Automotive Waste Heat Conversion to Power Program- 2009 Hydrogen Program and Vehicle Technologies Program Annual Merit Review

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BSST Program Overview

Timeline

Program Start Date:	Oct '04
Program End date:	July '09
Percent Complete:	80%

Barriers

High temperature (600^0C) material systems and packaging

Thermal cycling robustness of modules and assemblies

Cost-effective module design

Budget

Total Project funding:	
DOE Share:	$ 5,589,162
Contractor Share:	$ 1,863,054
FY08 & FY09 Funding Received:	$ 1,561,805

Partners

Project Lead:	BSST/Amerigon
OEM Partners:	BMW & Ford
Tier 1 Partner:	Visteon
University/Fed'l Lab Partners:	Caltech, JPL, NREL Virginia Polytechnic

BSST Partner Roles/ Responsibilities

BSST is leading the development of thermoelectric engines, modules and assemblies including integration with heat exchangers

Visteon is leading the development of high efficiency power conversion/control electronics and heat exchangers

BMW and Ford are leading the development of vehicle modeling and vehicle systems engineering for exhaust gas waste heat recovery.

Caltech and JPL are supporting advanced TE material development and characterization

Virginia Polytechnic is supporting the development of advanced Electric Power Conversion and Control

NREL is performing the final system test and evaluation on an engine dynamometer

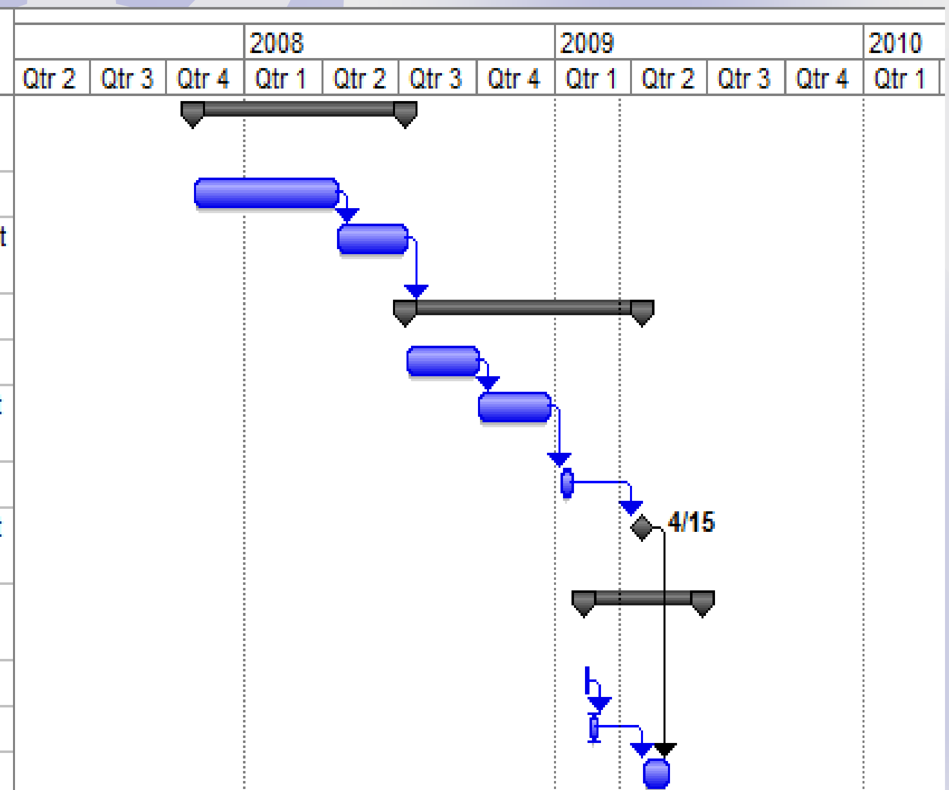
BSST Program Objectives

3rd Phase Objectives:

- Scale up low temperature (250^{0}C) TEG modules into a 500 watt TEG
- Develop high temperature (600^{0}C) modules
- Scale up high temperature TEG modules into a 125 watt TEG
- Establish a path to a 500 watt high temperature TEG for Phase 4 dynamometer testing at NREL

BSST Program Milestones

ID	Task Name
1	**Low Temperature TEG**
2	Module design, build and test
3	Full scale TEG design, build and test
4	**High Temperature TEG**
5	Module design, build and test
6	125 watt TEG design, build and test
7	125 watt TEG dyno test at Ford
8	500 watt TEG design, build and test
9	**Engine Dynamometer test and evaluation**
10	BMW Engine to NREL
11	Engine Set-up/checkout
12	TEG system integration



