2008 DOE FCVT Merit Review:
BSST Waste Heat Recovery Program

27 February, 2008

Program Manager: John LaGrandeur

FCVT Annual Review: BSST Program

- FCVT Goals and Objectives
- Barriers to meeting the FCVT Goals
- BSST's Technology Approach
- Performance Measures and Accomplishments
- Publications/Patents
- Collaborations/Interactions
- 2008 Work Plan
- Summary

FCTV Program Goals and Objectives

Improve over-all vehicle efficiency while maintaining low emissions through the development and application of waste heat recovery technology

- High efficiency thermoelectric systems (as well as other technologies) are sought for thermal energy recovery and direct conversion to electricity

Improve fuel efficiency by 10%

Show a path to commercialization

Assess economic feasibility

Barriers to Achieving the FCVT Goals

1. Wide variations in exhaust gas mass flow makes the design of an efficient Thermoelectric Generator Module (TGM) difficult
2. High temperature material systems (500^0C - 800^0C) that join TE materials to substrates/heat exchangers that limit parasitic losses and provide long cycle fatigue life aren't readily available
3. Performance models that integrate thermoelectric waste heat recovery into vehicle powertrain and bumper to bumper models are not commercially available.

Technology Approach

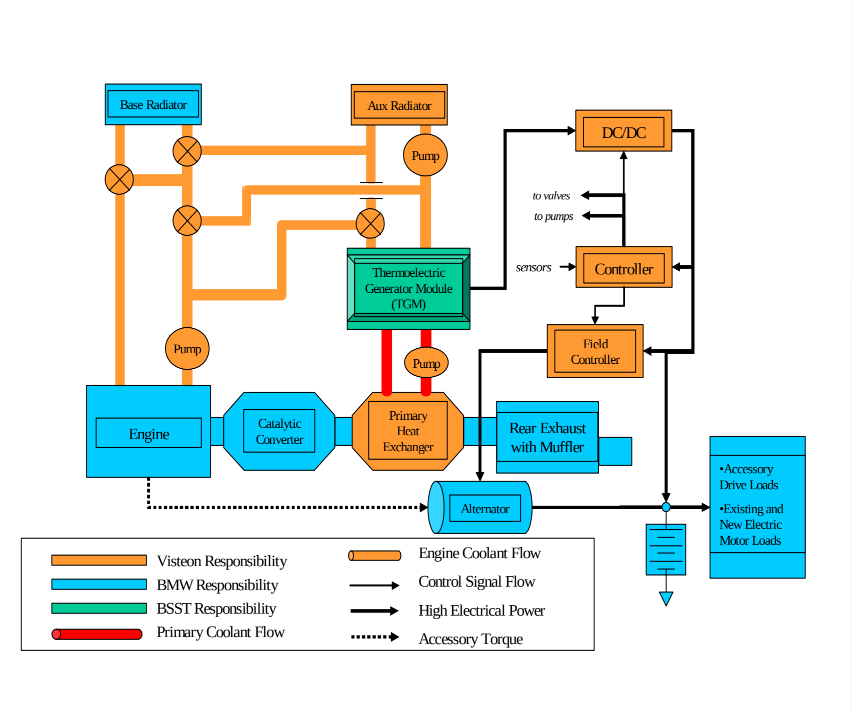
BSST Technology Approach:

Developing a System Architecture to Manage Wide Variations in Thermal Power

A system architecture was modeled in Phases 1 & 2 that used a secondary loop to help manage variations in exhaust gas thermal power

- Enabled high efficiency power conversion within the TGM
- Reduced TE material usage and TGM size, facilitating hermetic packaging and recycling

A new architecture is proposed that simplifies the initial system implementation while retaining some of the benefits of the secondary loop system



BSST Technology Approach:

New System Architecture

The new system architecture places TE assemblies in direct thermal contact between exhaust gas and liquid heat exchangers

