Development of a 500 Watt High Temperature Thermoelectric Generator

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Waste Heat Recovery Systems

Global CO_2 emission reduction goals requires greater fuel economy while customers want more auxiliary features that consume electrical energy.

- Most near term CO_2 reduction opportunities have been already identified and scheduled for introduction.
- Demand for comfort and features requires sources of electric power that do not degrade performance or reduce fuel economy.
- A growing percentage of customers are demanding greener vehicles.
- Waste heat is an untapped source for electric power that could reduce CO_2 3% - 7% near term and 5% - 10% longer term under typical driving conditions.

To address these challenges the US DOE started programs with four companies in Q4 2004. BSST is leading a team including BMW, Ford Motor Company and Visteon.

BSST Waste Heat Recovery Program Overview

The program is organized into 5 development phases:

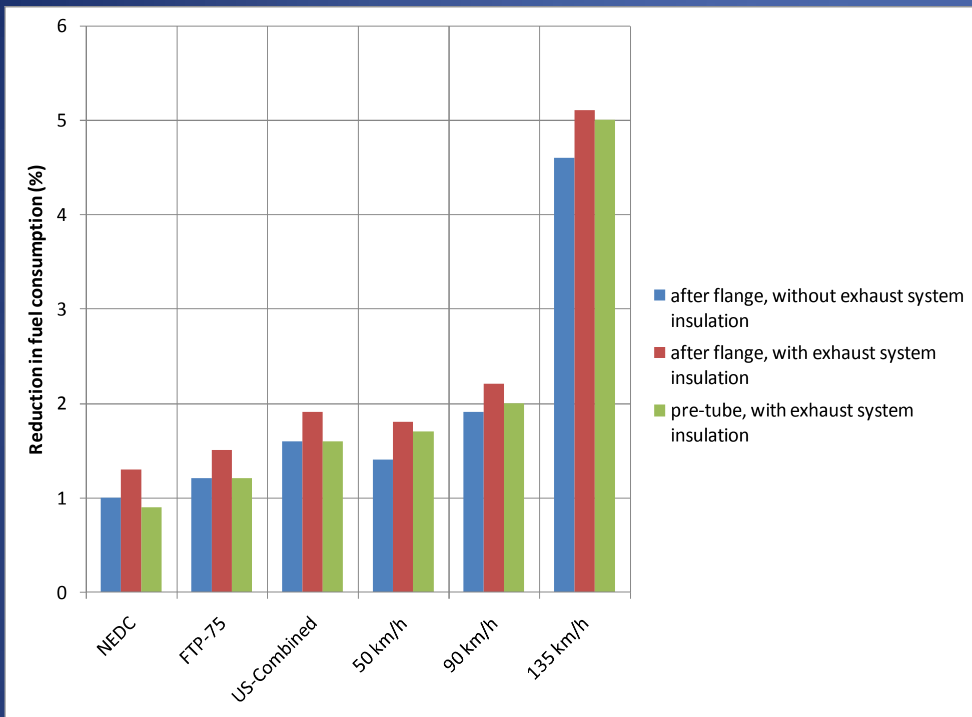
- **Phase 1** (Q3 04 thru Q2 05) A system architecture was created and bumper to bumper model created using ADVISOR. Initial system FE savings were shown to reach 12%

- **Phase 2** (Q3 05 thru Q4 06) Key subsystems (Primary Exhaust Gas Heat Exchanger, Thermoelectric Generator Module TGM), Power Conversion Electronics) were built and tested. BMW converted the bumper to bumper model to a Gamma Technologies modeling platform

BSST Waste Heat Recovery Program Overview

- **Phase 3** (Q1 07 thru Q3 08) Low and high temp TEGs were built and tested with other key subsystems:
  - A BiTe TGM was built and tested demonstrating > 500 watts electrical power output.
  - A high temperature TEG was built and tested in Q4 2008 showing greater than 100 watts of power
  - The Waste Heat Recovery System was operated on a test bench using a hot air in Q3 2008
  - The single layer high temp TEG was installed on a single cylinder engine at Ford and tested on an engine dyno in Q4 2008
- **Phase 4** (Q4 2008 – Q3 2009) A 500 watt high temperature TEG will be integrated and tested with BMW's in line 6 cylinder engine on an engine dynamometer at the NREL Federal Laboratory
- **Phase 5** (Q3 2009-Q4 2009) Integration into vehicles at BMW and Ford

Estimated Fuel Economy Benefits



BMW 3l turbocharged 5 passenger sedan. ZT average = 0.85

Cycle	Ave. Cycle Power (W)	% FE Increase
Highway	348	1.5
City	91	1.2

Ford 2.5l Hybrid SUV

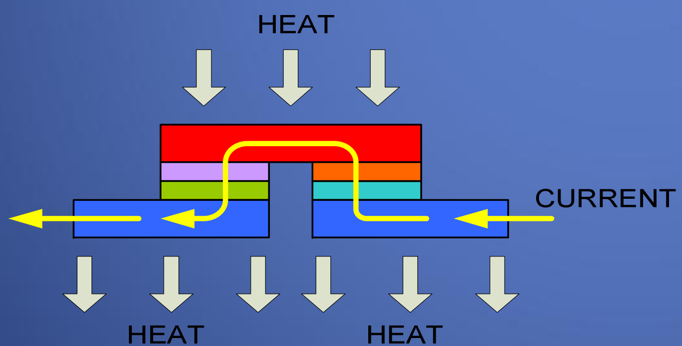
To minimize exhaust back pressure, the flow was limited to 40 g/s