Technical Approach: Cost Effective TEG Design

Critical Design Limitations

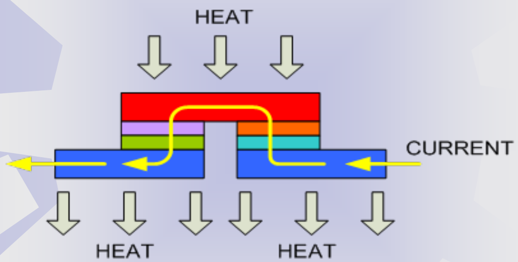
- Parasitic electrical and thermal resistances
- require long TE element designs
- Tensile and shear stresses reduce
- durability in large arrays
- As a result TE material power density is low, requiring large amounts of TE material

Solutions

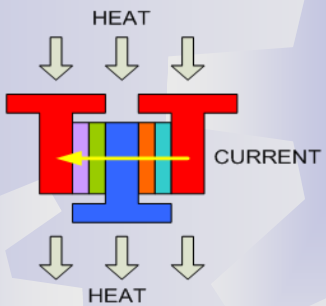
- Stack design reduces parasitic losses
- Compressive forces independent for low electrical and thermal resistances

Results

- Increased longevity and stability
- 75% - 84% TE material usage reduction
- Reduced impact of CTE mismatch
- However, custom designs are expensive at low
- volume manufacture and early prototype production



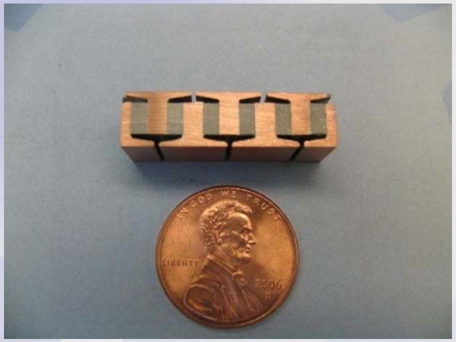
TRADITIONAL CONFIGURATION

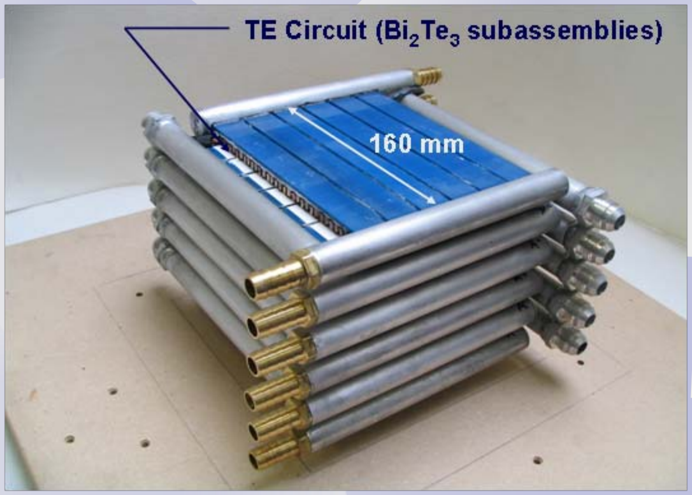


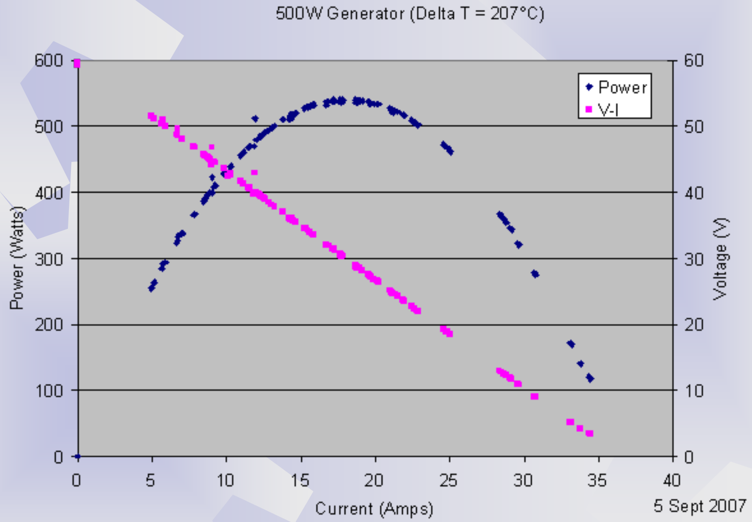
BSST HIGH POWER DENSITY CONFIGURATION

Technical Accomplishments

- The initial Phase 3 TEG comprised BiTe material and operated using hot oil.
- The five layer BSST built TEG was based on a proprietary stack design and produced 530 watts electric power at a ΔT of 207^0C