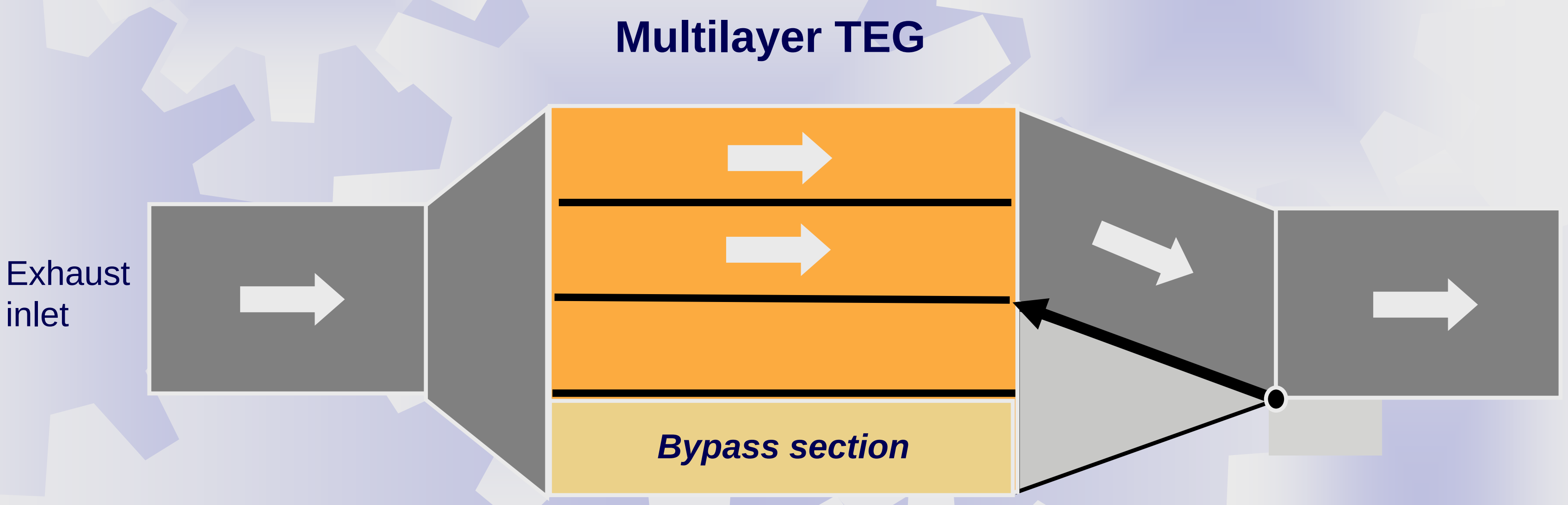
The flow of exhaust gas to each TE circuit layer is controlled so that the number of active TE layers is proportional to gas flow

Each circuit layer has the following features:

- The TE layer is subdivided into high, medium and low temperature sections in the direction of gas flow to maximize the performance of the TE material used as the heat exchanger temperature decreases
- Each temperature specific section has a unique TE assembly design to maximize performance
- Each temperature section is electrically separated from the other sections

BSST Technology Approach:

New System Architecture



Exhaust gas enters a diffusor upstream from the multi-layer TEG

The number of TEG layers exposed to exhaust gas is proportional to total mass flow

An exhaust gas valve controls gas distribution to layers downstream from the TEG

BSST Technology Approach:

