

# ***Status of Segmented Element Thermoelectric Generator for Vehicle Waste Heat Recovery***

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**Thermoelectric Applications  
Workshop  
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# Program Overview

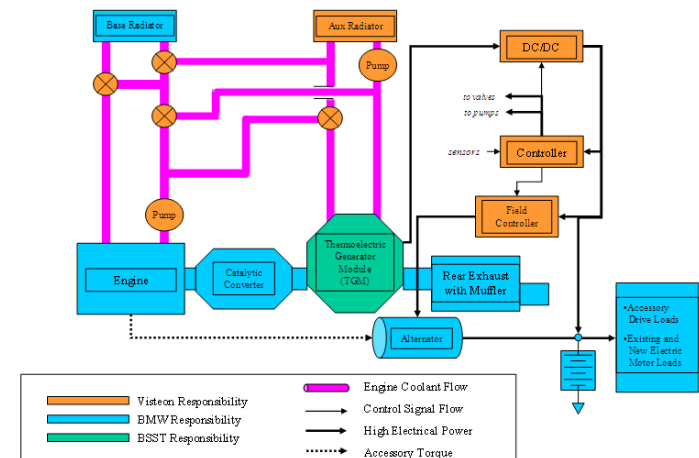
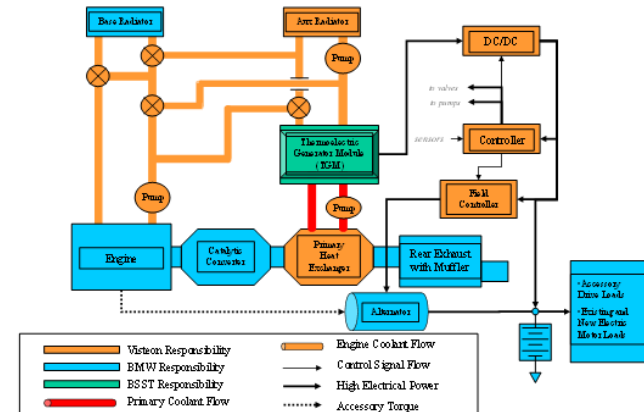
BSST led DOE team includes BMW,  
Ford and Faurecia

\$9 ½ M five phase program.

Phase 1: System modeling and  
architecture evaluation

Phase 2: Subsystem design, build  
and bench test

Phase 3: System integration.  
Planar configuration TEG with  
primary HEX and secondary  
loop, power converter



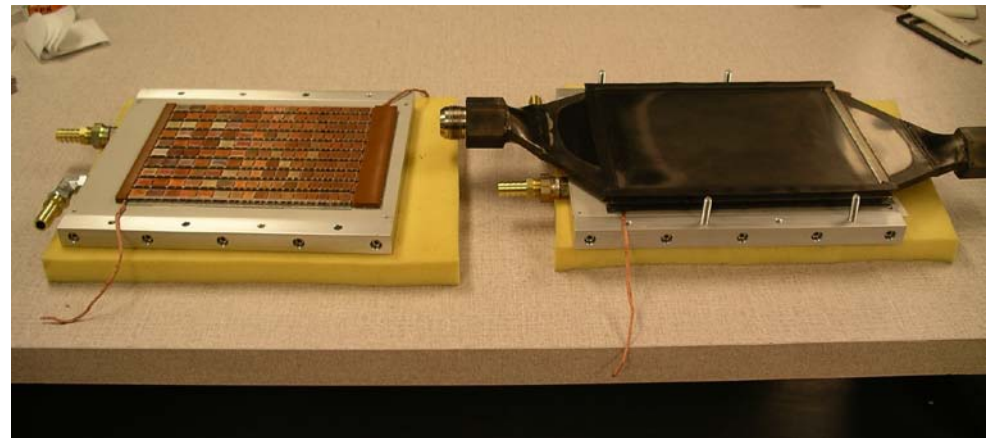
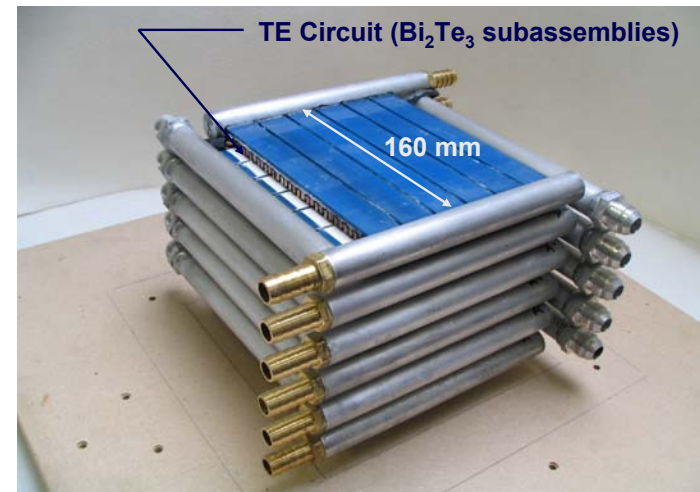
# Program Overview

Phase 3: 500 watt BiTe TEG built and tested, 125 watt high temp TEG built and tested

Architecture transitioned to direct flow through TEG (no secondary loop)

Phase 4: TEG design transition from planar to cylindrical, design and integration of bypass valve with coaxial bypass feature, Full scale, high temperature Gen 1 cylindrical TEG built and tested

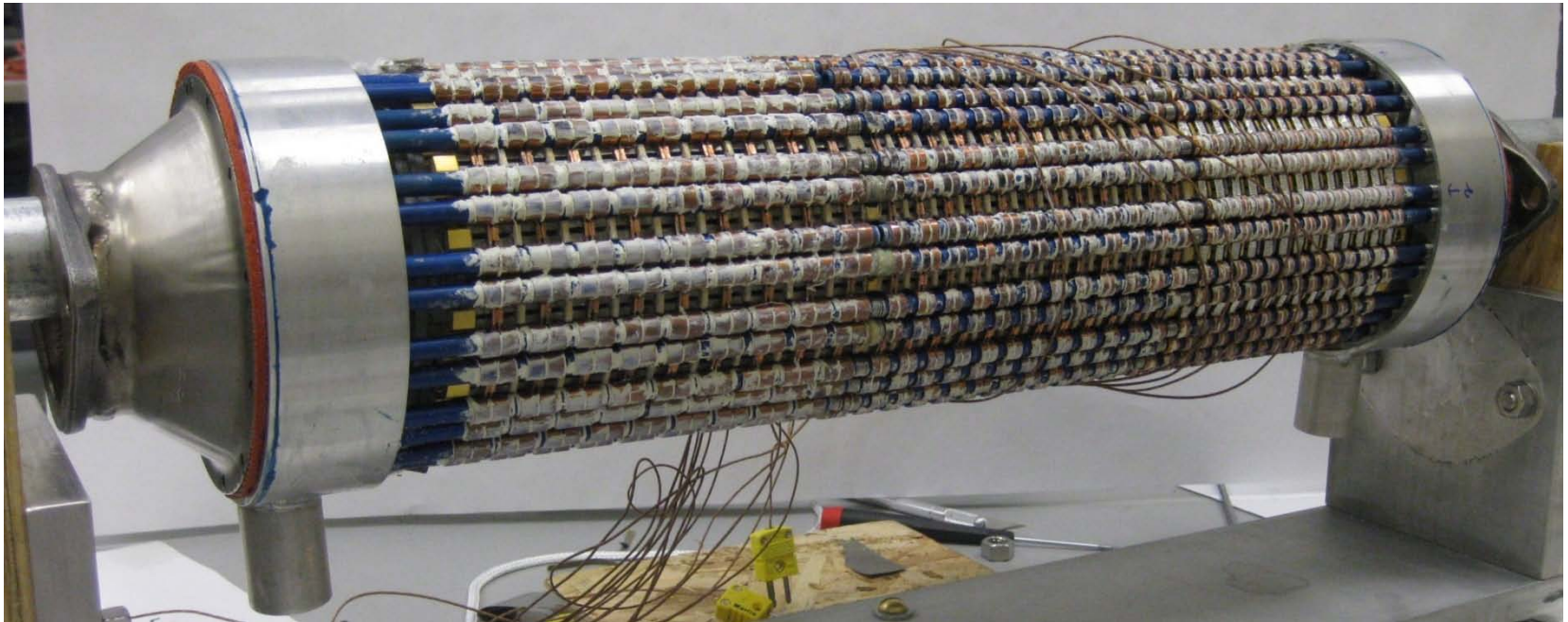
Phase 5: Cylindrical TEG Gen 2 design/build, integration with BMW X6 and Ford Fusion vehicles. test and evaluation (completion planned for Q1 2011)



# *Phase 4 Thermoelectric Generator*

The complete TEG shown below includes gas diffusor cones, completed liquid circuit and over 500 TE engines.

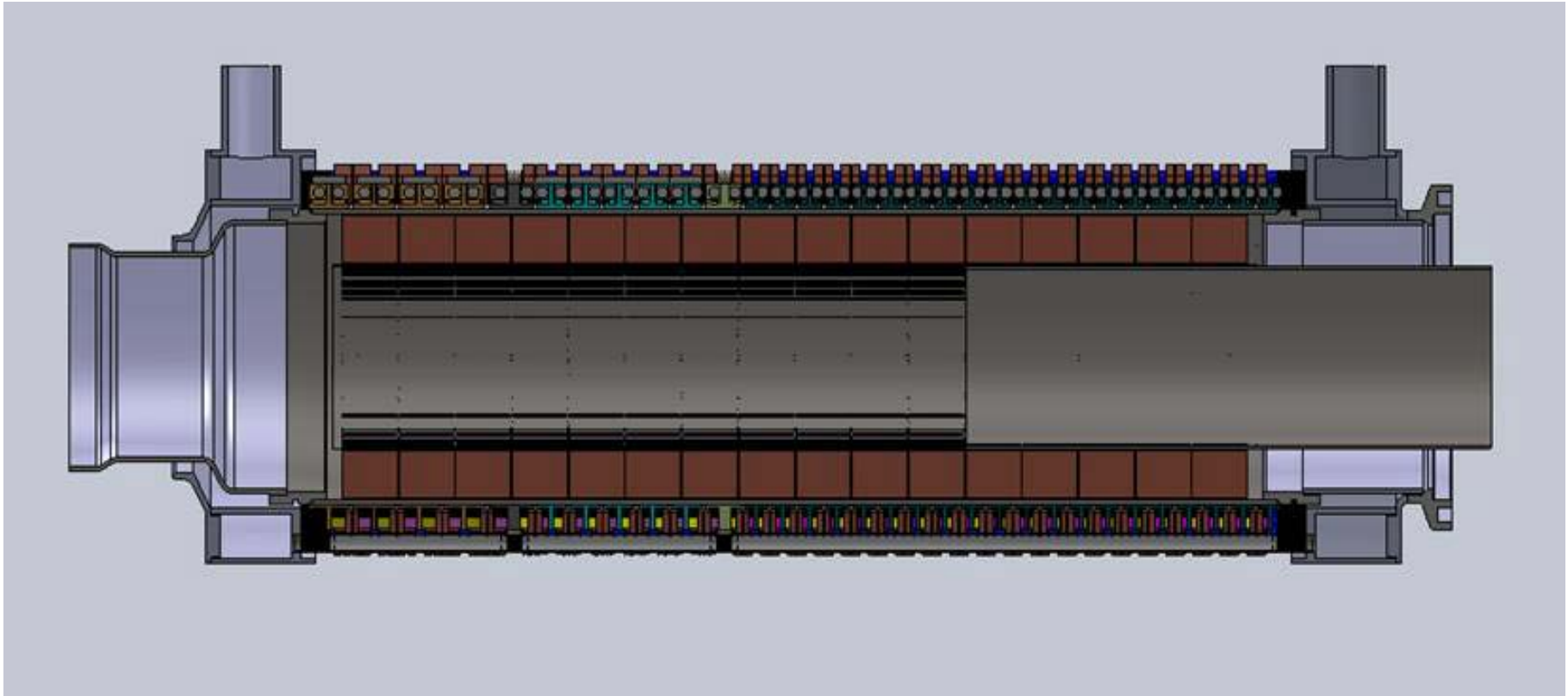
The approximate weight is 10.5 kg and is designed to produce 500 watts power at 40 grams/sec - 600 °C gas flow.