Technical Accomplishments: TEG Power Management

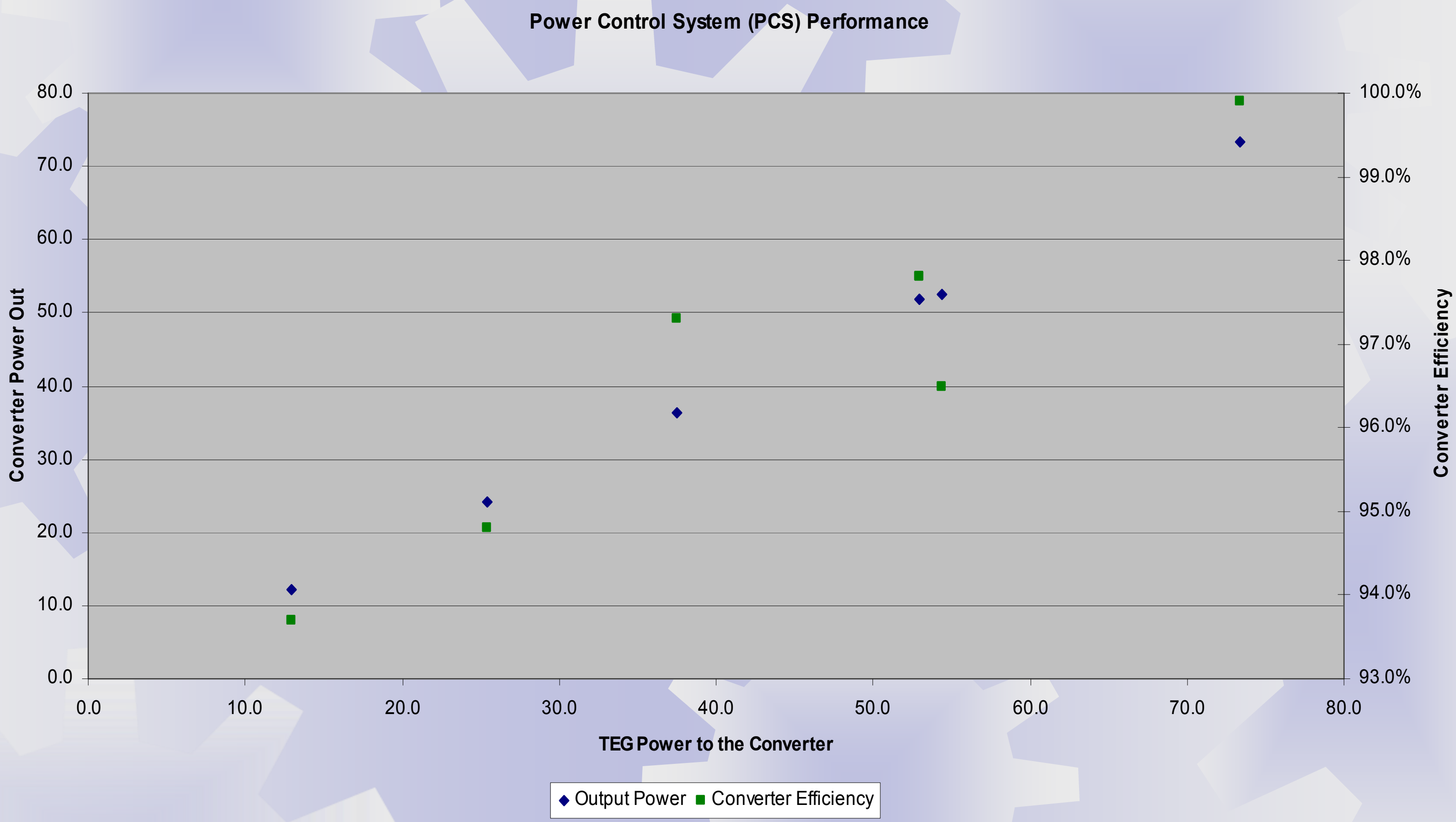
A 100 watt BiTe TEG was tested with a prototype Power Control System (PCS) and resistive load.

The prototype PCS includes:

- Boost and buck converters with microprocessor control to provide a maximum voltage of 12.8 VDC (resistive load maximum operating voltage)
- Serial data interface to report input and output voltage, current, power and converter efficiency

Three 50 watt automotive headlamps were used to test the PCS with the TEG.