New System Architecture

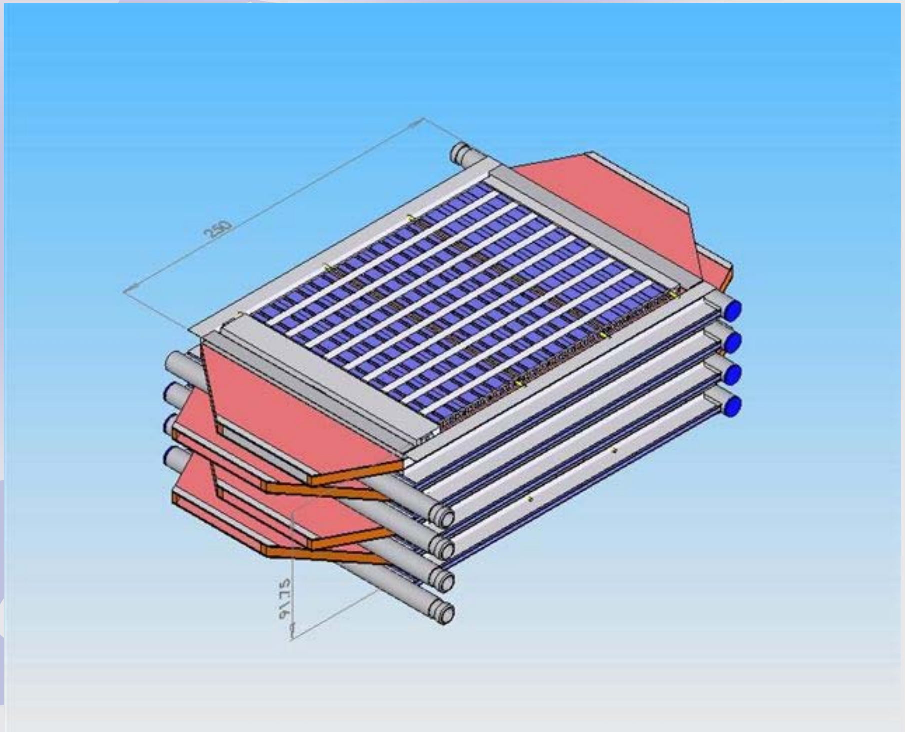
The TEG is designed for 750 watts power production at design flow/temperature

Four exhaust gas flat plate heat exchangers are used with TE circuits on each side (8 TE layers total)

Coolant flows through interleaved layers (5 total) in counterflow

Exhaust gas distribution to each layer is controlled. The number of layers that are active is proportional to the flow of exhaust gas.

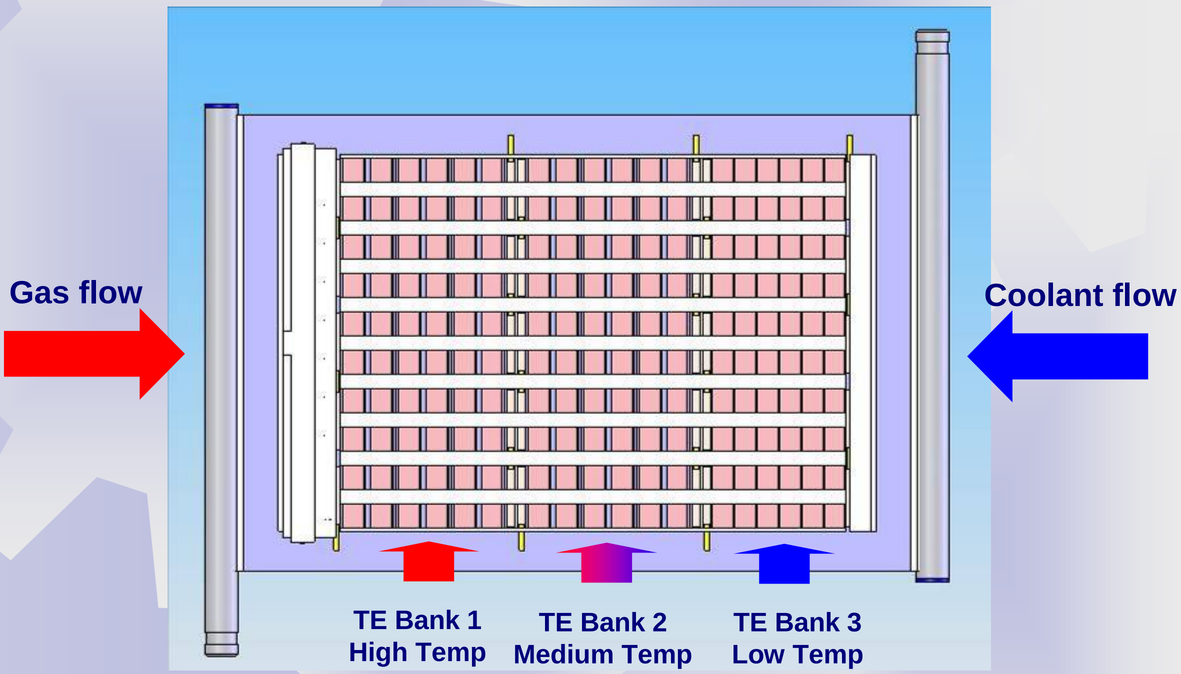
At extremely high mass flow, gas is bypassed



Performance Measures and Accomplishments

Cold Hx Layer with TE Pack

- Counter flow design
- Three temperature zones to match temperature gradient in heat exchanger with maximum TE performance
- Each zone is a separate electrical circuit



BSST Technology Approach.
System Modeling Approach.