# *Phase 5 TEG Design*

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# TE Engine Architecture

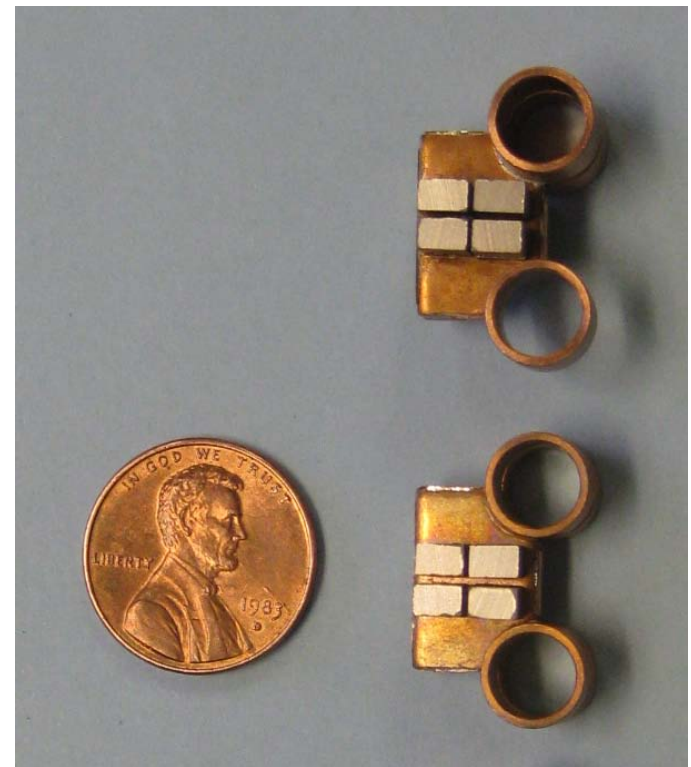
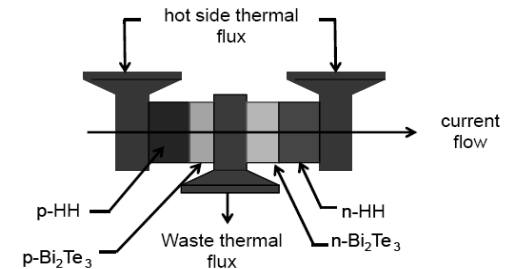
High and medium temperature TE engines are shown in the photo-right

The engines incorporate segmented Half Heusler and BiTe elements

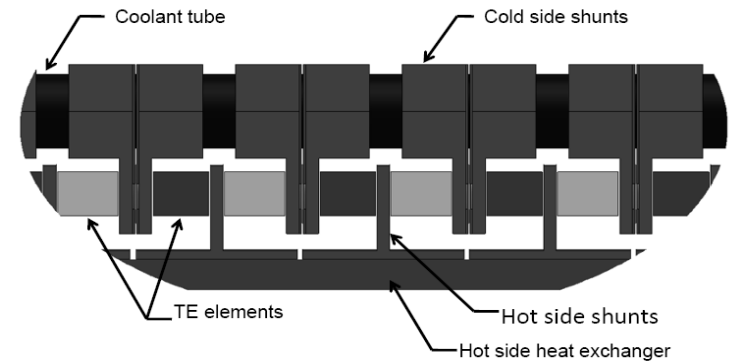
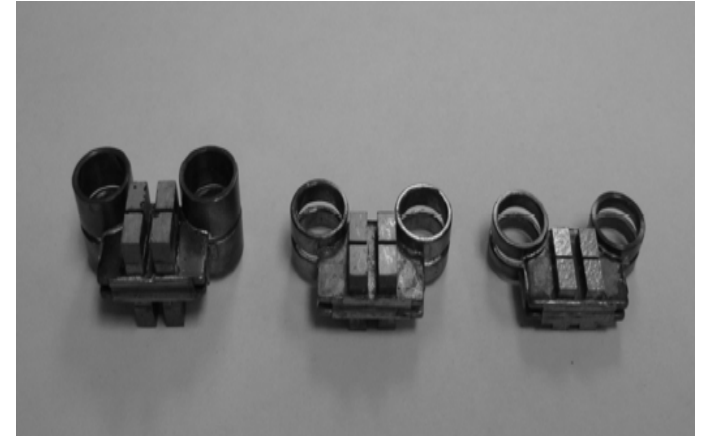
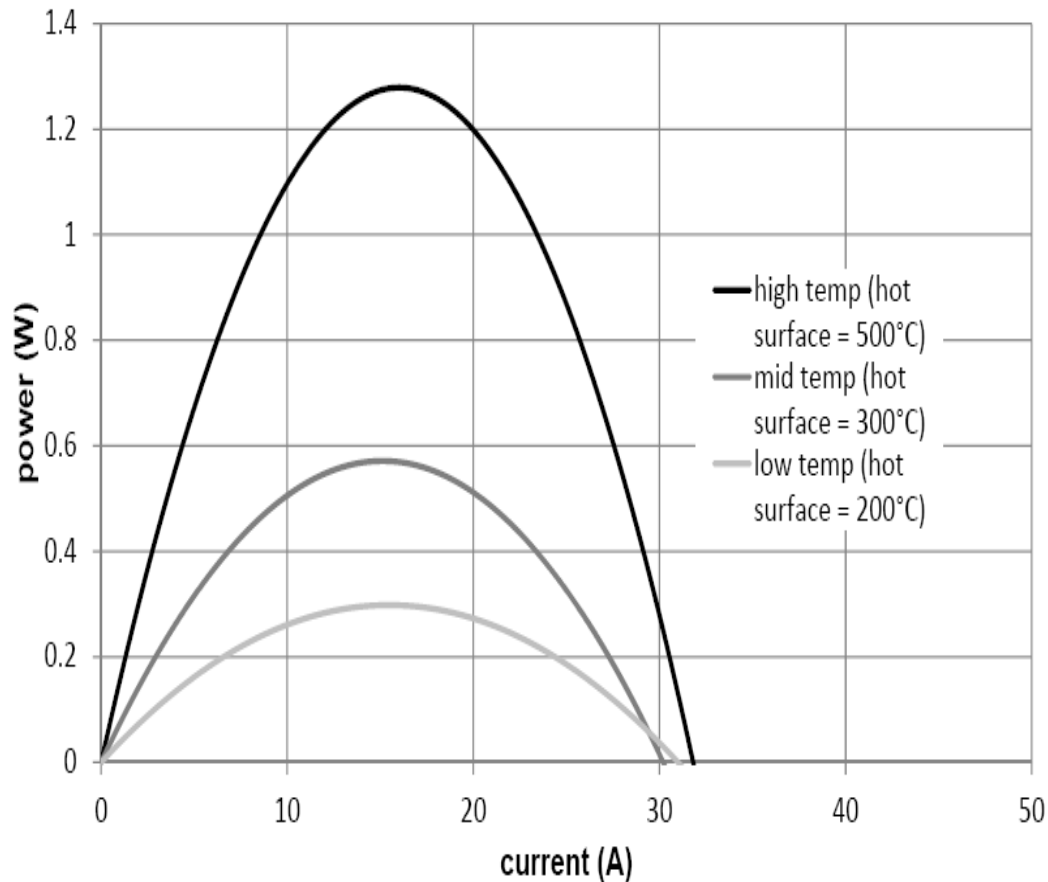
The geometry of each element (n & p, HH and BiTe) are tailored according to the thermal flux environment and other design considerations

The engines are inserted between copper rings (shunts) fixed to the gas heat exchanger

Copper sleeves are attached to reject heat to a fluid circuit



# Phase 4 TE Engine Design



# Test Results- TE Engines

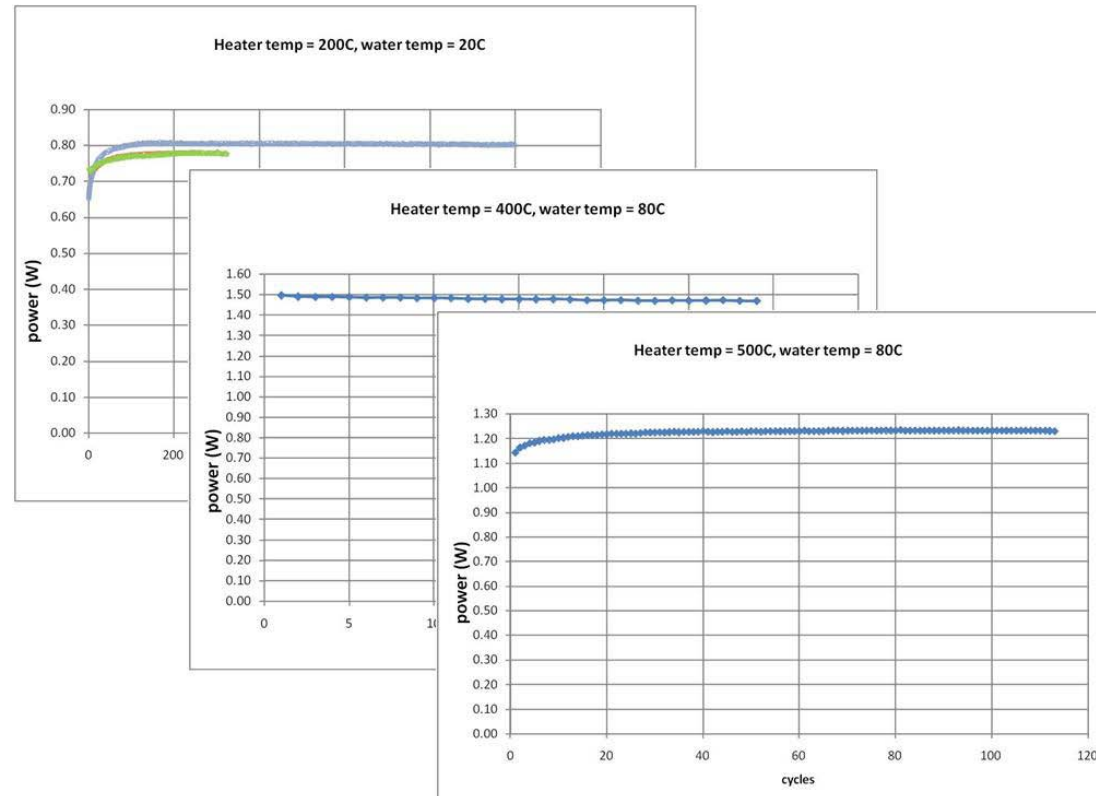
Thermal cycling of TE engines has been ongoing for > five years.

