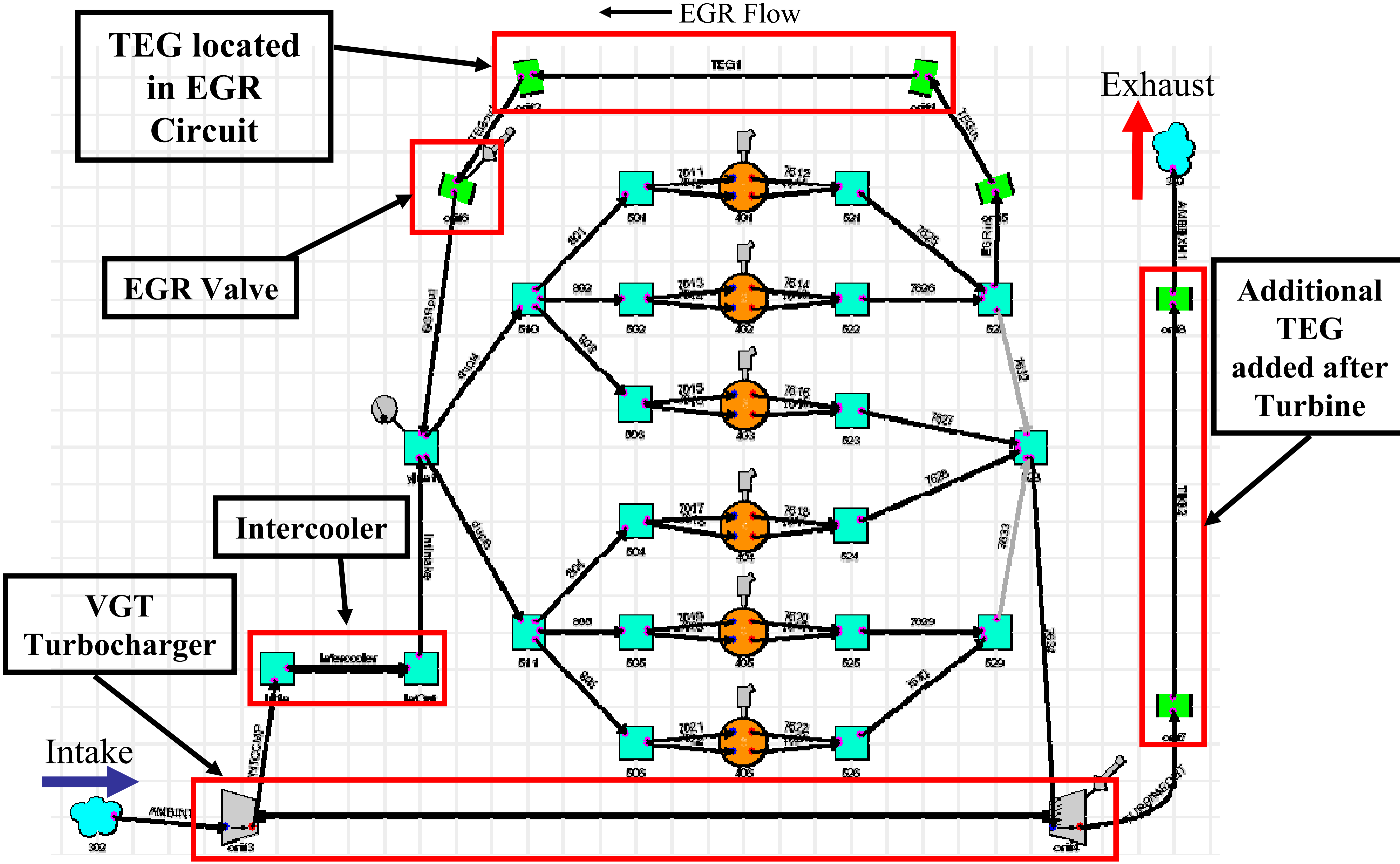
$$\text{1 Cylinder into 1 TEG (6TEGs)} = \frac{31.9(6)(0.091)(0.96)(0.93)}{334.6 \cdot 0.746} = 6.2\%$$

$$\text{3 Cylinders into 1 TEG (2 TEGs)} = \frac{50.2(2)(0.11)(0.96)(0.93)}{334.6 \cdot 0.746} = 4.0\%$$

$$\text{6 Cylinders into 1 TEG (1TEG)} = \frac{64.5(1)(0.123)(0.96)(0.93)}{334.6 \cdot 0.746} = 2.8\%$$