A transient bumper-to-bumper vehicle model has been implemented in GT Cool including:

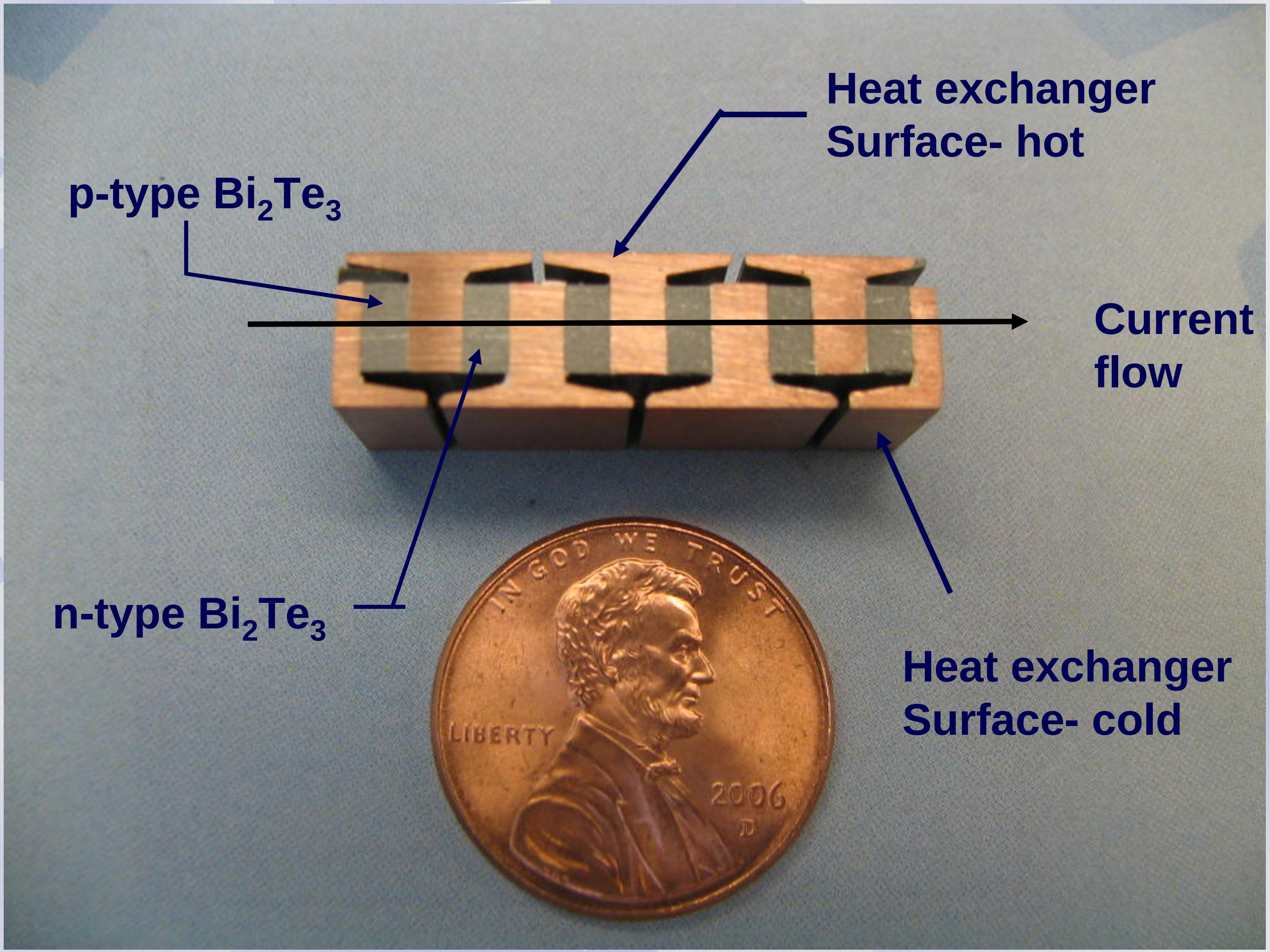
- The in line 6-cylinder engine, alternator, powertrain cooling and exhaust systems.
- Transient TEG model, with variable heat exchanger parameters and TE material properties.