Testing is performed using electric heaters as the thermal power source and a liquid circuit for heat rejection.

Cycling is performed to simulate the different temperature environments that TE engines will be exposed to in the direction of gas flow along the underfloor exhaust component.

Cycle times range from 5 to 60 minutes.

Hot side temperatures range from 200 °C to 500 °C at the TE material-substrate interface.



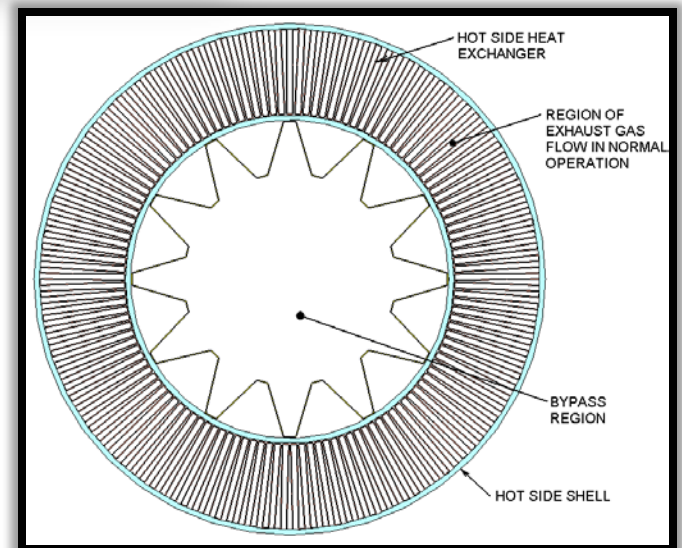


# Exhaust Gas Heat Exchanger

Internal folded fin, offset heat exchanger brazed to tubular housing

Fins are stainless steel clad copper

Internal exhaust bypass duct prevents overheating and controls back pressure



# Hot Side Shunt

Copper rings are in intimate thermal contact with the gas heat exchanger to provide consistent and effective heat transfer to TE elements

The rings are electrically isolated from the gas heat exchanger

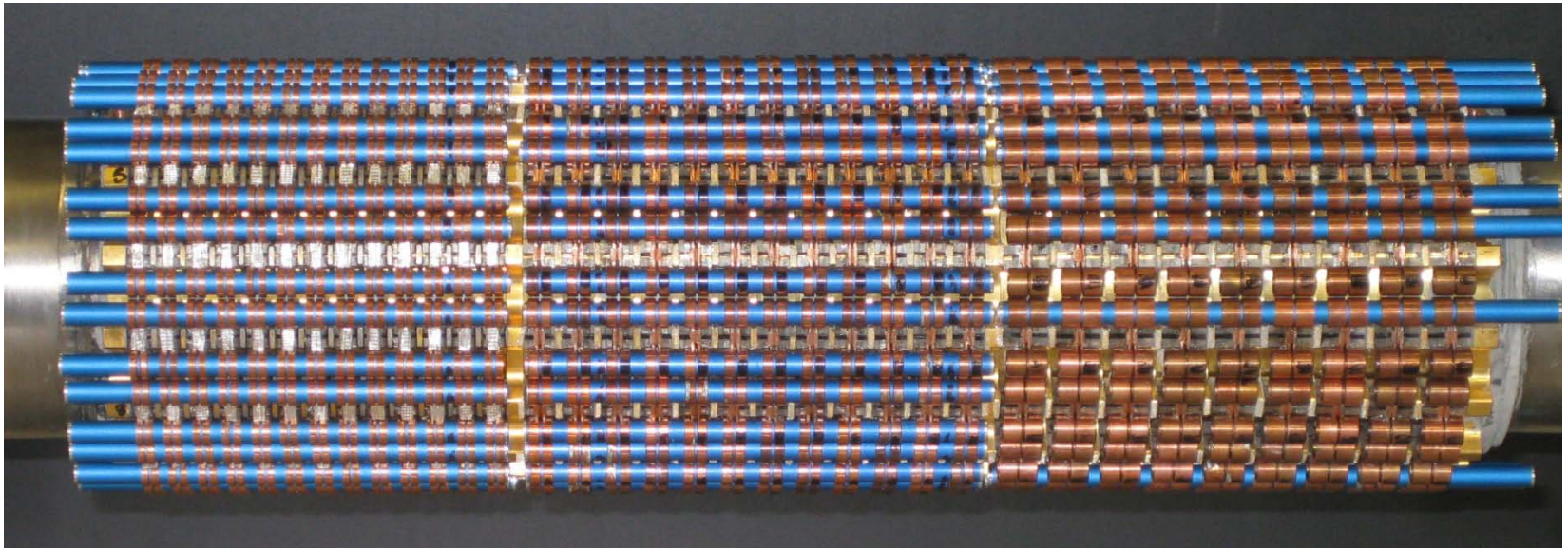
Shown at right is a low temperature ring which includes TE elements



# *Cold Side Circuit*

Liquid tanks are attached at each end of the TEG. The cooling liquid flows counter to the flow of hot gas.

Liquid carrying aluminum tubes (blue color) reject heat via copper sleeves connected to each TE engine.



# TE Element Model

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Equations used to model the TE elements were defined by Snyder

Temperature gradient across the TE element is predefined and then subdivided into smaller equal temperature steps

Three basic material properties, Seebeck coefficient, electrical resistivity, and thermal conductivity, which are defined as functions of temperature, are calculated at each of the temperature steps

Reduced current density, the ratio of the electric current density to the conduction-driven heat flux, is calculated at each step using the measured TE material properties

Initial reduced current density is defined as 
$$u_1 = \frac{I}{Q_h - \alpha_1 I T_1}$$

Temperature variation along the length of the TE element is calculated as a function of the reduced current density. The sum is equal to the current density times element length.

Constraint for the optimization is that the TE elements must match a predefined element length.

# TE Element Model

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Using MATLAB's FMINCON optimization function, the model makes initial assumptions for heat flow and current. It iteratively solves for the heat flow and current that maximizes TE element efficiency

Electrical interfacial resistance is a model input. It indirectly measured in validated heating and cooling experiments

Thermal interfacial resistance is related to electrical interfacial resistance by the Wiedmann-Franz law

Reduced current density is also evaluated at the temperature step created by the electrical contact resistance and the temperature drop caused by the thermal contact resistance

In this way, the metallization and other interfacial attributes of the elements are evaluated.

To model segmented elements, more interfaces are added, but the evaluation method remains the same.



# Device Model Attributes

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Electrical and thermal resistances, including interfacial, are rigorously modeled

Conduction, convective, and radiation heat loss factors are captured

Different operating environments can include air, argon, xenon, or vacuum as well as different types of insulation

Different fin correlations can be defined, including straight, offset, wavy, annular, as well as other more specialized correlations

# Device Model Attributes

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- Electrical load resistance can be selected or set equal to the internal resistance of the TEG for maximum power output
- Different TE materials including  $\text{Bi}_2\text{Te}_3$ , PbTe, TAGS, Half Heusler, and Skutterudite
- Different fluids including air, water, helium/xenon, water/glycol, exhaust gas, and other specialized fluids
- Other materials of the device can be selected including copper, aluminum, SST, molybdenum, clad materials, and various ceramic materials