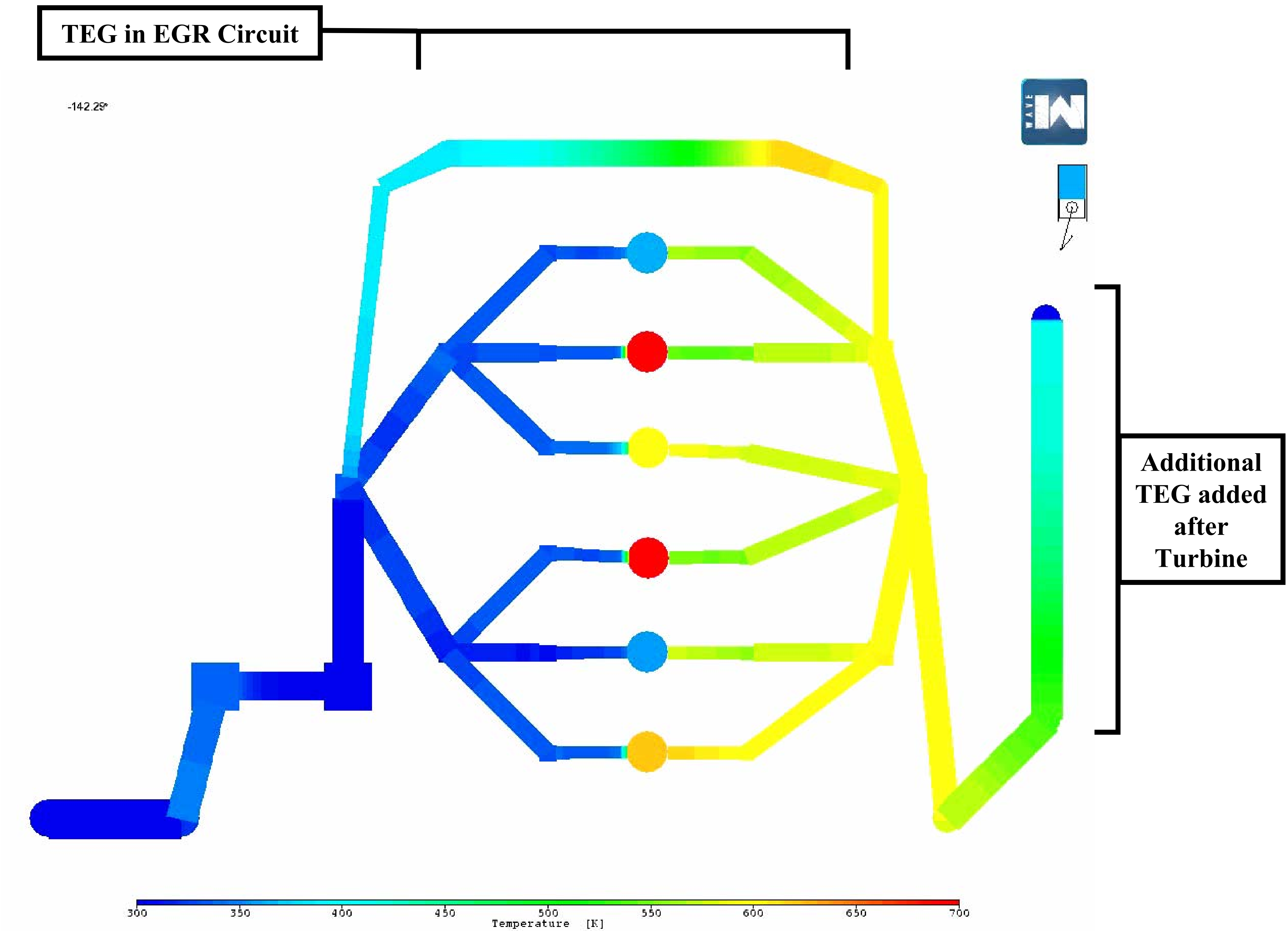
Note: This does not include improvement in BSFC by utilizing an ISG which has an efficiency 2x that of current alternators or the higher TEG efficiencies at higher load operation