Additional performance gains can be realized with advanced materials and better system optimization

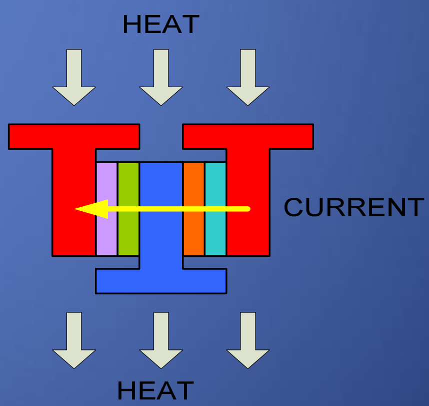
BSST TE Engine

BSST stack design allows:

- Optimum compressive loads for thermal and electrical interfaces
- Tailored n and p type element geometries for highest efficiency
- TE material reduction of 75% or more

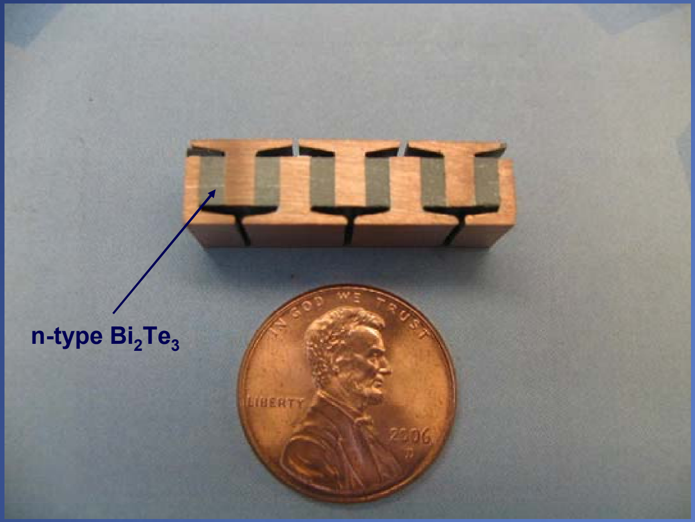


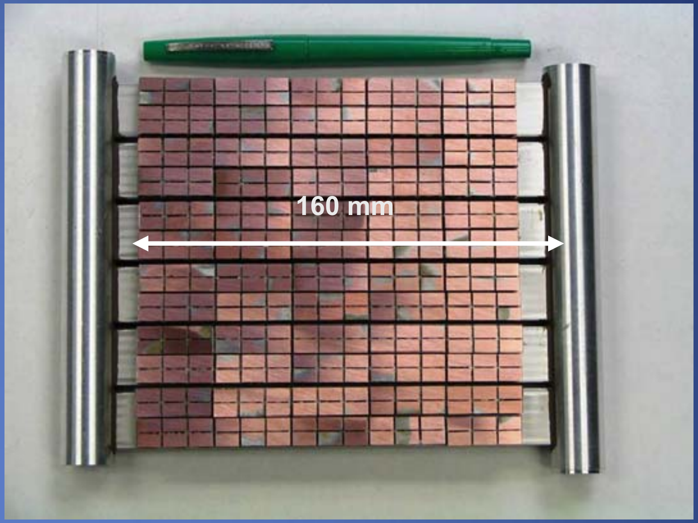
TRADITIONAL CONFIGURATION

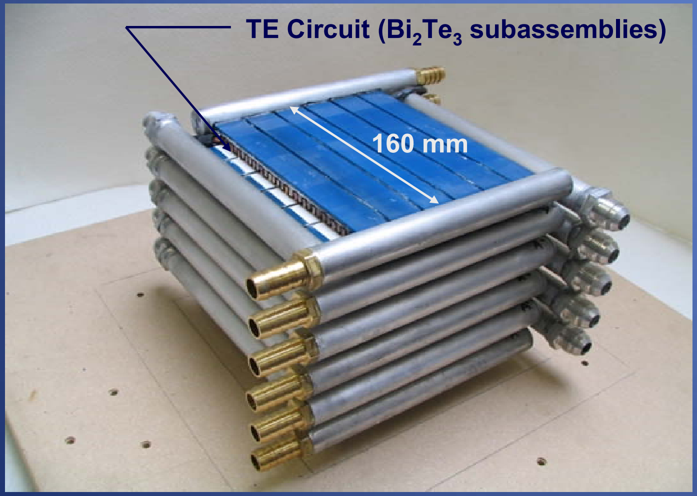


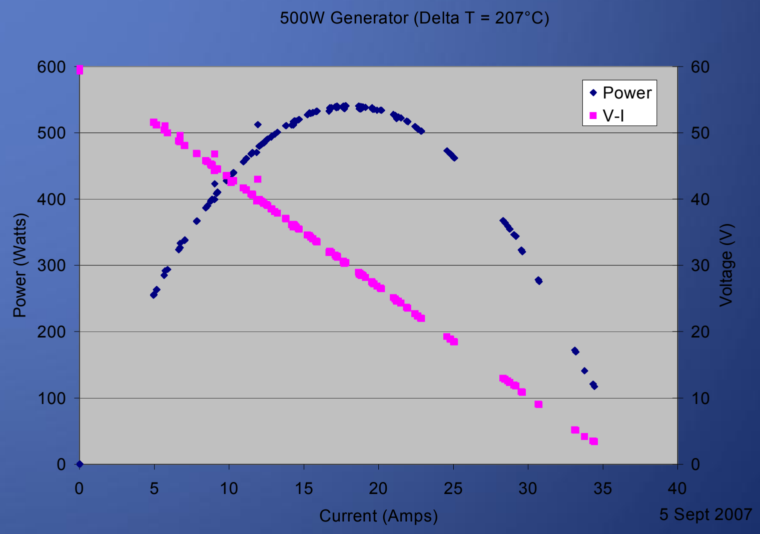
BSST HIGH POWER DENSITY CONFIGURATION

Phase 3
Low Temp 500W TEG







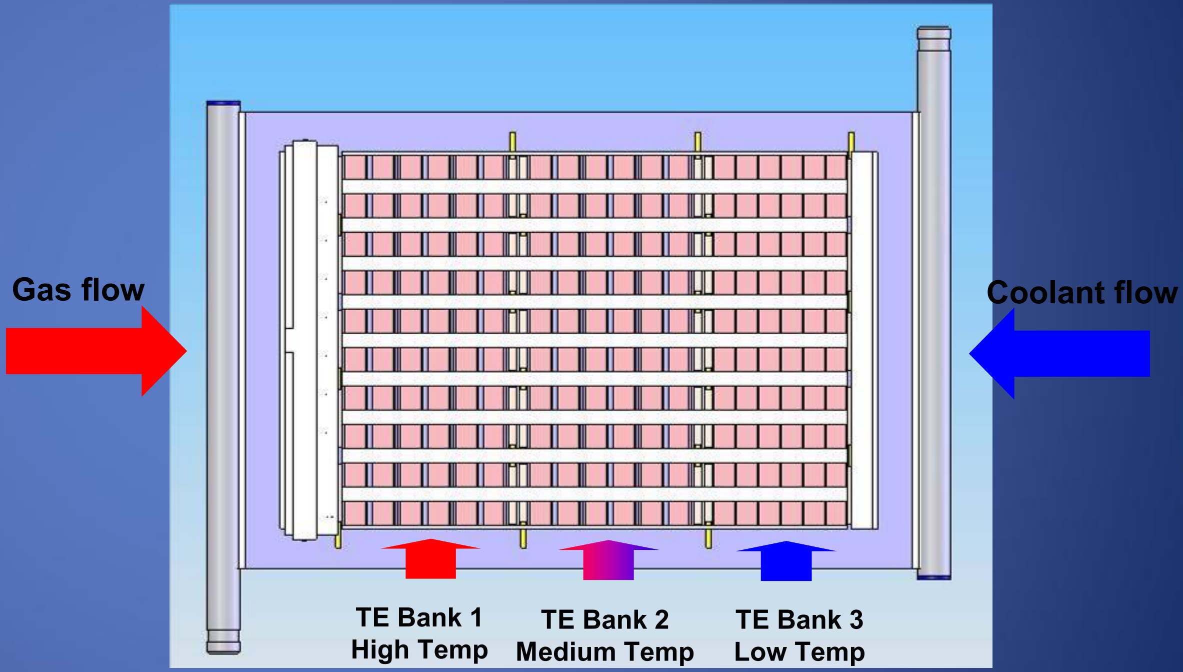