Technical Accomplishments: PCS Performance- BiTe 100 Watt TEG



Technical Approach: High Temperature TEG Design

A high temperature TEG was designed that incorporated the low temperature BiTe subassembly technology and added medium and high temperature segmented TE subassemblies

PbTe/TAGS, Half Heusler, Skutterudite and other high temperature materials were evaluated for basic properties and performance at the couple level

Half Heusler material segmented with BiTe was selected for the initial high temperature TEG build and test

- High temperature robustness
- Volume production capability
- Suitable TE basic properties to reach 500 to 750 watt TEG power capacity

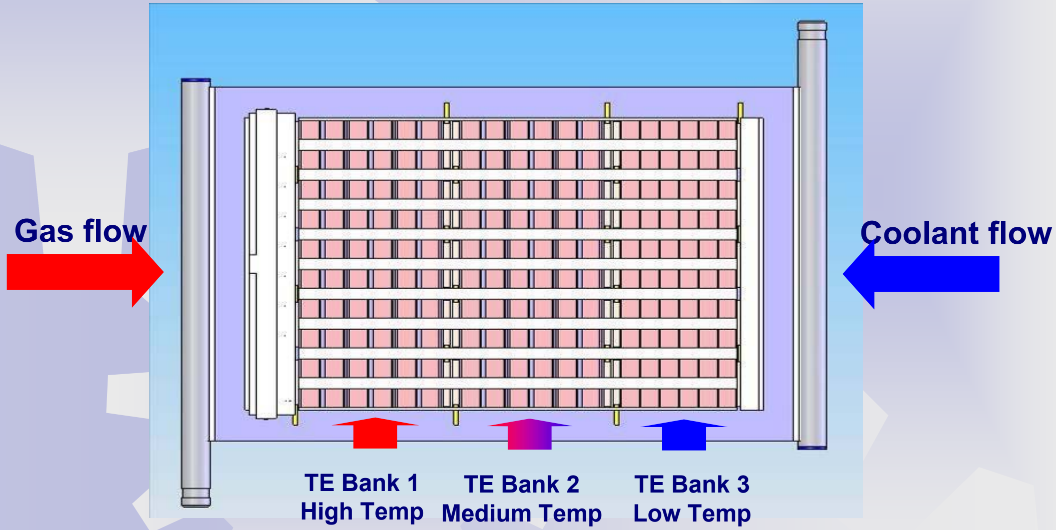
Technical Accomplishments: High Temperature TEG Design, continued

Building on the lessons learned from the low temperature TEG BSST designed and built high temperature TE subassemblies and scaled them up into a TEG