WAVE Diagram of ISX Engine Layout: Secondary TEG attached to Turbo Exhaust

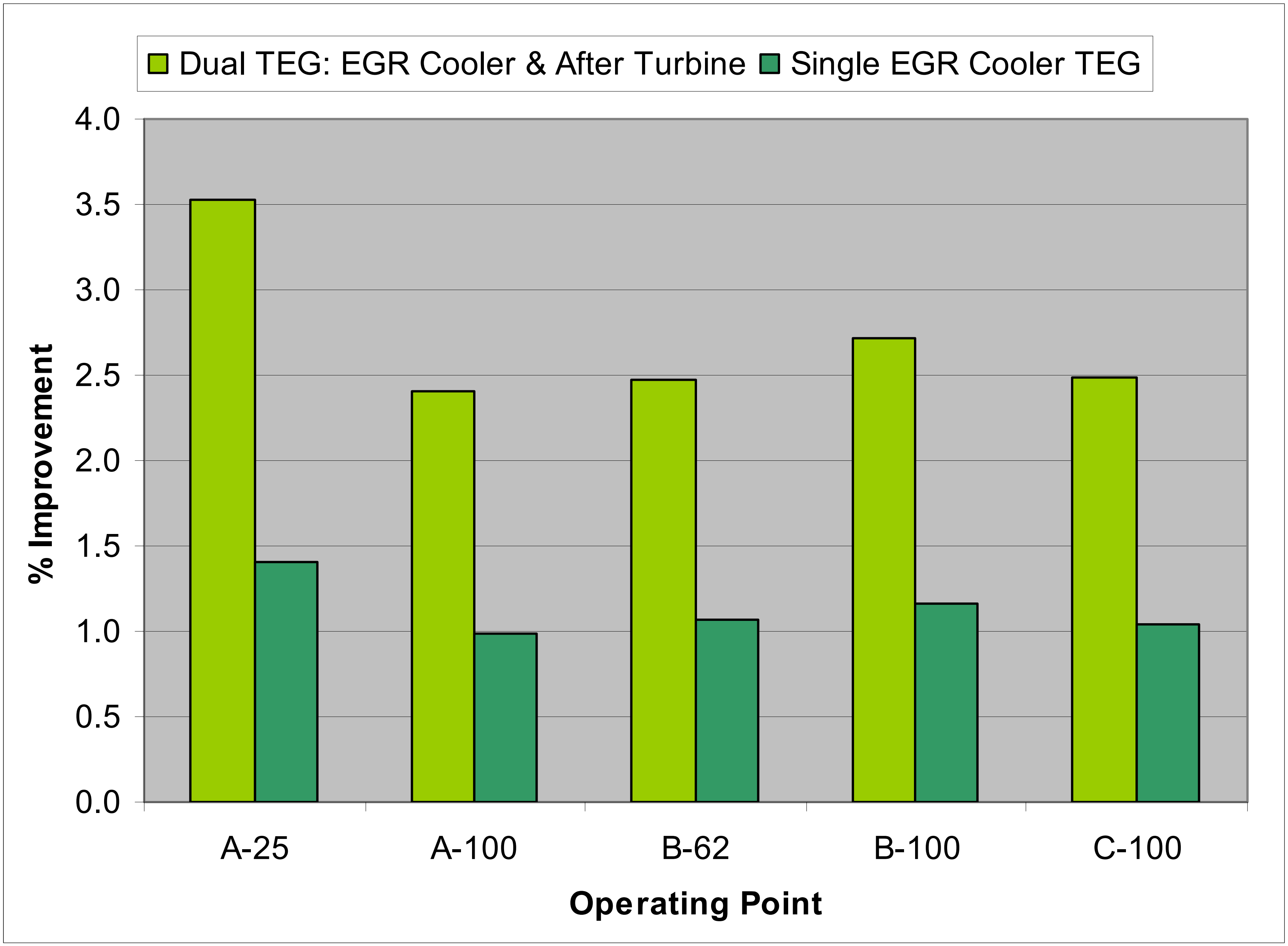


Note: Both TEG lengths have been increased from 150cm to 200cm from Phase I studies

Animation of Temperature Gradients



BSFC % Improvement:
Single TEG EGR Cooler and Dual TEG



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

- Characterization of dry milled LAST (Lead-Antimony-Silver-Tellurium) thermoelectric material, Pilchak, A., Ren, F., Case, E., Timm, E. and Schock, H., submitted to Philosophical Magazine, Spring 07
- Nanostructured Thermoelectric Materials and High Efficiency Power Generation Modules, Hogan, T., Downey, A., Short, J. et al., prepared spring 07
- The Young's modulus and Poisson's ratio of lead-telluride based thermoelectric materials as a function of temperature, Ren, F., Case, E., Timm, E., Schock, H., Lara-Cuzio, E., Trejo, R., Lin, C.H.,Kanatzidis, M., submitted to International Journal of Applied Ceramics Technology, Spring, 07
- Hardness as a function of composition for n-type LAST thermoelectric materials, F. Ren, E.D. Case, E.J. Timm, and H.J. Schock, Journal of Alloys and Compounds, (2007) doi:10.1016/jallcom.2007.01.086
- Young's modulus as a function of composition of n-type lead-antimony-silver-telluride (LAST) thermoelectric materials, F. Ren, E.D. Case, E.J. Timm, and H.J. Schock, submitted to Philosophical Magazine, Spring 07
- Weibull analysis of the biaxial fracture strength of a cast p-type LAST-T thermoelectric material, F. Ren, E.D. Case, E.J. Timm, M.D. Jacobs and H.J. Schock, Philosophical Magazine Letters, Vol. 86, No. 10, Oct. 2006, 673-682