High Temperature TEG Design Summary

- Hot side heat exchanger redesigned for 500^{0}C exhaust gas (BiTe TEG used liquid heat exchangers with 200^{0}C oil)
- Three different TE subassemblies designed to match exhaust gas temperature gradient in the direction of flow to provide maximum TE material performance
- TEG thermal and electrical interfaces modified to withstand high temperature environment

100 Watt High Temperature TEG

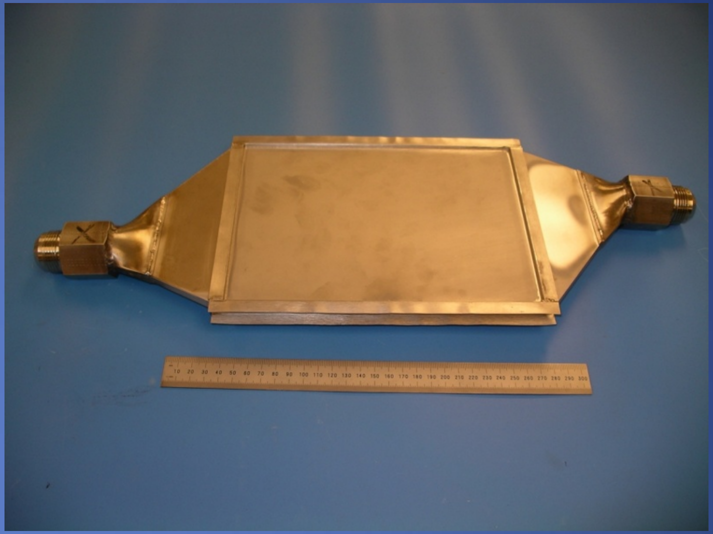
- Counter flow design
- Three configurations of TE subassemblies designed to match the temperature gradient in the heat exchanger for maximum TE performance