Greater than 20 different design variables, including fin and TE dimensions

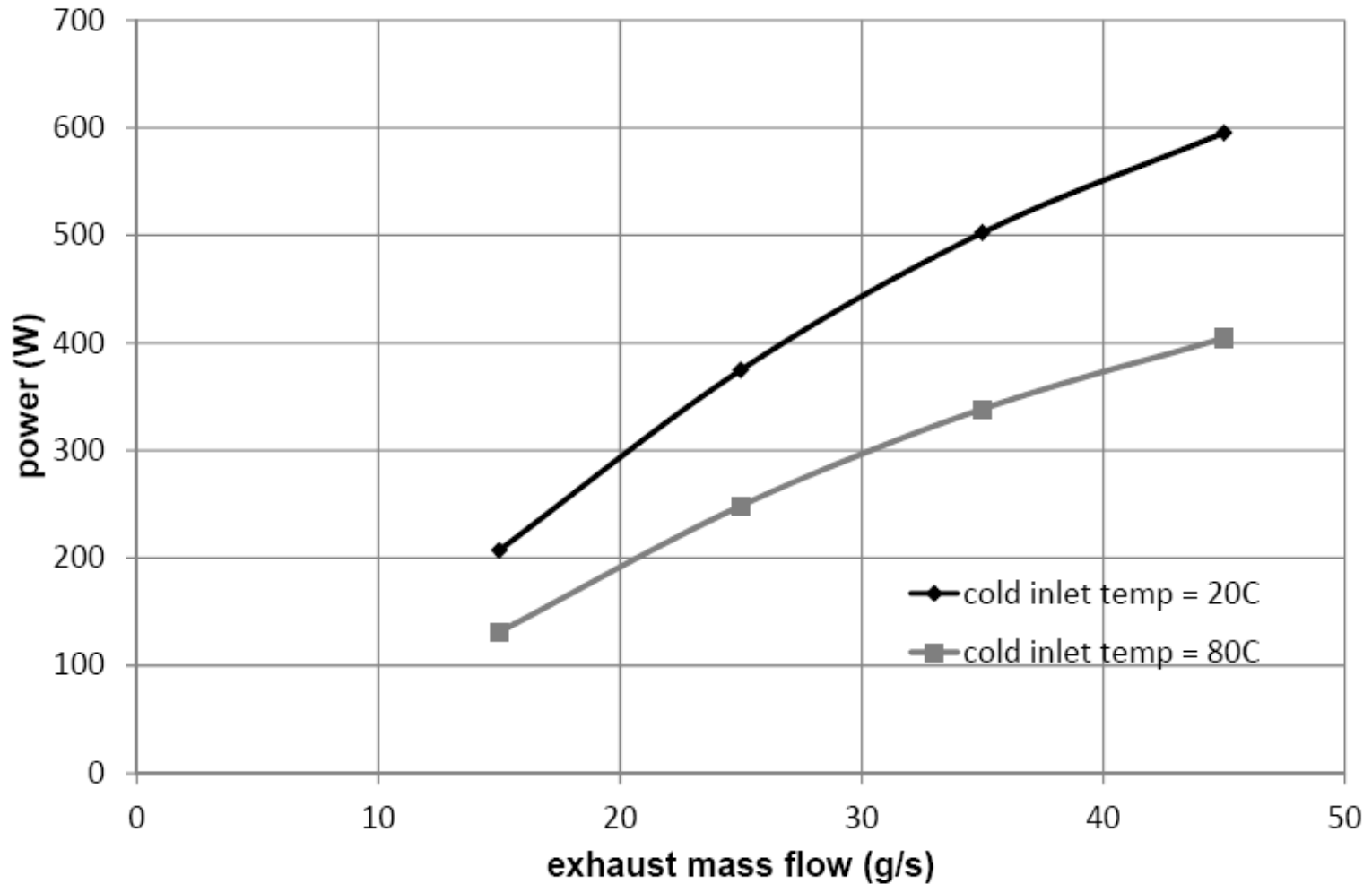
Dozens of different design parameters, including operating conditions

Variety of different constraints, including minimum power density, maximum hot and cold side pressure drops, maximum total mass, and minimum output power

Also maximum TE surface temperature and maximum temperature gradient per unit length across the TE elements to help improve design robustness

Objective function can be maximum gross or net power, maximum efficiency, or maximum gross or net power density, which can be based on either total or TE mass.

# Power Production vs Mass Flow

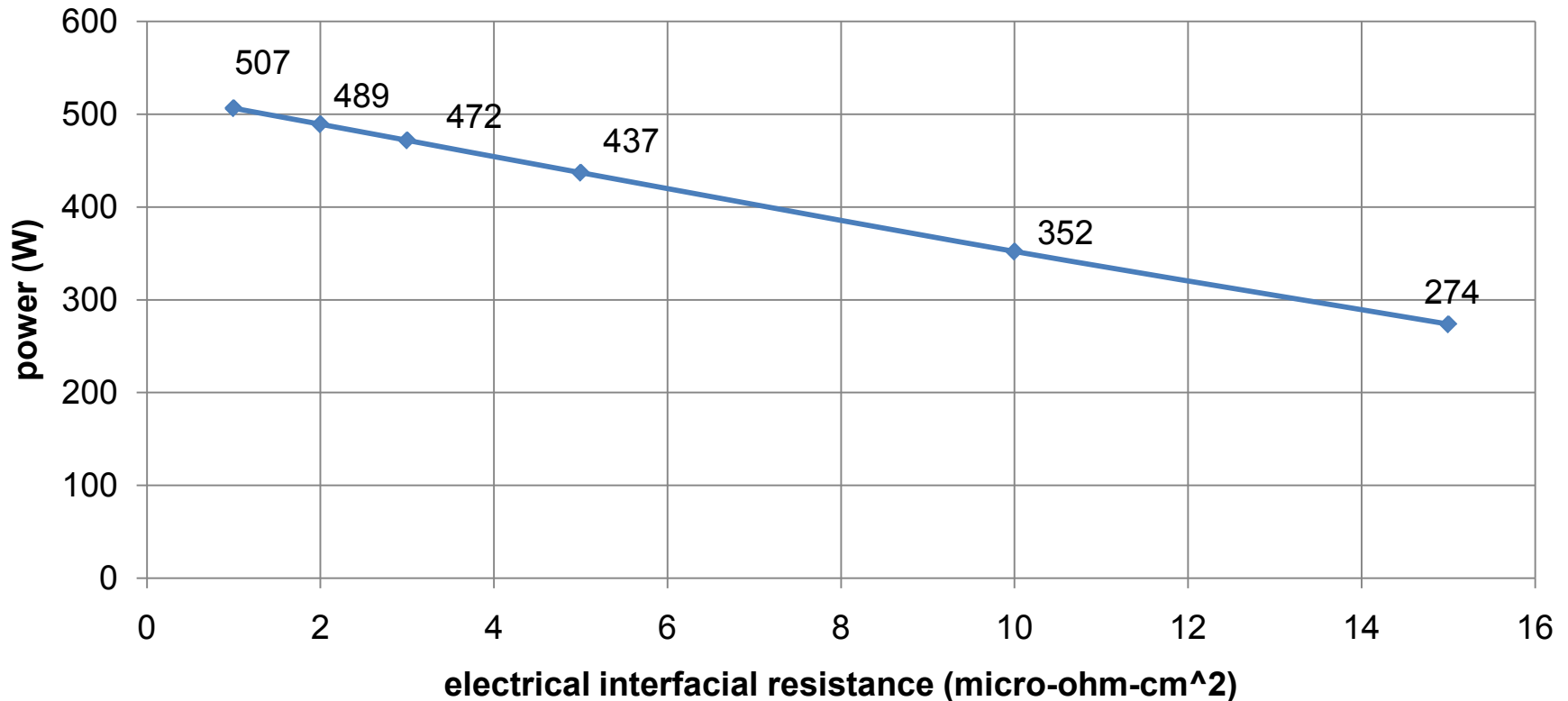


# Interfacial Resistance Analysis

## TEG Performance as a Function of TE Electrical Interfacial Resistance

( $T_{\text{hot, inlet}} = 580^{\circ}\text{C}$ ,  $\dot{m}_{\text{hot}} = 39 \text{ g/s}$ )

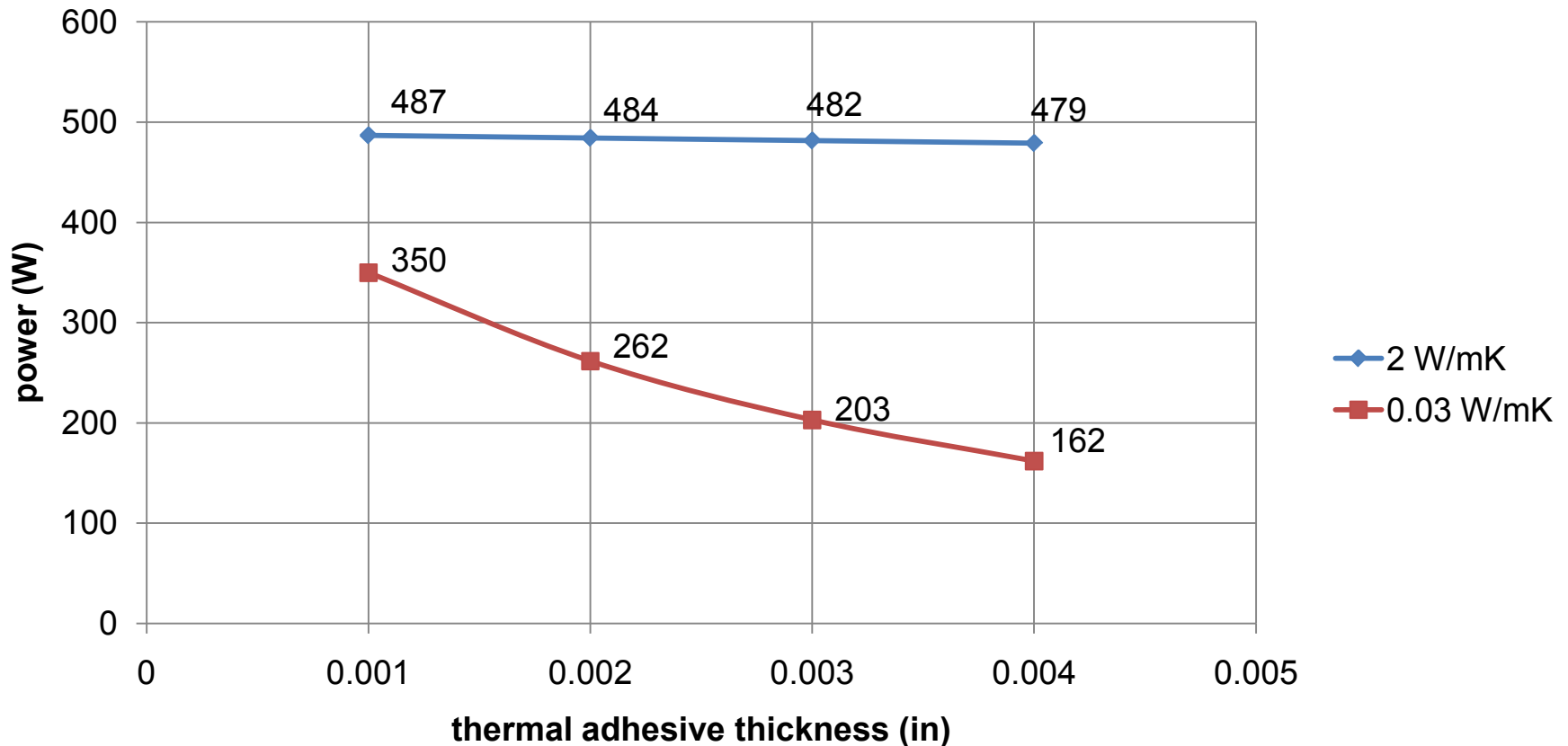
( $T_{\text{cold, inlet}} = 27^{\circ}\text{C}$ ,  $\dot{m}_{\text{cold}} = 20 \text{ lpm}$ )