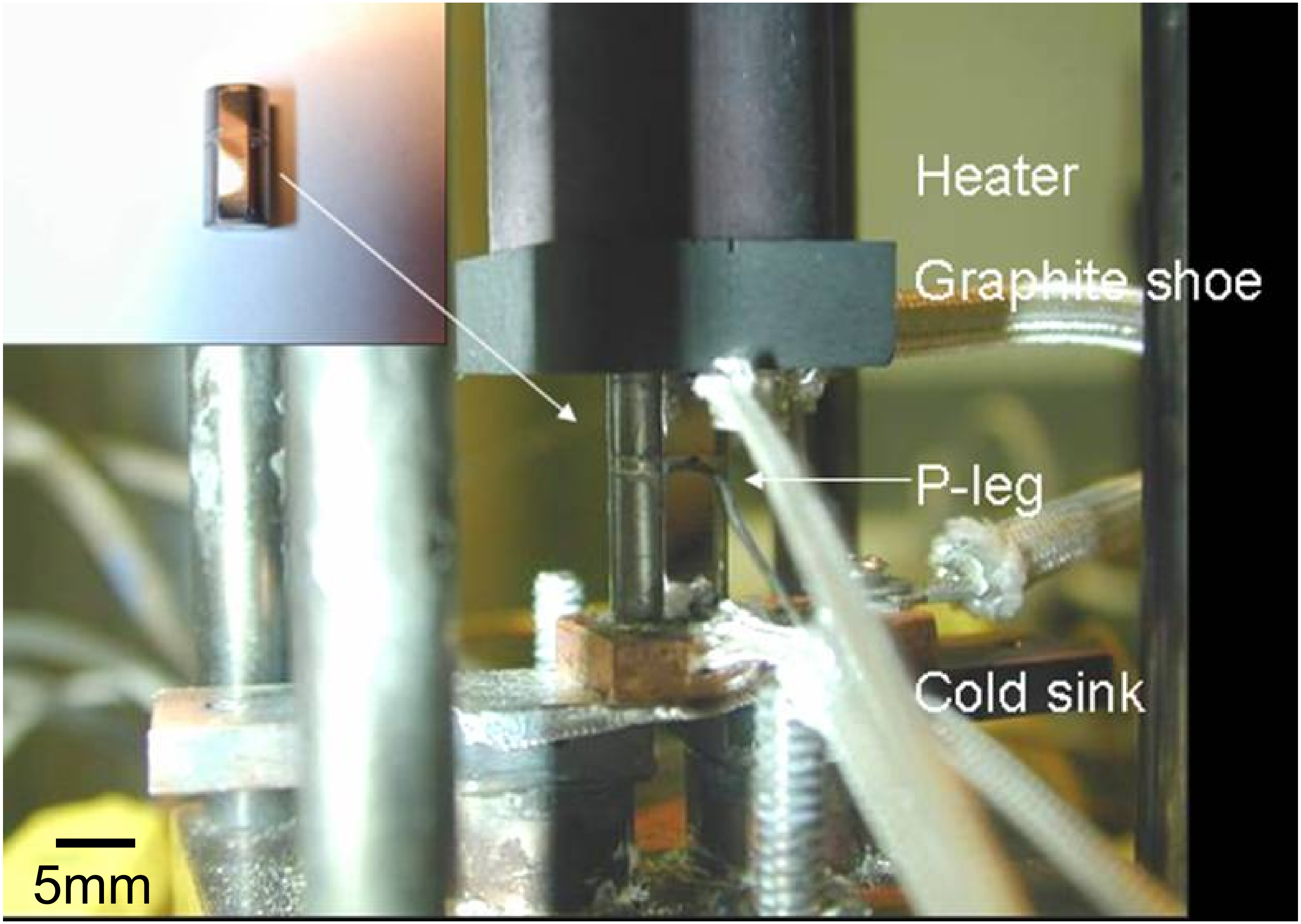
Plans for the Rest of the Year

- July ~ Aug, 2007: Modules being fabricated, segmented concepts testing and powder processing method development ongoing
- Aug ~ Dec. 2007 Evaluation of new TE systems and stoichiometries
- Sept ~ Dec. 2007 Demonstrate power electronics for 100 watt TEG
- Aug ~ Nov, 2007: High efficiency module construction and performance testing
- Sept ~ Nov, 2007: Design of heat exchanger and numerical simulation of expected system performance
- Dec, 2007: Preparing quarterly project report