Prototype Heat Exchangers

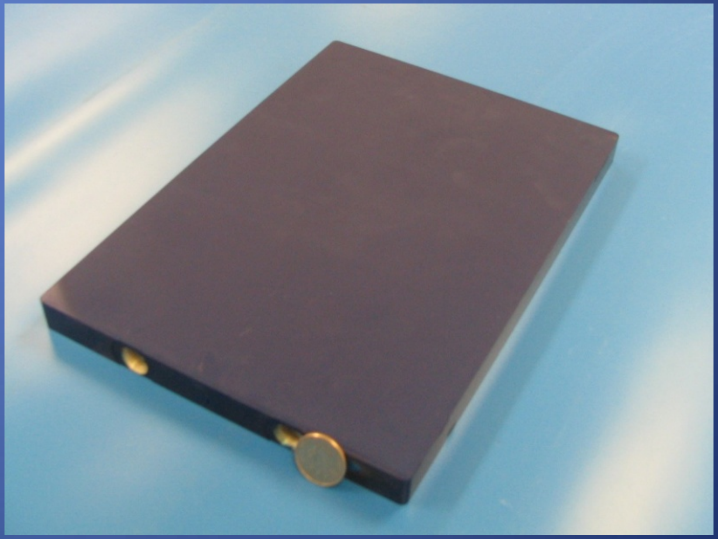
Hot side:

- Stainless steel brazed construction with wavy fin
- Diamond surface coating for electrical isolation

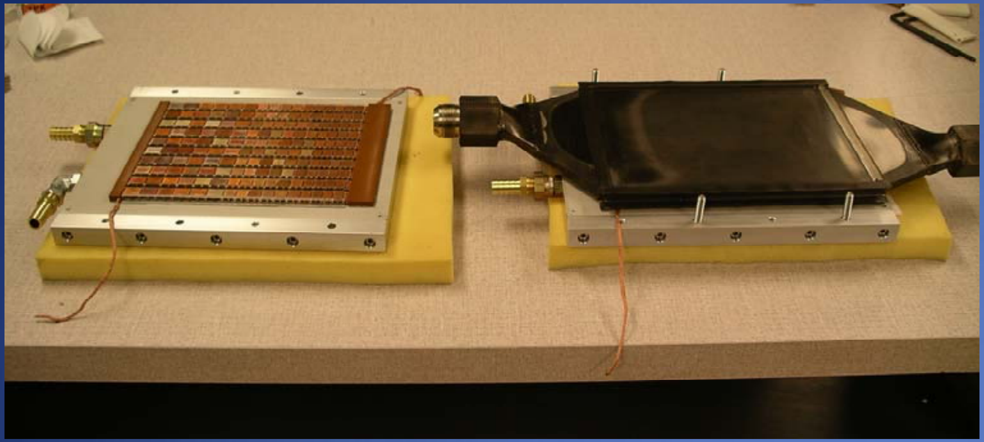


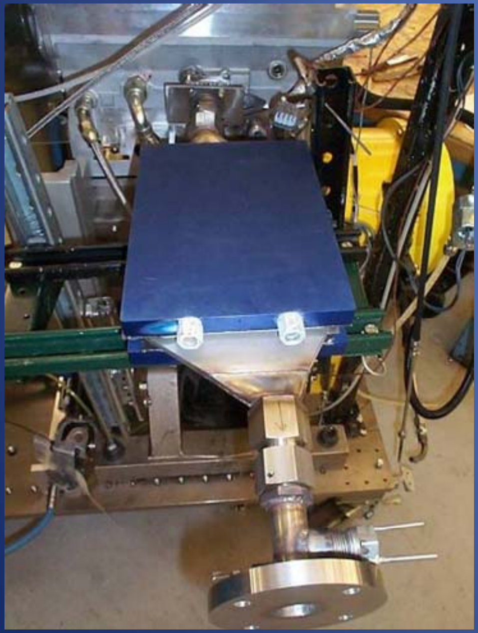
Cold side:

- Lytron off the shelf aluminum cold plate
- Surface finish: clear anodized for electrical isolation