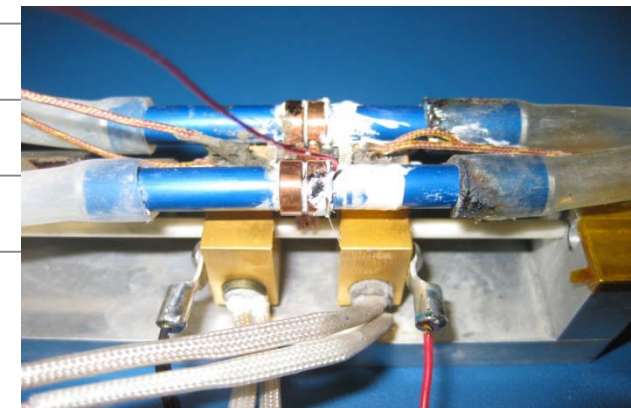
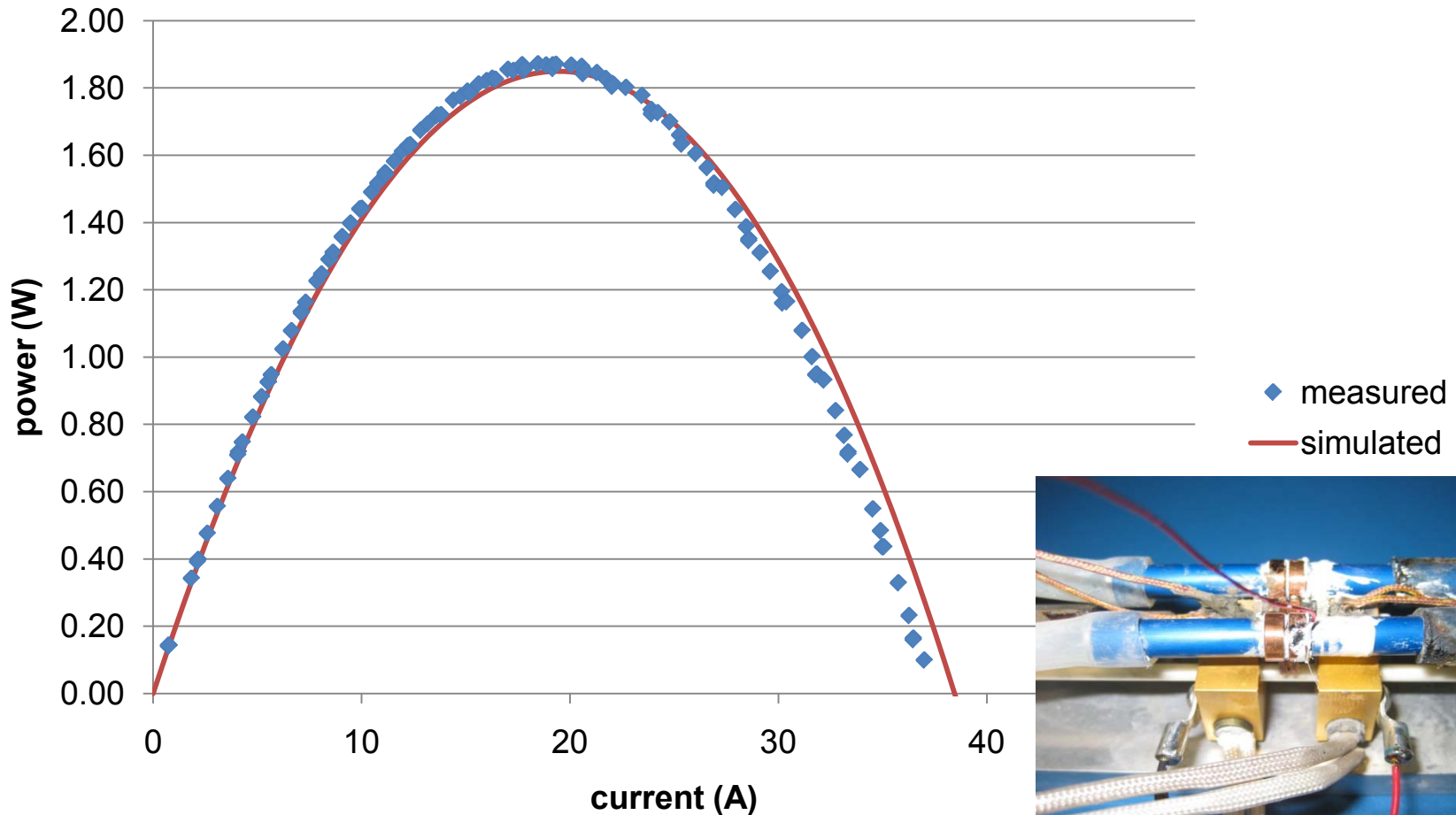
# Parasitic Loss Impact on Performance

**TEG Performance as a Function of Hot Side Thermal Adhesive**  
( $T_{hot, inlet} = 580^{\circ}\text{C}$ ,  $\dot{m}_{hot} = 39 \text{ g/s}$ )  
( $T_{cold, inlet} = 27^{\circ}\text{C}$ ,  $\dot{m}_{cold} = 20 \text{ lpm}$ )



# Phase 4 Subassembly Performance

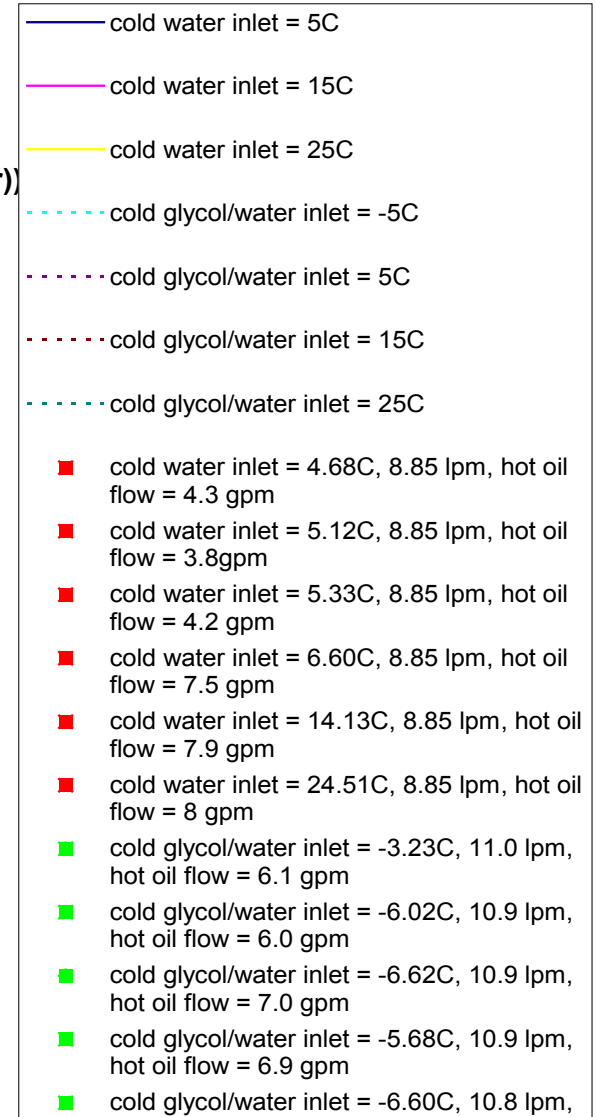
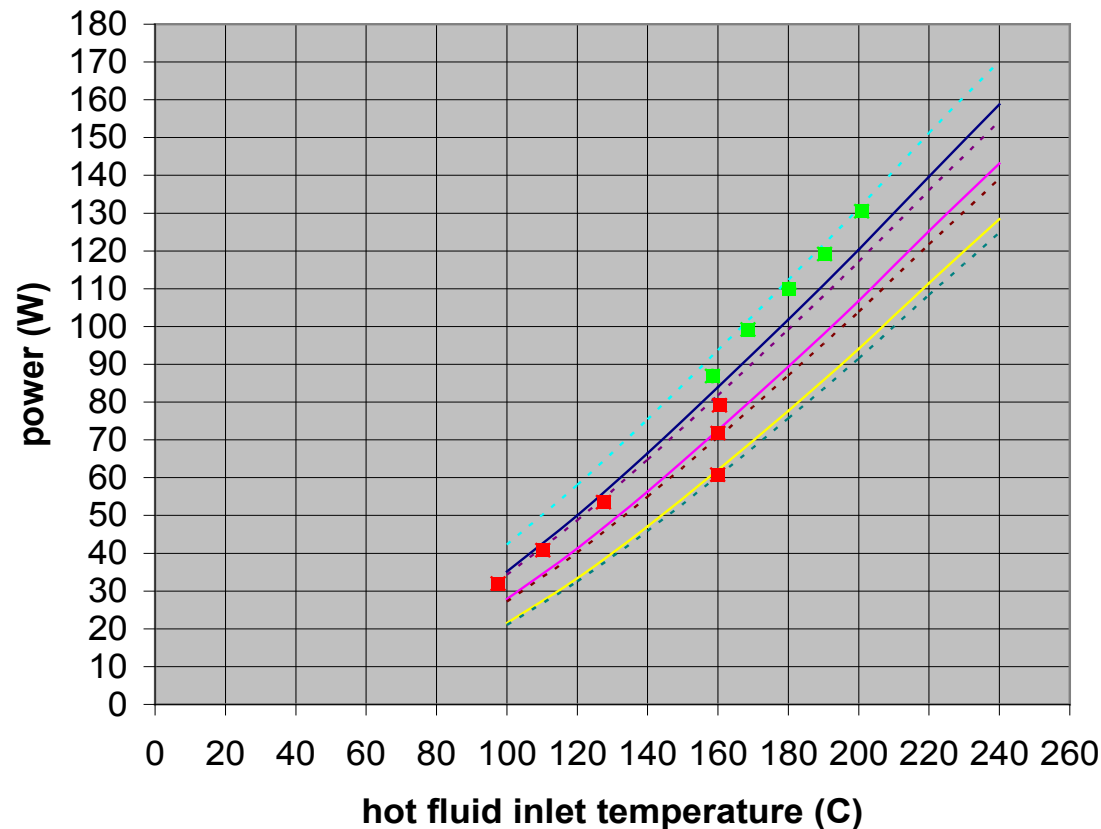
**High Temperature Subassembly Performance**  
(heater temperature = 507.5C, water temperature = 20C)  
(half Heusler/Bi<sub>2</sub>Te<sub>3</sub> Segmented elements)