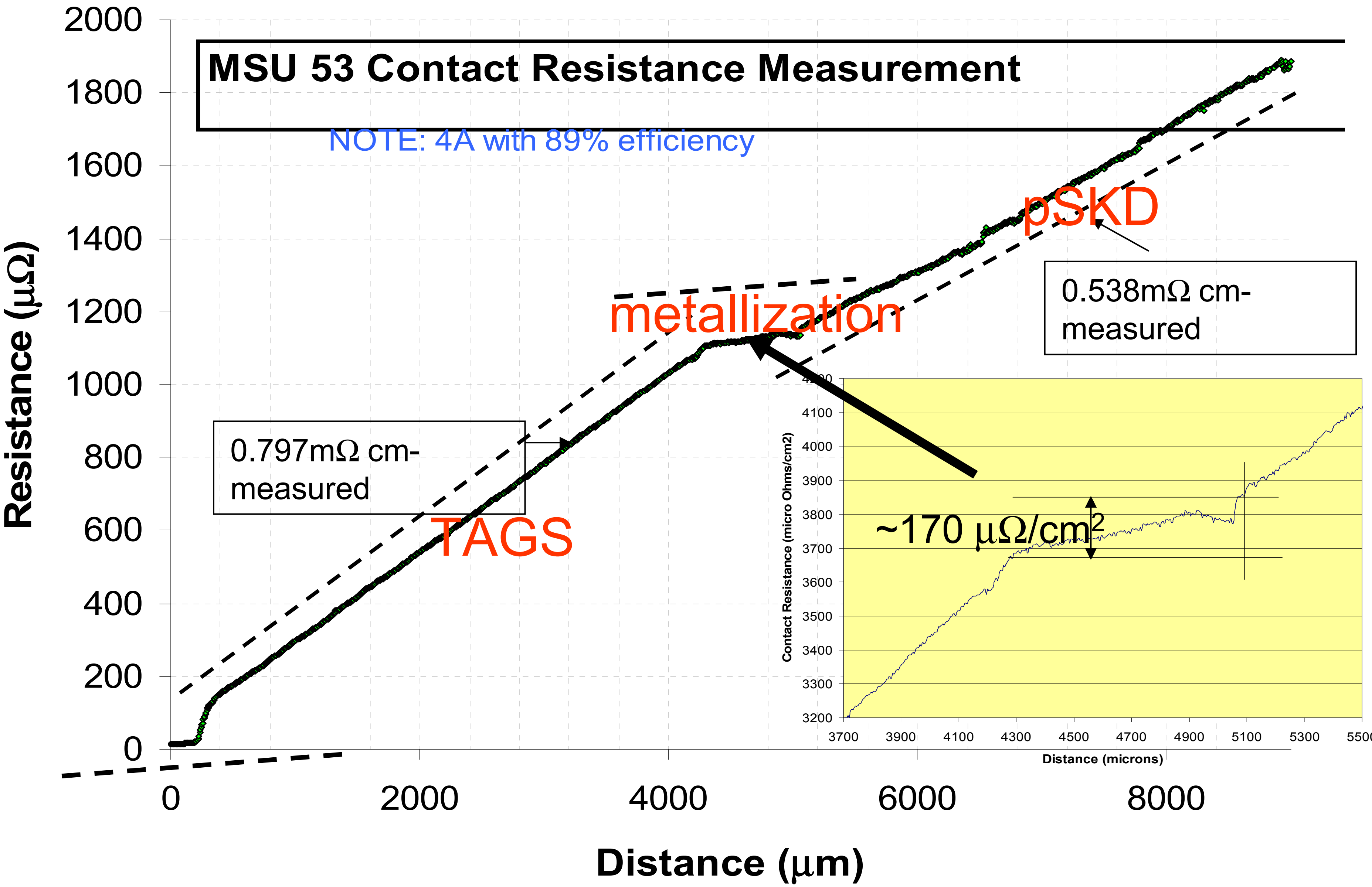
Summary

- Systems for material synthesis, powder processing, hot pressing, leg and module fabrication are operational at MSU
- Facility in place to produce materials required for a 40 watt module in one week …thus new concepts can be evaluated in about one week
- Thermoelectric performance testing of legs and modules at MSU is in agreement with others doing similar measurements
- Power conditioning electronics for maximum power tracking and fault mitigation are being 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