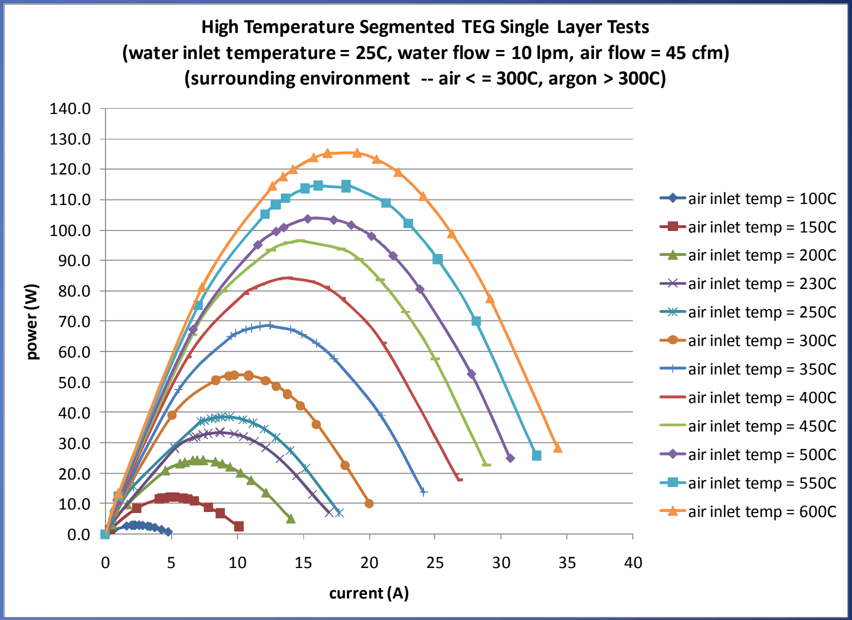
Subscale High Temp TEG Test





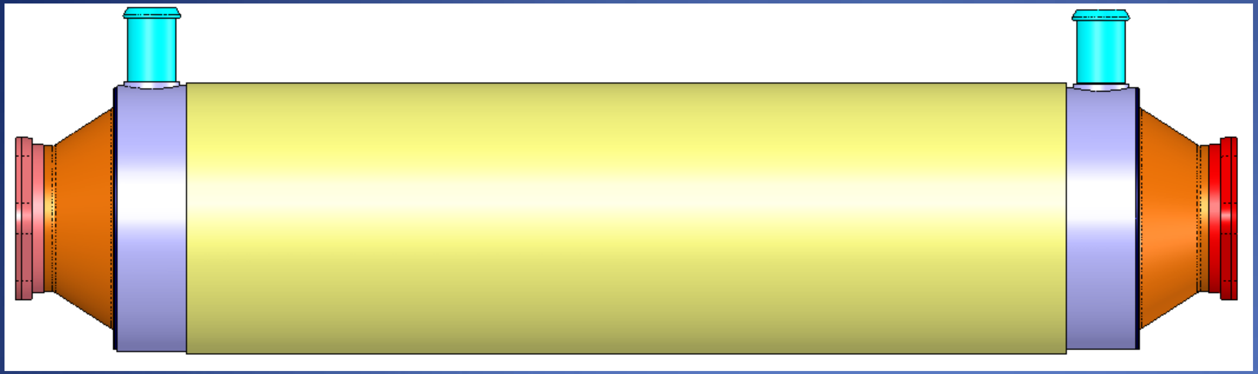
High Temp. TEG Installation

Engine Installed in Dyno

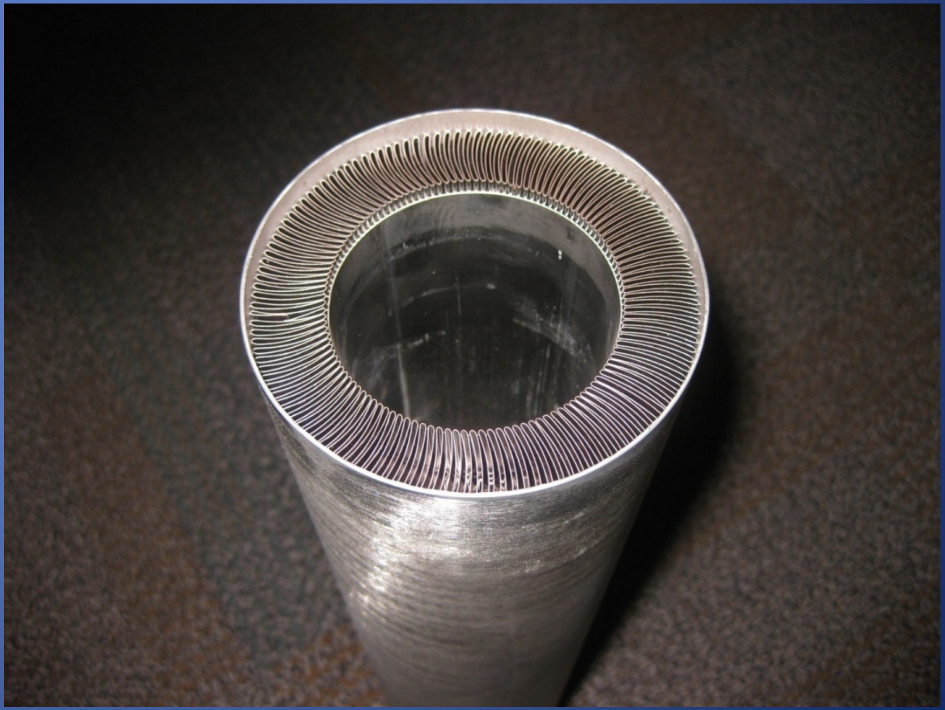


Test results for single layer high temp TEG