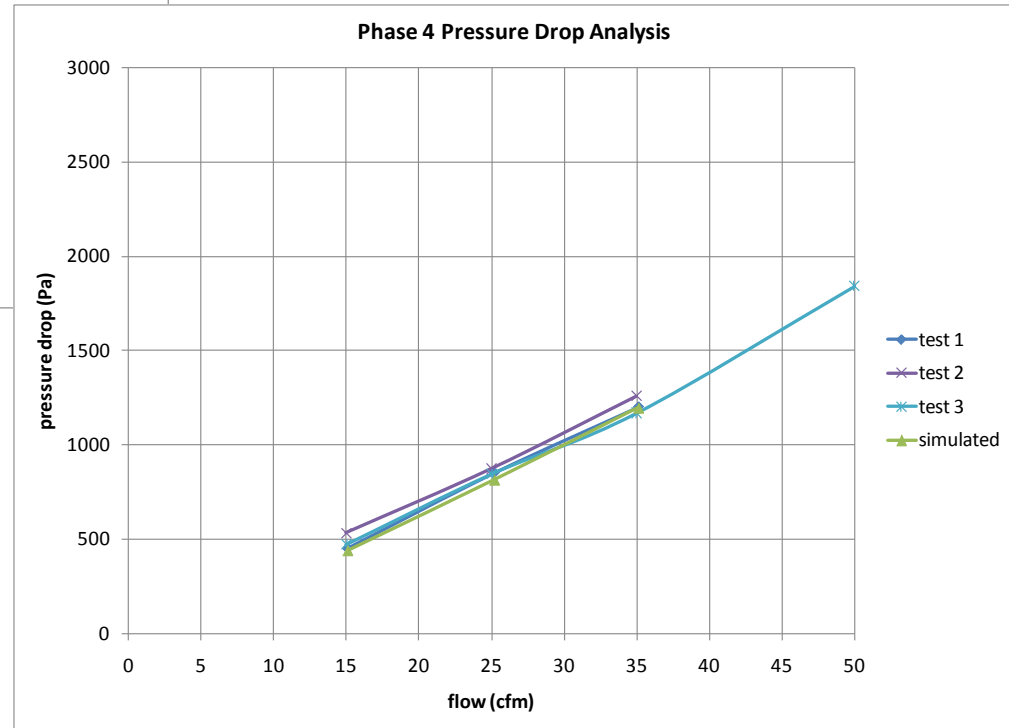
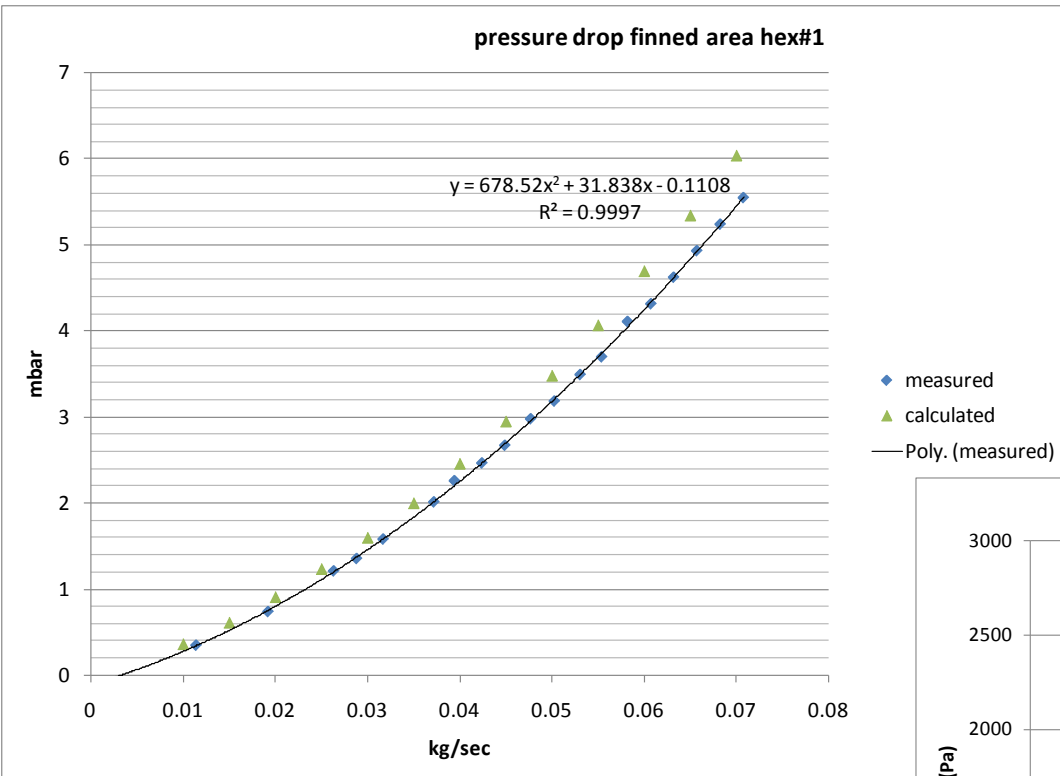
# Low Temperature Planar TEG Performance Validation

## Single plate

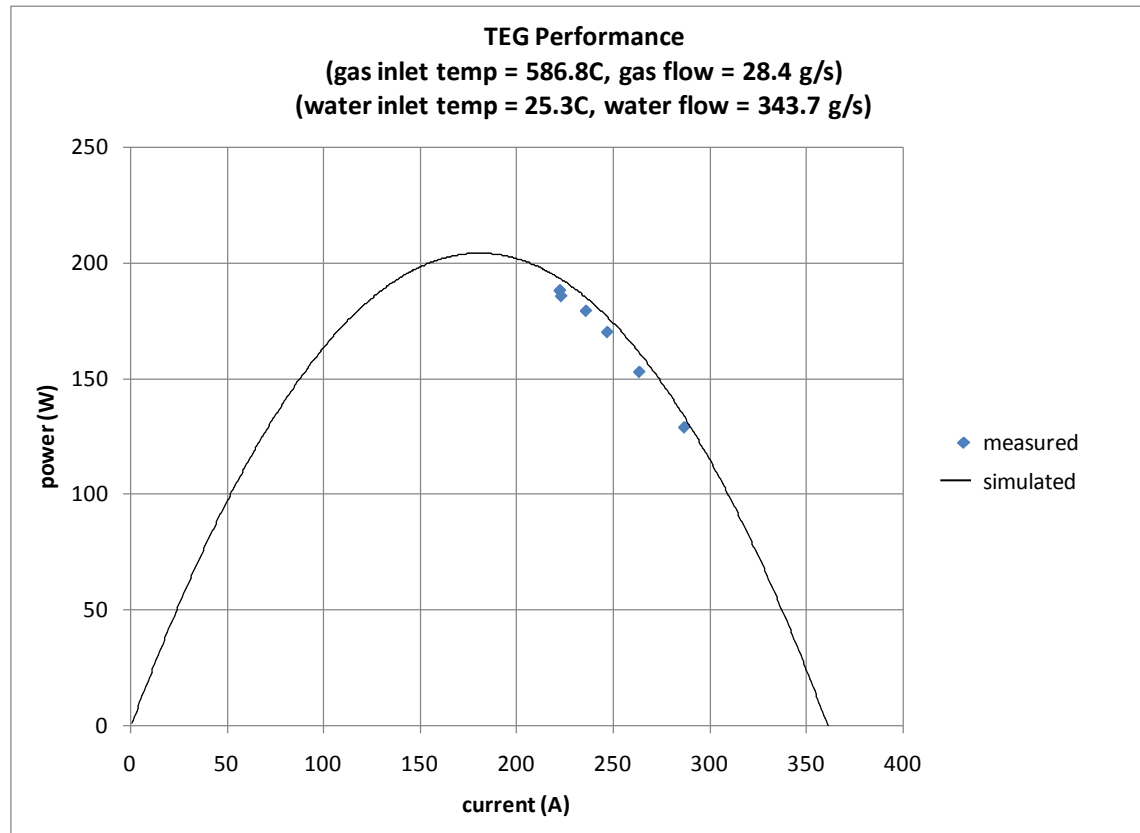
(interfacial resistance =  $2\mu\Omega\text{cm}^2$ ,  
hot volume flow = 8 gpm (Xceltherm 600),  
cold volume flow = 8.85 lpm (water or glycol/water))



# Cylindrical Gas Heat Exchanger Validation – Pressure Drop



# Phase 4 TEG Measured Performance



## Analysis of Results

- Bench test results demonstrated excellent electrical isolation between TE assemblies and heat exchanger, coolant circuit and housing.
- Analysis indicated inadequate heat transfer (both hot and cold sides) and higher than predicted electrical circuit resistance
- Phase 5 TEG slated for Q1 2011 vehicle installations includes a number of validated countermeasures



# Transient Differential Equations

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Steady state model gives an effective means to choose a nominal design point and optimize the design for this set of operating conditions