FE performance results are inclusive of total system weight, aerodynamic drag coefficient modification and DC/DC-converter efficiency.

Influence of the increased exhaust backpressure on the FE performance is not yet considered but is maintained at a low level.

Performance Measures and Accomplishments

2^{nd} Generation Bi_2Te_3 Subassembly



Performance Measures and Accomplishment

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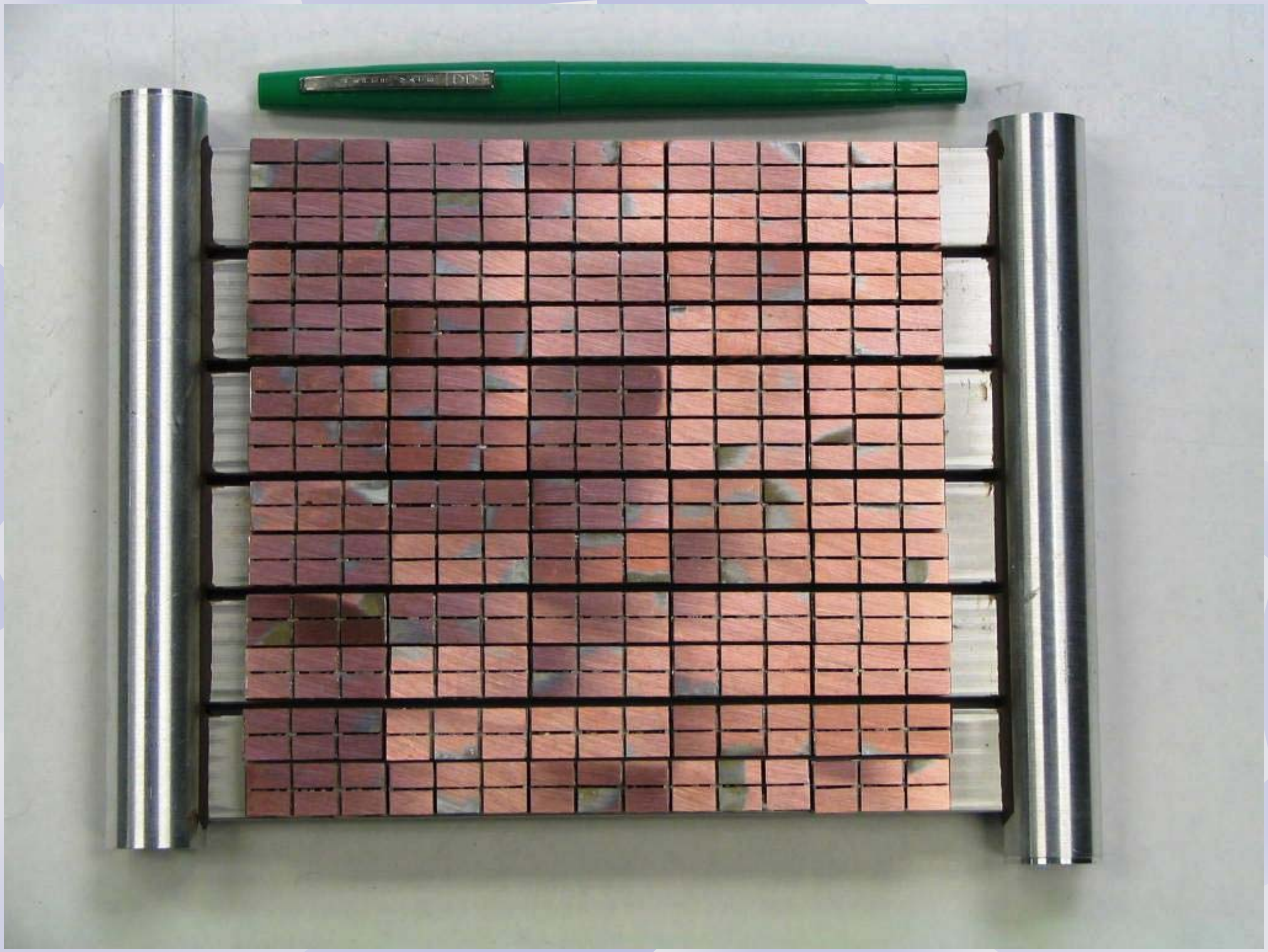
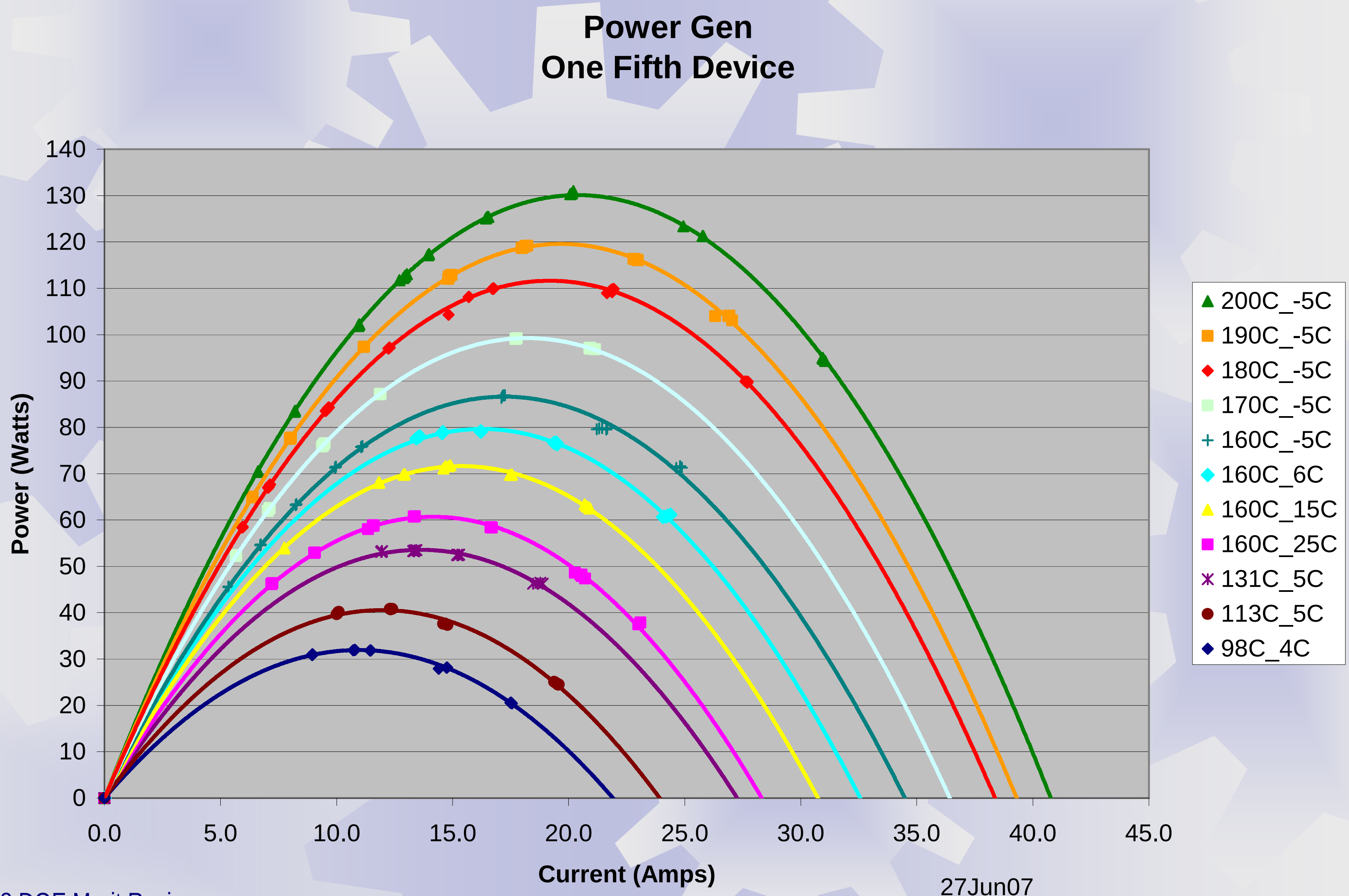
Performance Measures and Accomplishments