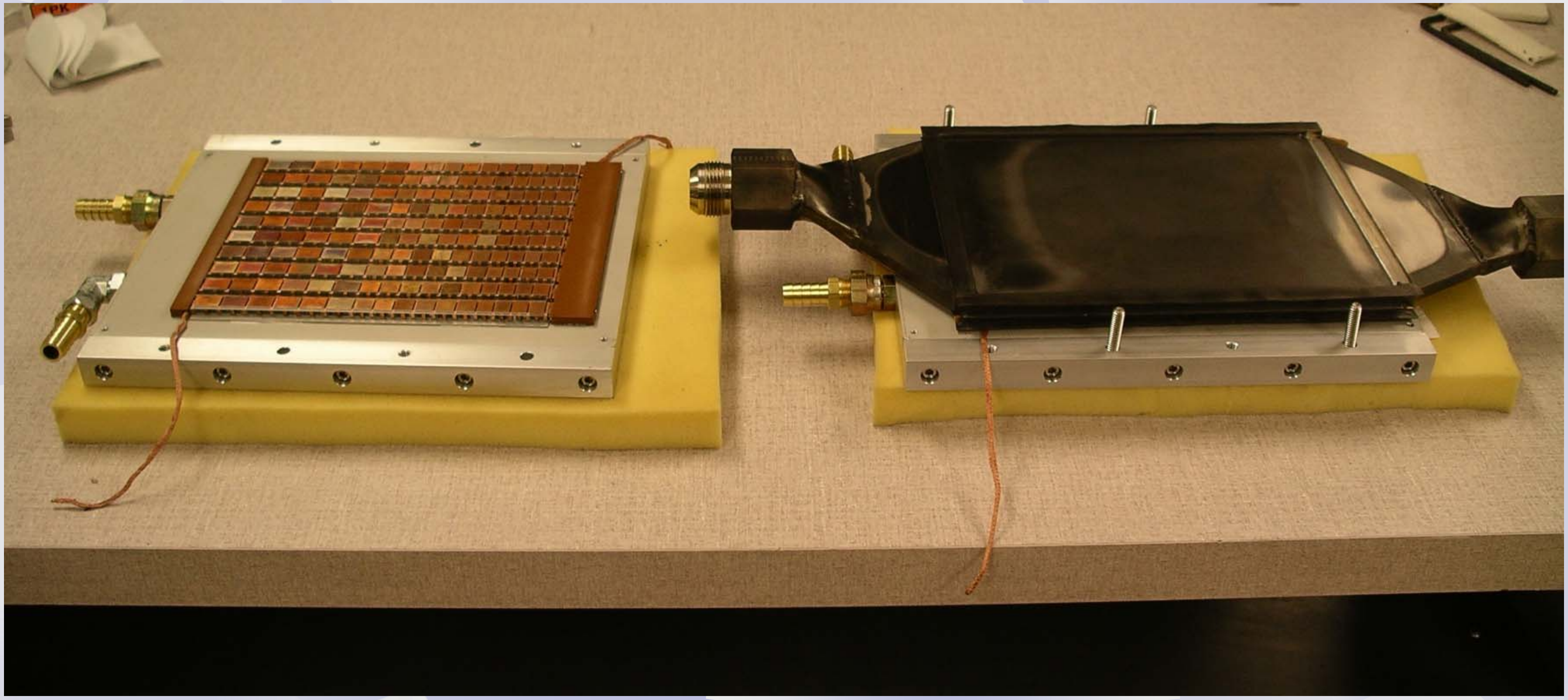
Segmented TE subassembly

Temperature Graded Design

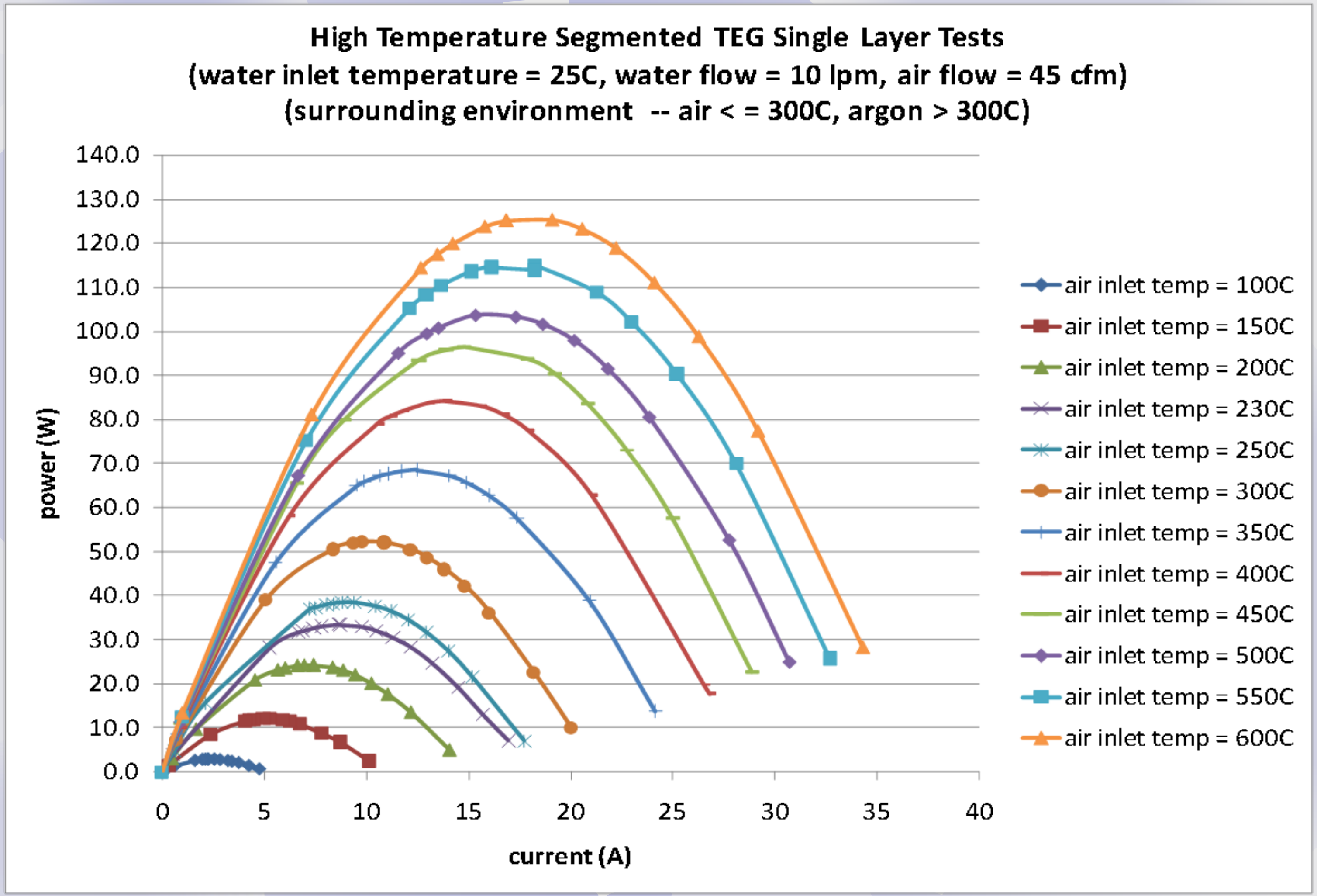
Three configurations of TE subassemblies designed to match the temperature gradient in the heat exchanger for maximum TE performance