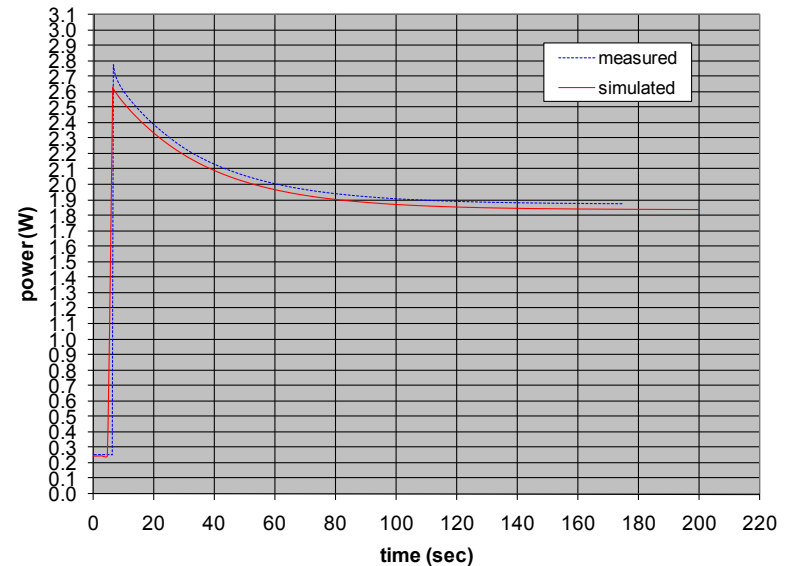
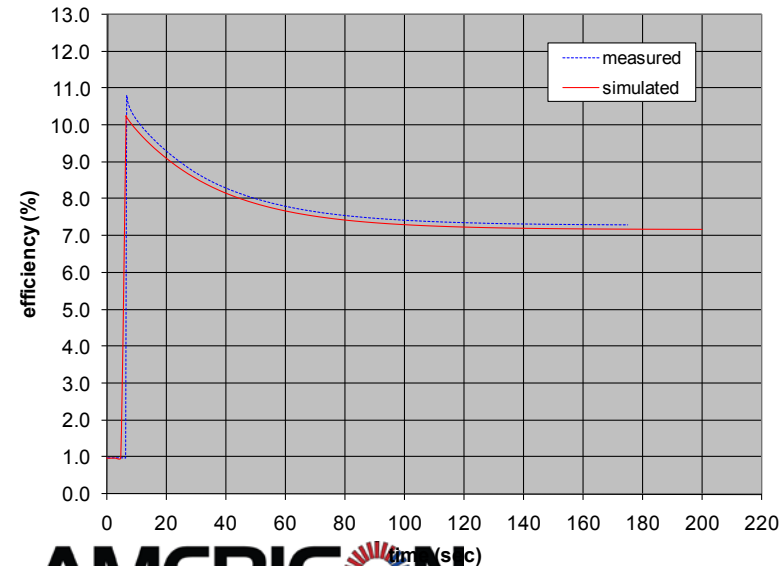
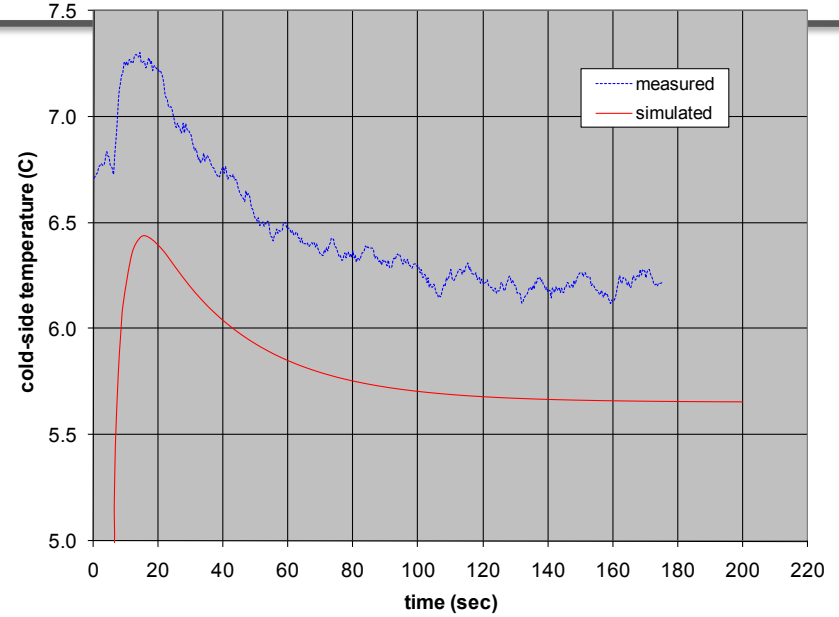
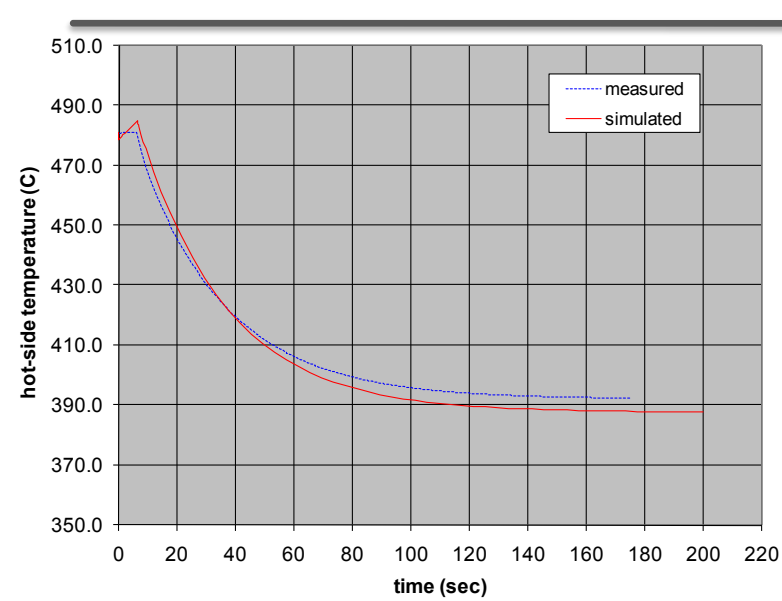
TEG may see a wide array of operating conditions that may change as a function of time

This is certainly the case when the TEG is integrated into a car or truck

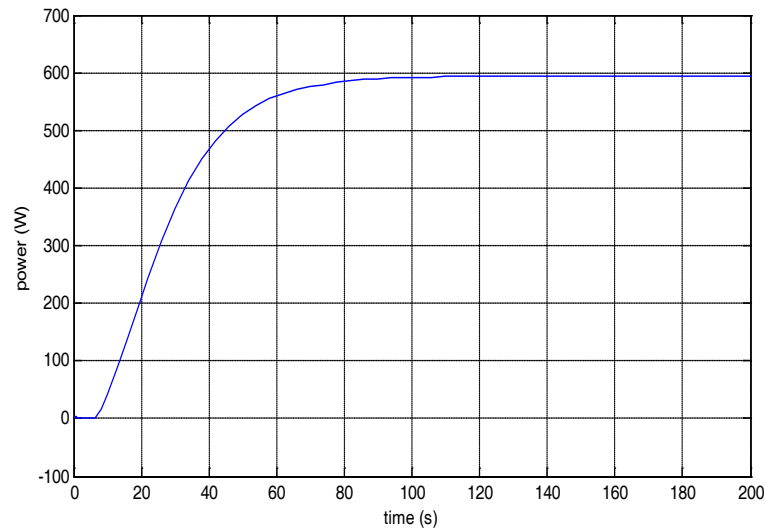
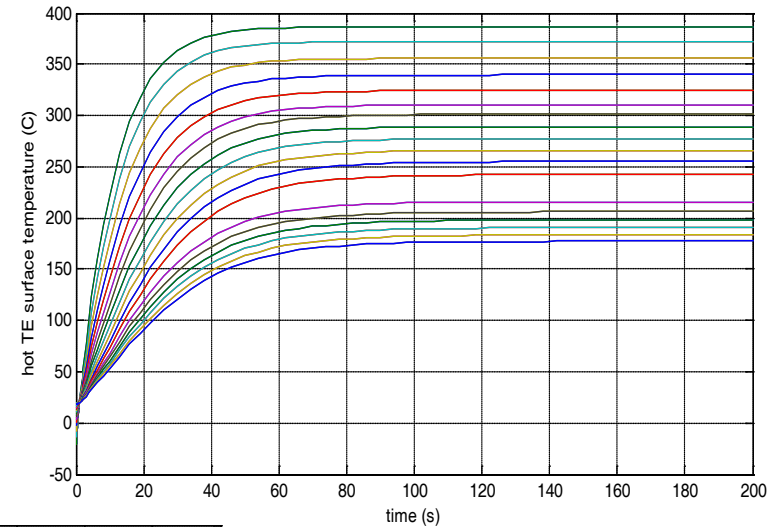
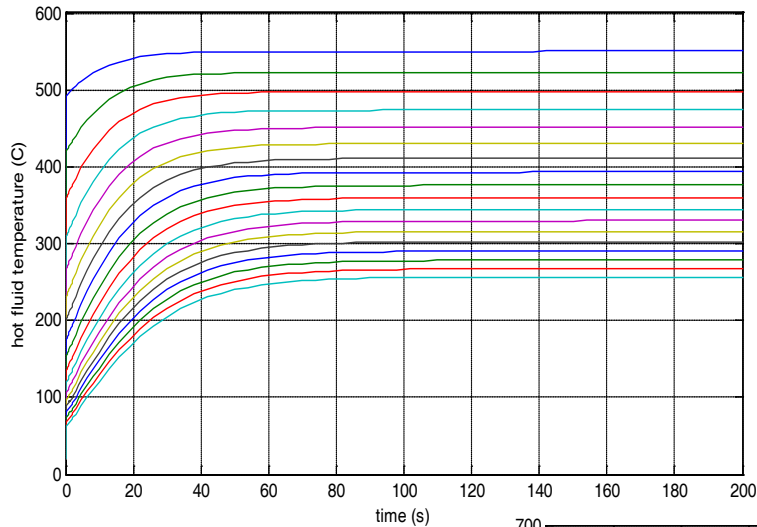
To extend the steady state model to a transient model, the energy balance equations were transformed as differential equations based on  $mC_p \frac{dT}{dt} = Q_1 - Q_2$  and integrated into the S-function template of MATLAB/Simulink

The  $mC_p$  term is the thermal mass of each control volume

# Transient Segmented Element Subassembly Performance

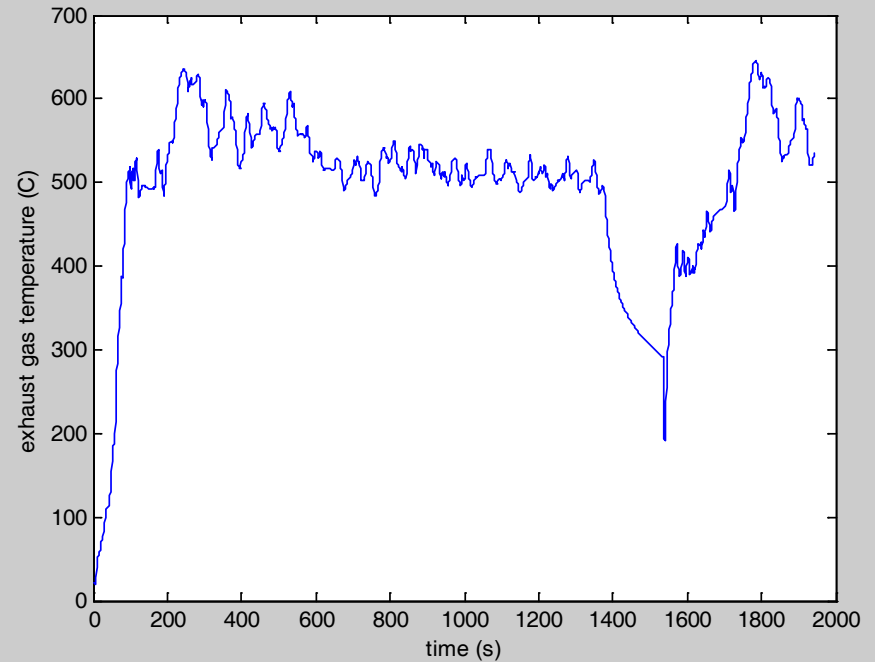
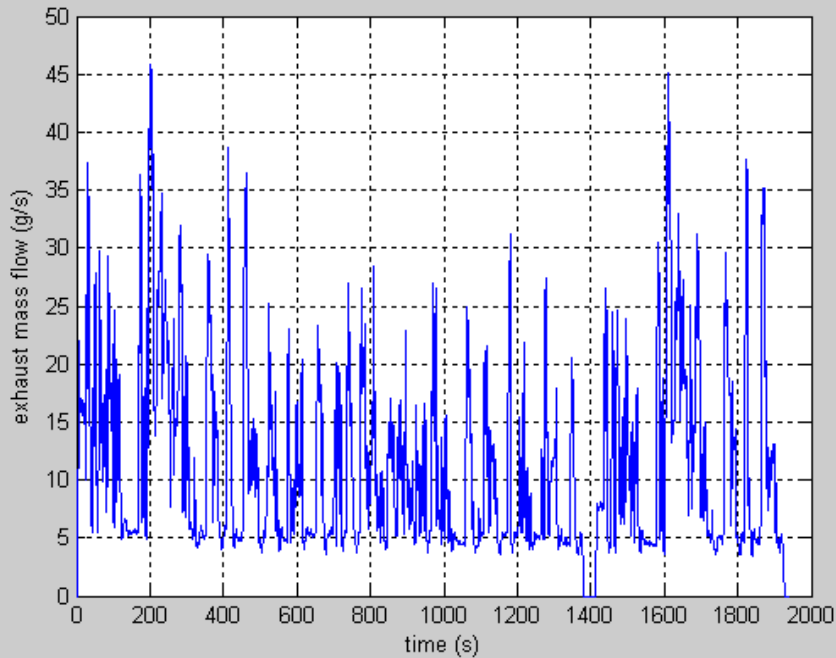