Fractional BiTe TEG



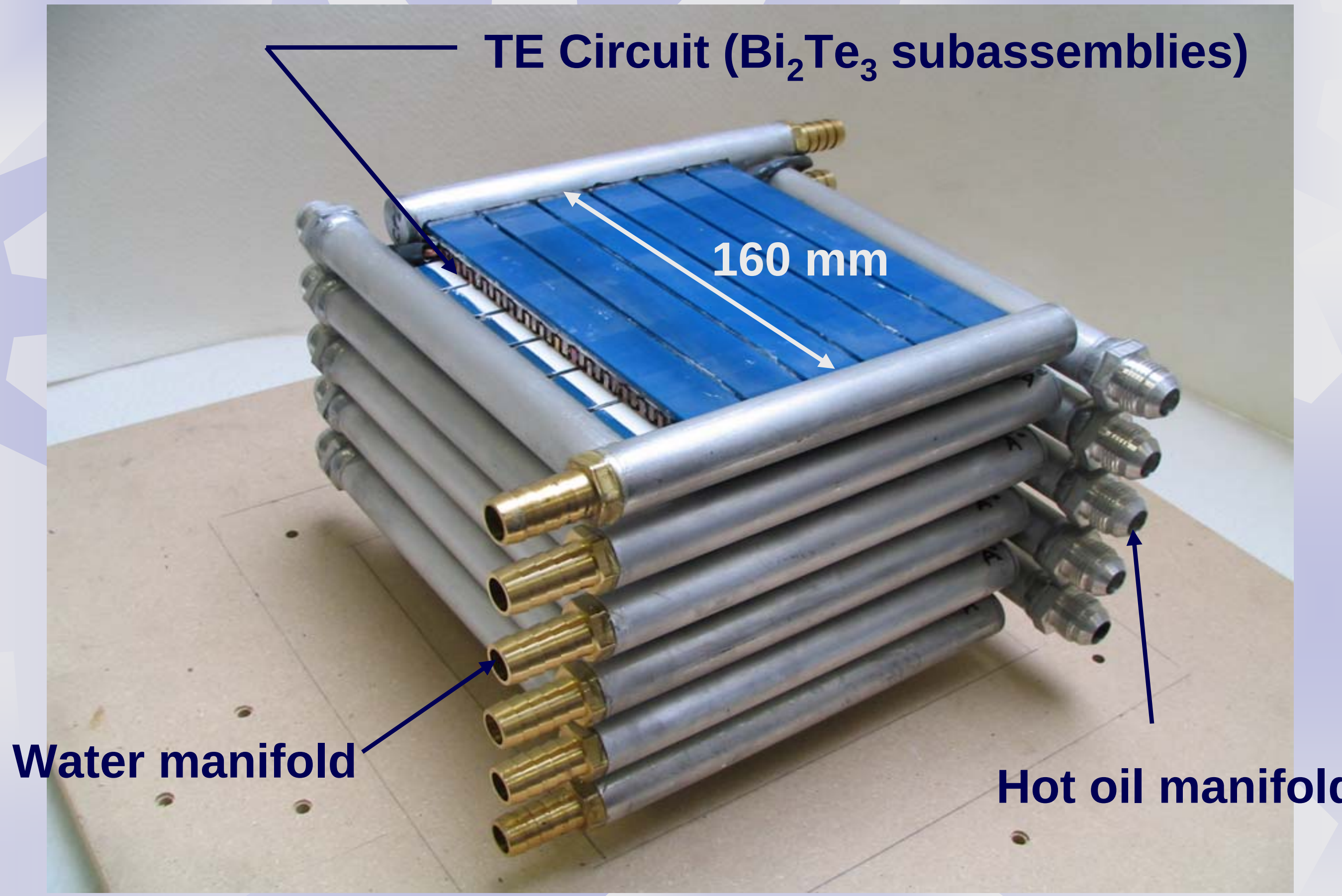
Performance Measures and Accomplishments