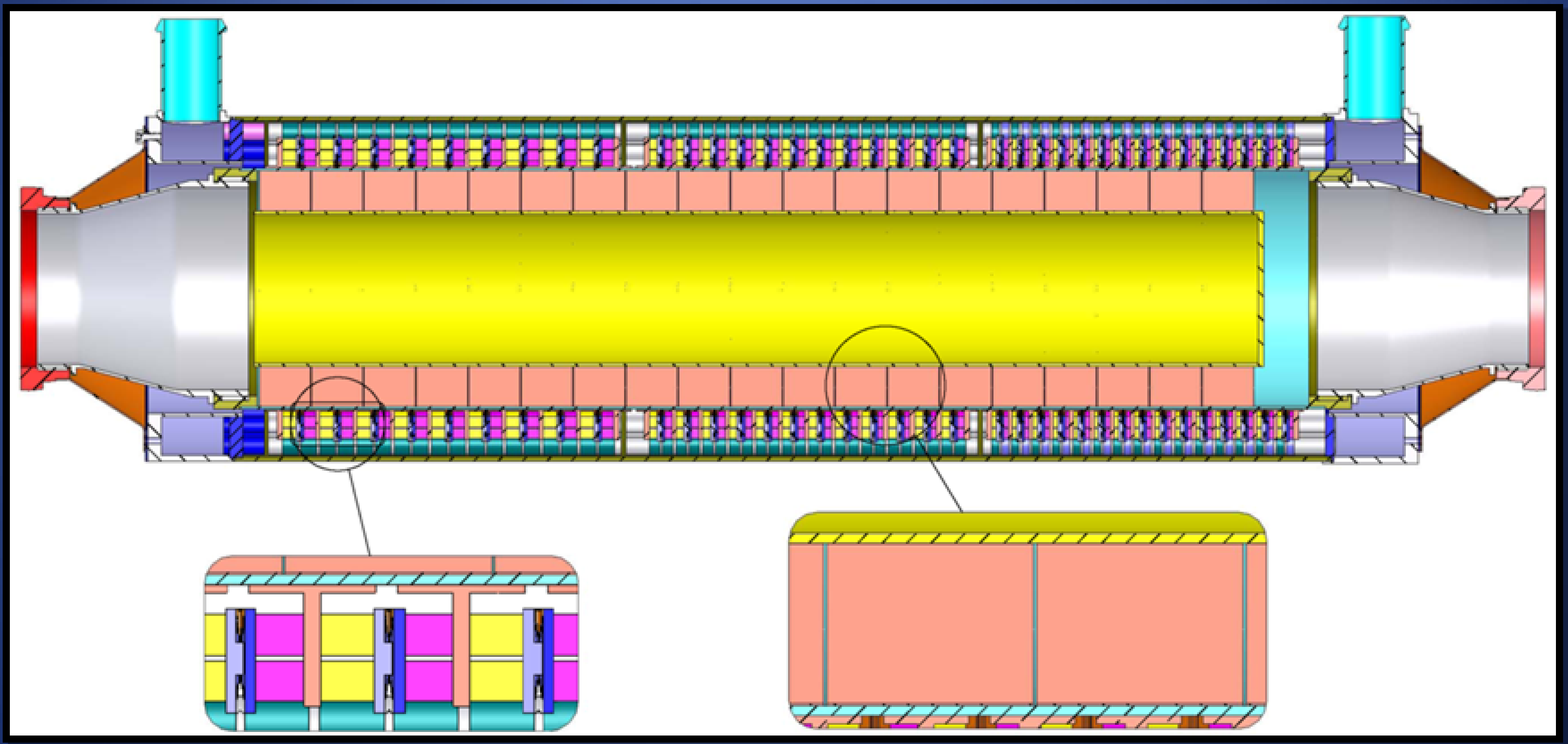
Phase 4 Full Scale TEG



- TEG redesigned to cylindrical configuration to improve packaging and reduce thermal stresses
- Exhaust bypass integrated through center of heat exchanger
- Allows for greater output with single gas & coolant connections