# Constant Operating Condition Simulation Results

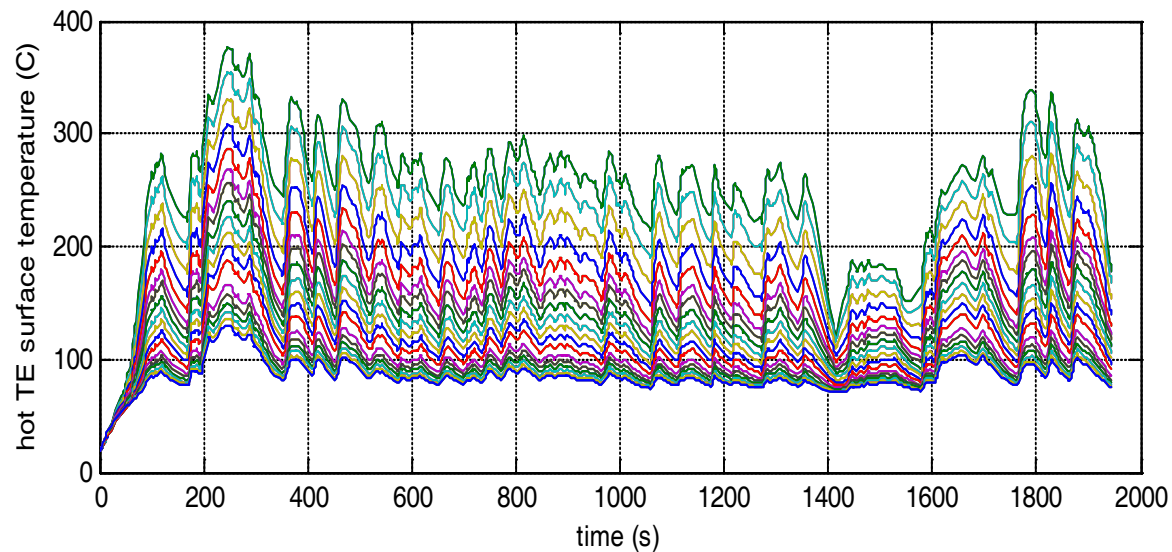
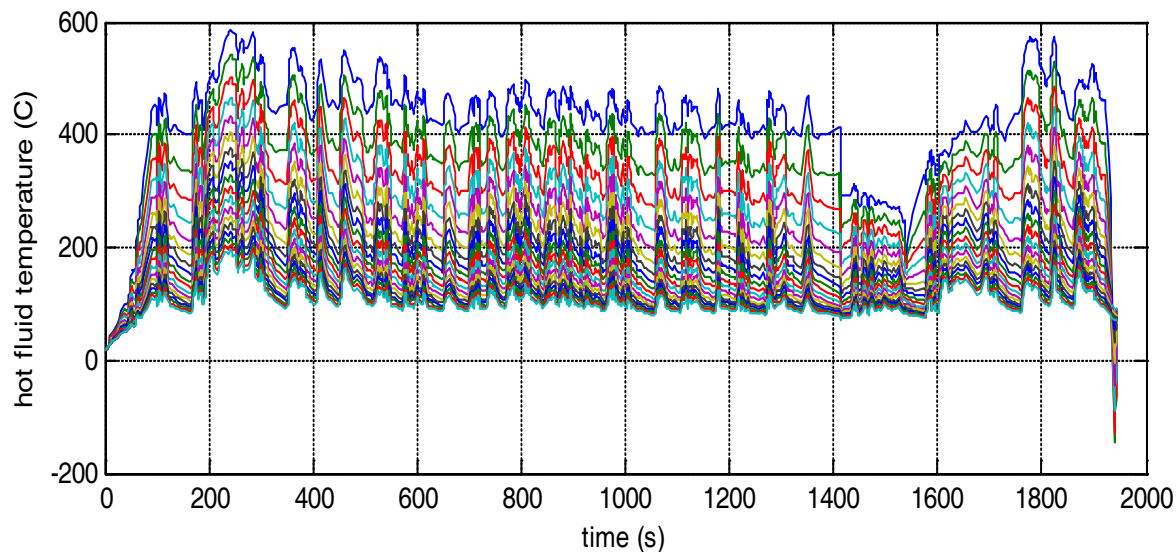


Different temperature curves represent different locations along the TEG in the direction of exhaust gas flow

# FTP-75 Drive Cycle Thermal Variations

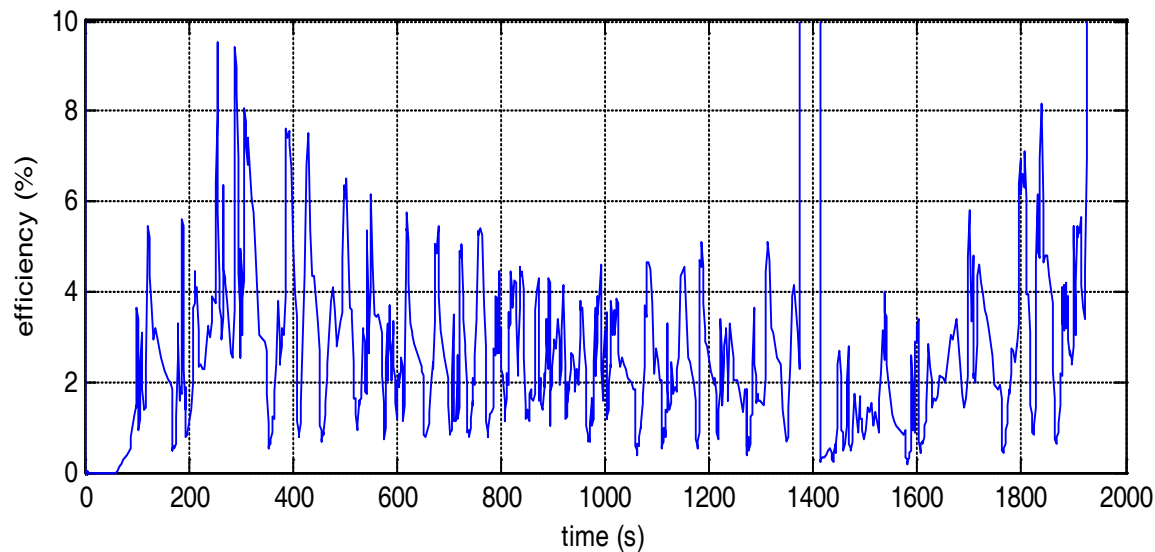
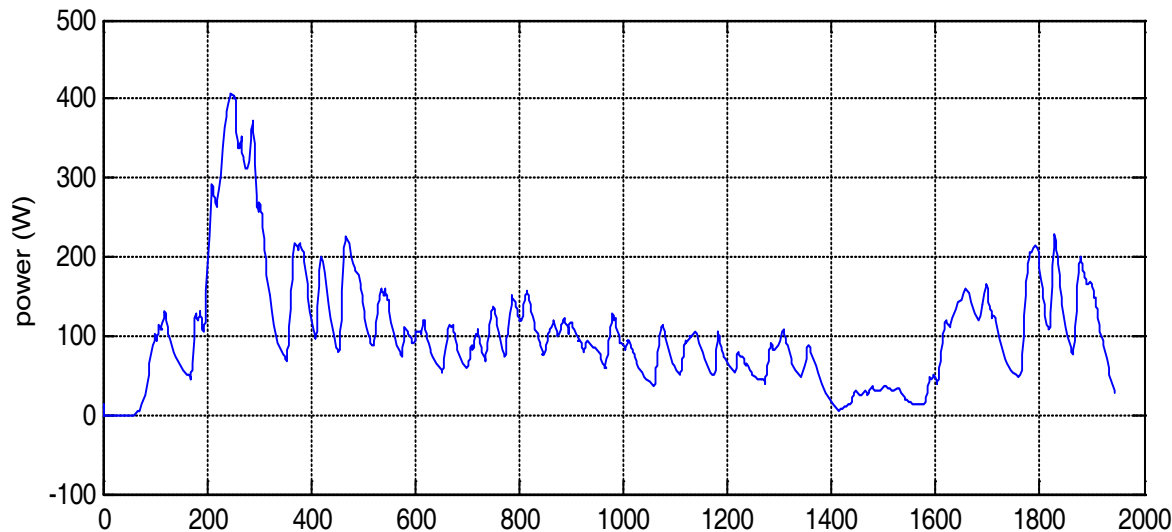


# FTP-75 Simulation Results





# FTP-75 Simulation Results



# Summary and Conclusions

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The US DOE funded Waste Heat Recovery Program has enabled BSST and its partners, BMW, Ford and Faurecia, to evaluate TEG subsystem and vehicle architectures for technical and economic feasibility.

A cylindrical TEG subsystem architecture with stack designed TE engines evolved over the multi year program. This approach provides attractive solutions to overall subsystem volume, weight and cost challenges.

Steady state and transient models of thermoelectric generators have been introduced for element, segmented couple, device and system level simulations.

Transient validation results for a segmented TE couple are shown to be within 5% of measured values

# Summary and Conclusions

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Transient simulation tools have been integrated for vehicle level simulation tools and used to compute performance for design conditions including automotive drive cycles

High temperature interfaces (thermal and electrical) and the scale up of power generation TE material are still challenges, as is translating the prototype design into a manufacturable configuration with the requisite environmental withstanding.

Vehicle level evaluations in 2011 by BMW and Ford will help provide answers to fundamental questions regarding cost benefit and initial system architectures.



# Acknowledgments

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US Department of Energy: John Fairbanks

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*And a special thanks  
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Bell!*