Technical Accomplishments: Single Layer High Temperature TEG Build

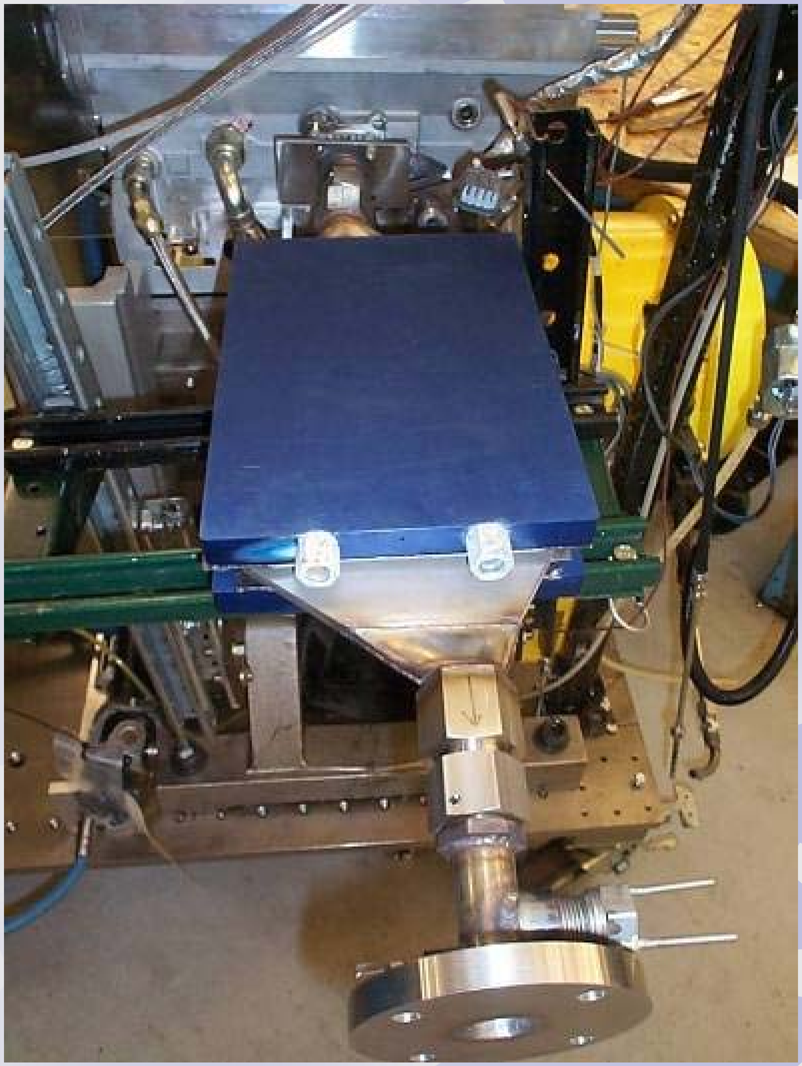


Technical Accomplishments: High Temp TEG Test Results

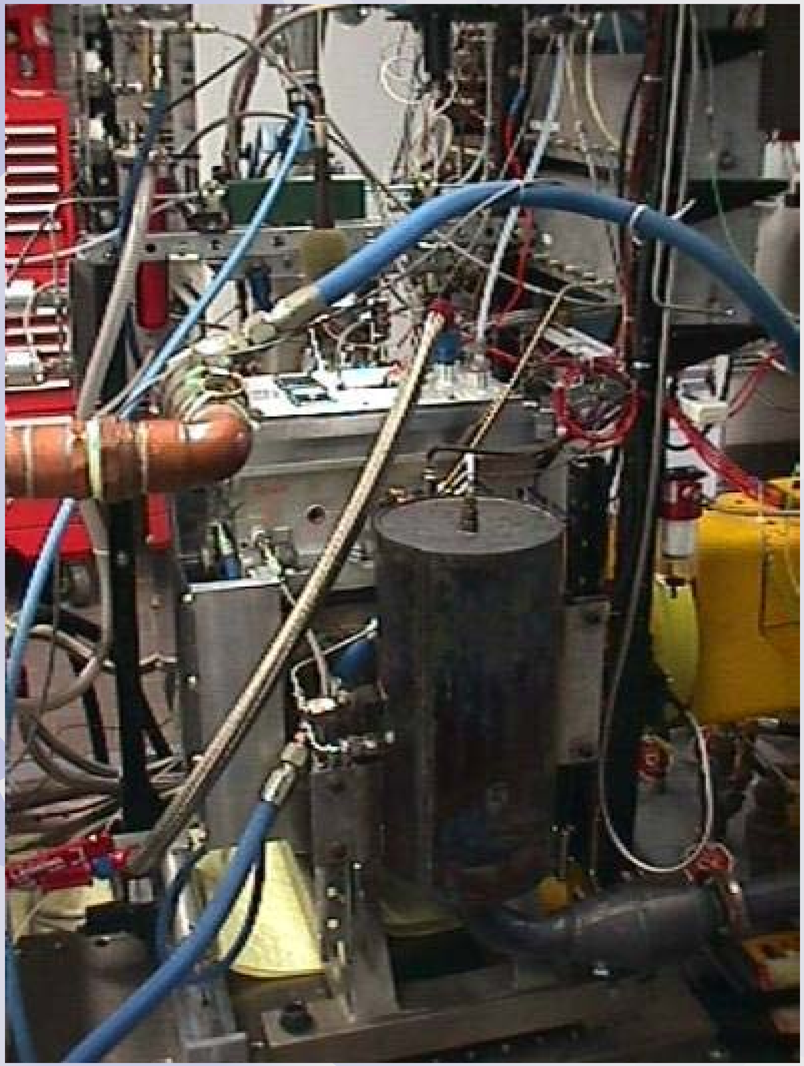


Technical Accomplishment: Single-Cylinder Dyno Testing

Courtesy of Clay Maranville, Ford Motor Company



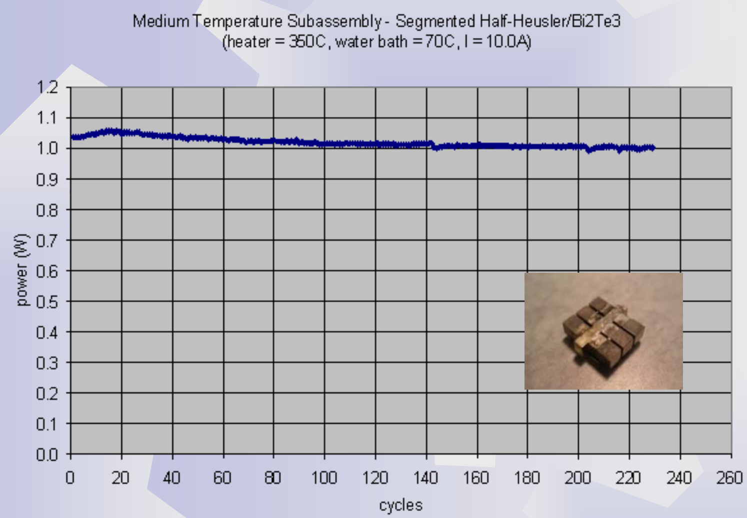
High Temp. TEG Installation

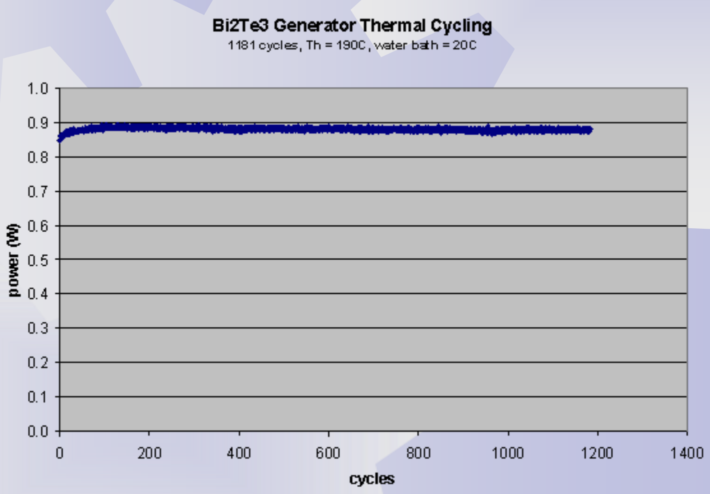


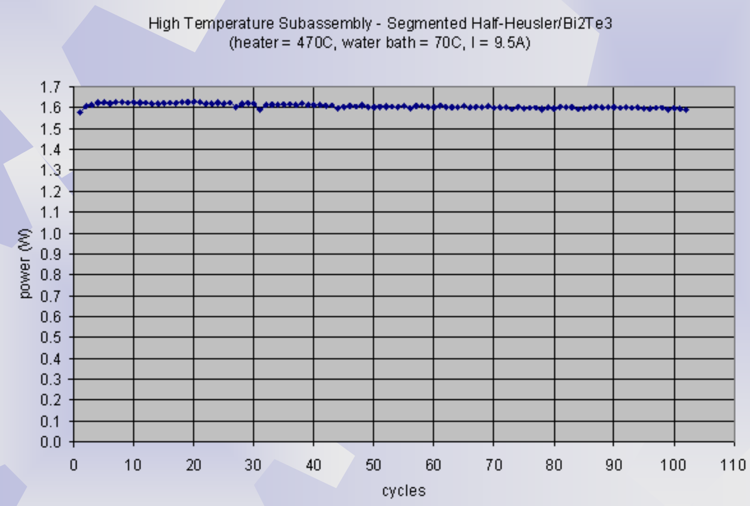
Engine Installed in Dyno

Technical Accomplishments: Thermal Cycling TE Subassemblies

TE Subassemblies were thermal cycled to evaluate long cycle fatigue performance







Technical Accomplishment:
Transition of the total system simulation.

- **The bumper-to-bumper vehicle model has been updated to the state-of-the-art turbo charged engine.**
  - ➢ New exhaust temperature map.
  - ➢ New exhaust line geometry.
  - ➢ New fuel efficiency map.