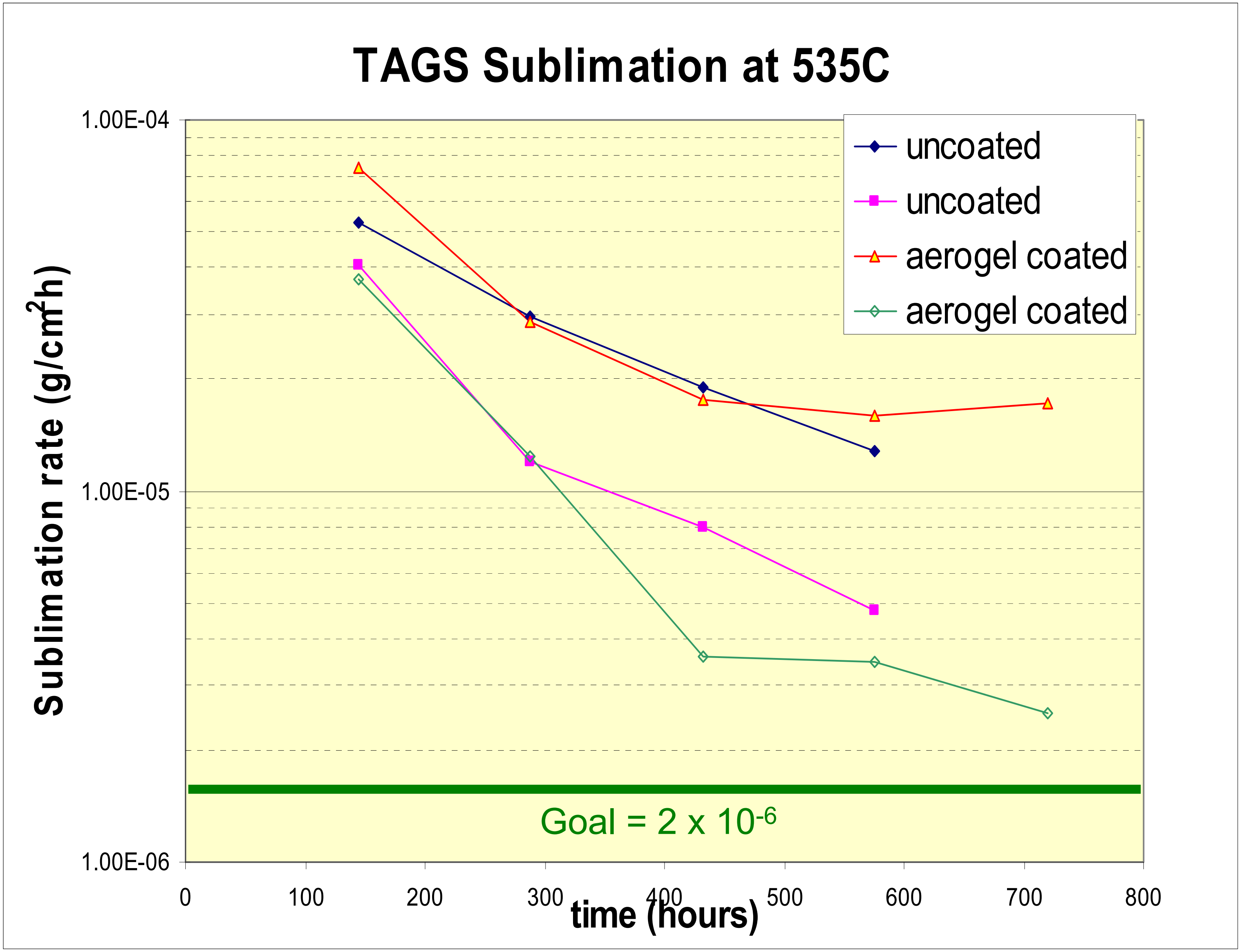
MSU53: Metallized (end-end) Segmented pSKD+TAGS leg



•Test set up for validating power output of pSKD/TAGS segmented leg



- Contact resistance measured using new 100nm step scanning probe
- Measured resistivity of TAGS & pSKD within +/- 2% of published data
- Contact resistance at segmented interface is low and can be reduced by reducing thickness of metallurgical bond



❖Aerogel suppressed sublimation by a factor of 10 and is approaching the 10years of operation goal at 535C