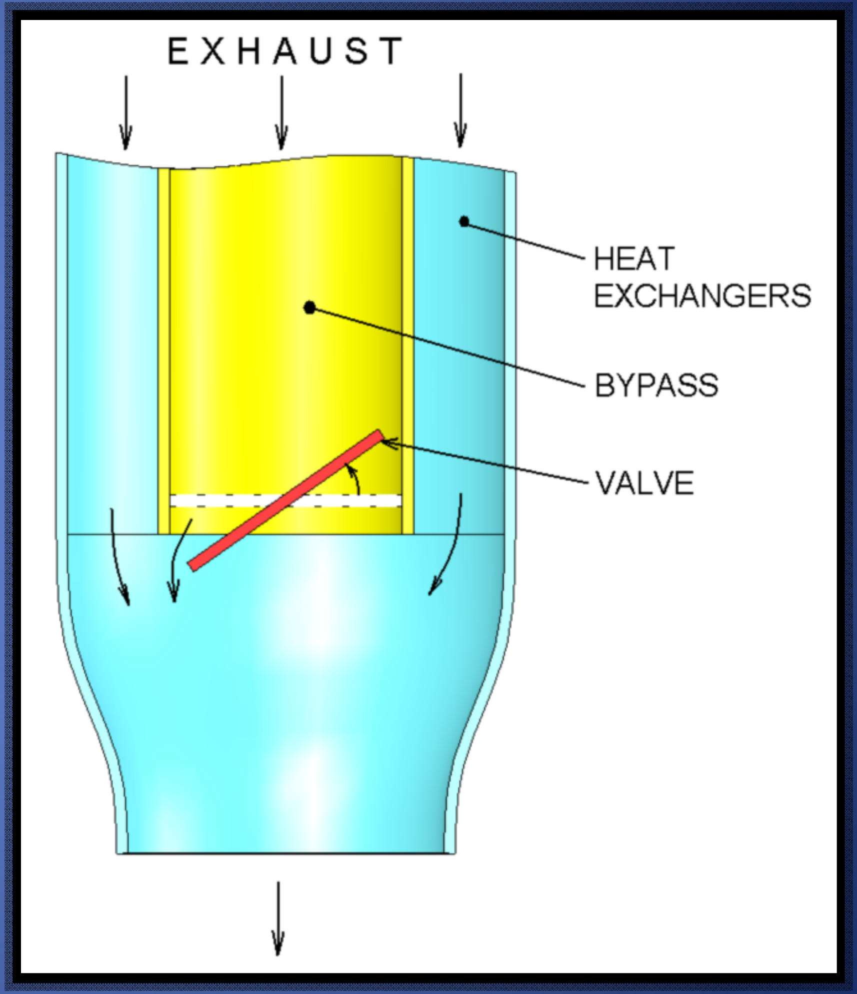


TEG Cross-Sectional View



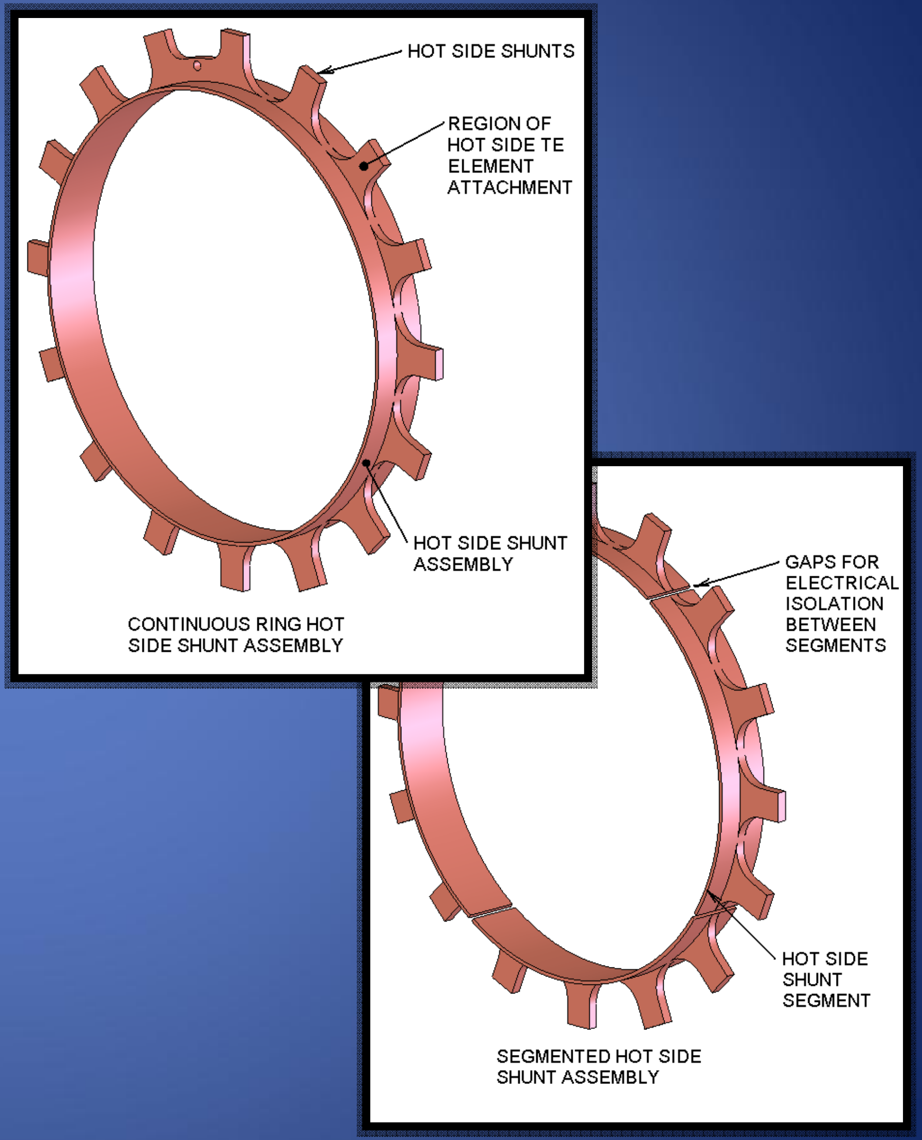
Exhaust Flow Control

- Under normal operation, valve is closed and exhaust gas flows through the heat exchanger assembly
- At very high mass flow rates, high exhaust gas temperatures and under high coolant heat flux loads, some or all of the exhaust gas flows through the central bypass region valve in exhaust streams
- Valve can have proportional control to optimize system performance. Flow between the two regions is selected based on data processed by TEG and engine control systems



Hot Side Shunt Design

- Continuous ring hot side shunt assembly has groups of TE elements in parallel. Each ring produces high current, low voltage. Generally 10-20 rings are connected electrically in series
- Electrically isolated ring segments (with gaps) operate at higher voltage and lower current. Entire array of segments can be connected electrically in series
- With either arrangement TE elements are in a series parallel arrangement, significantly increasing reliability and design robustness