- **New integration into the cooling system of the powertrain.**

- **The latest transient TEG model by D. Crane (BSST) was integrated into the total system simulation model.**
  - ➢ ZT can be adjusted by changing the material properties (thermal/electrical conductivity and Seebeck coef.) separately.
  - ➢ Includes thermal and electrical contact resistances.

Future Work

Phase 4 key objectives include:

- Full scale BMW engine dynamometer testing of a 500-750 watt high temperature TEG at NREL
- Vehicle installation readiness and preparation for ICE and hybrid vehicle platforms
- Commercialization preparation including TE material and waste heat recovery key subsystem production roadmaps

Summary: Thermoelectric Waste Heat Recovery.
FE improvements for a 535i.

Position	Insulation	ZT	NEDC	FTP	US-Combined
after Flange	no	0,85	1,5%	2,8%	3,1%
after Flange	no	1,25	1,9%	3,4%	3,9%
after Flange	no	2	2,4%	4,2%	5,0%
Pretube	no	0,85	0,9%	1,5%	1,8%
Pretube	no	1,25	1,1%	1,9%	2,4%
Pretube	no	2	1,4%	2,4%	3,0%
Pretube	yes	0,85	1,2%	2,2%	2,4%
Pretube	yes	1,25	1,5%	2,7%	3,2%
Pretube	yes	2	1,9%	3,4%	4,1%

Position	Insulation	ZT	50 kph	80 kph	100 kph	130 kph	160 kph
after Flange	no	0,85	1,4%	1,3%	1,9%	3,4%	3,0%
after Flange	no	1,25	2,1%	1,9%	2,5%	4,1%	3,6%
after Flange	no	2	3,0%	2,7%	3,5%	5,2%	4,7%
Pretube	no	0,85	0,9%	0,9%	1,4%	2,8%	2,5%
Pretube	no	1,25	1,4%	1,4%	1,9%	3,4%	3,1%
Pretube	no	2	2,0%	1,9%	2,7%	4,4%	3,7%
Pretube	yes	0,85	1,1%	1,1%	1,6%	3,0%	2,7%
Pretube	yes	1,25	1,7%	1,6%	2,2%	3,7%	3,3%
Pretube	yes	2	2,4%	2,2%	3,1%	4,7%	4,3%

New cooling system integration shows higher benifits during engine warm-up but higher coolant temperatures during constant speeds.

FE results includes the influence of increased weight and exhaust backpressure

FE results for higher values of ZT do not reflect TEG optimization. For ZT = 2 BSST anticipates FE savings to reach 10%