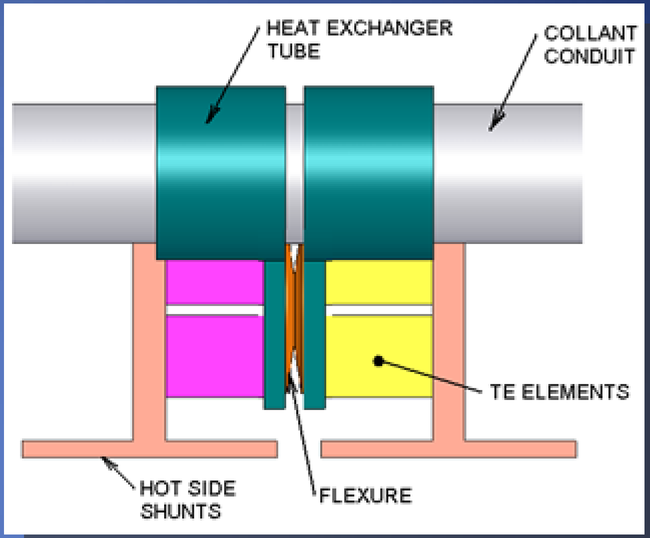


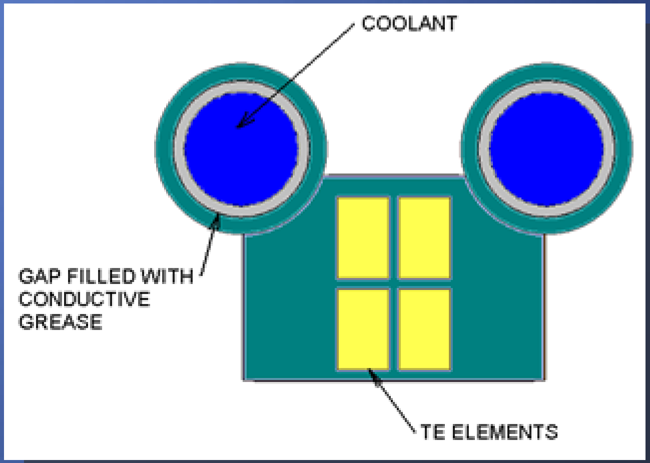
Cold Side Design

Cold side heat exchanger is tube-in-tube design, with thermally conductive grease between tubes

- Allows relative movement between inner and outer tubes
- Provides low interfacial thermal resistance between tubes without any applied radial forces
- Inner tube is constructed of high thermal conductivity, electrically insulating material such as alumina or anodized aluminum

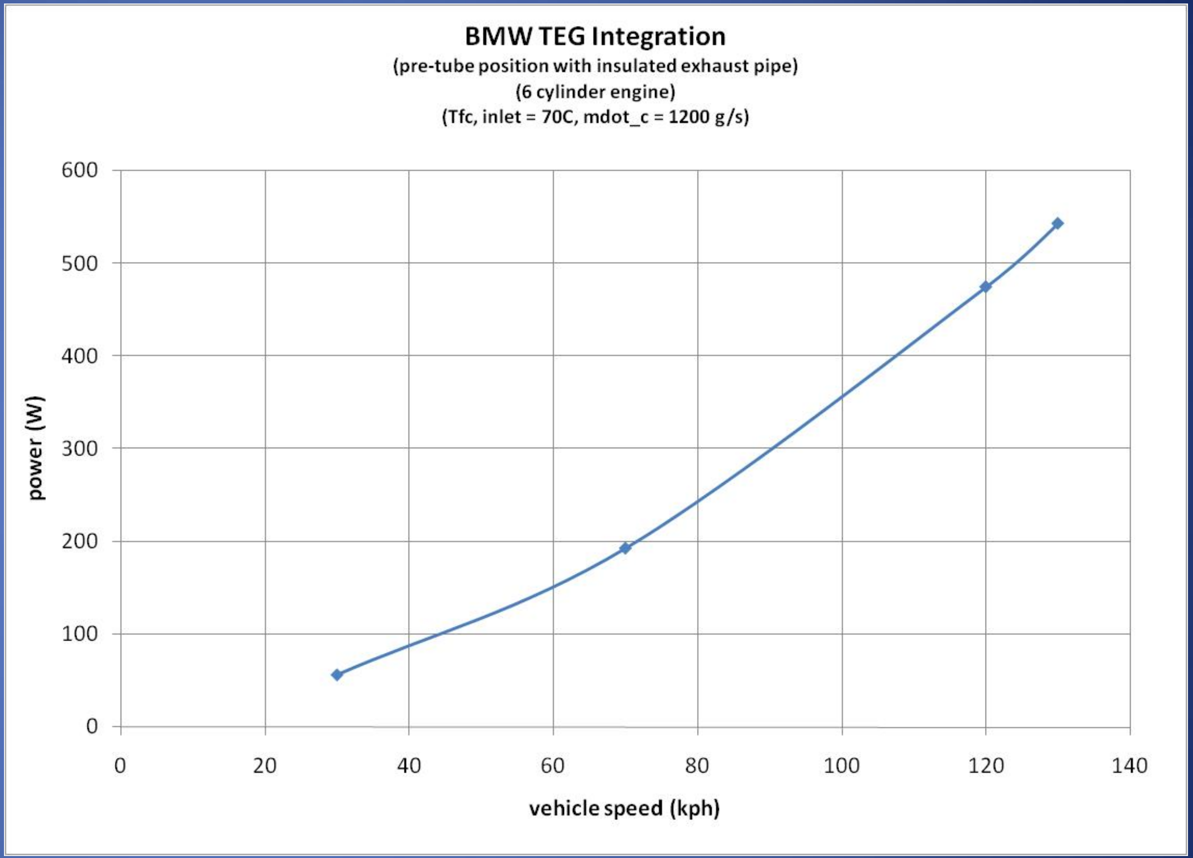
Flexure transmits electric current with low interfacial losses





Phase 4 TEG

- Cylindrical TEG currently under construction
- Will be tested on bench at BSST, then shipped to NREL for testing with BMW inline 6 cylinder engine on dyno



Additional Aspects of New TEG Design

- Cold side tubes connected to cold shunts with grease, but without the need for additional thermal compression
- CTE mismatch and TE element compression in the electrical flow direction handled by having a split cold shunt
- Coating applied to the hot side heat exchanger to provide thermally conductive electrical insulation
- Different electrical circuits introduced for each bank
- Hot side fin material is SST clad copper

Summary and Further Work

- A low temperature TEG has been built and tested providing over 500 watts electric power at a ΔT of 200^0C
- A subscale single layer high temperature TEG has been built and tested on bench and engine dyno
- A new design cylindrical TEG is currently being assembled for testing to begin in Q3
- A low temperature TEG has been tested on a diesel engine producing 88W in vehicle.

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