Test Results- Fractional BiTe TEG- Maximum Peak Power of 130W



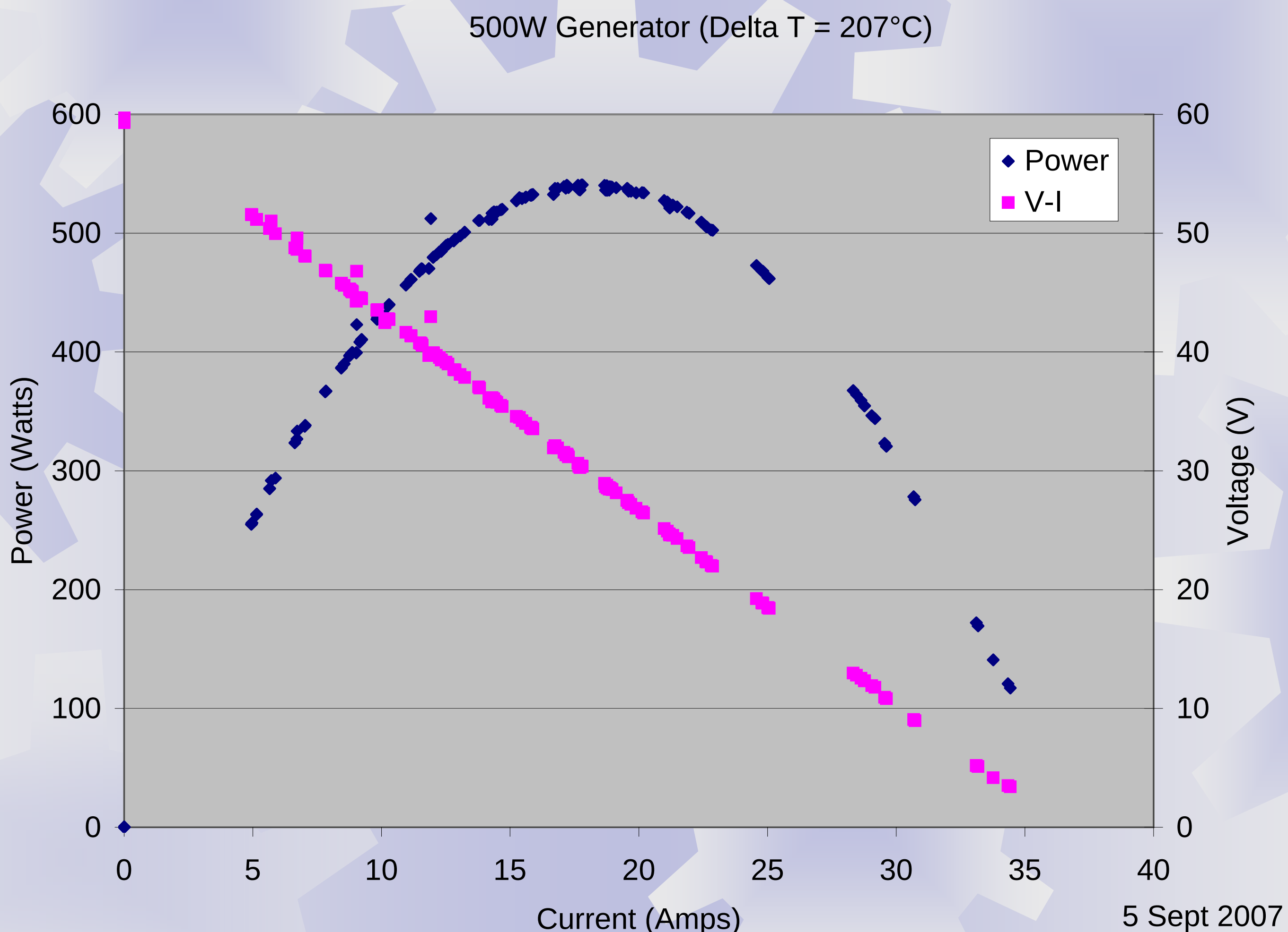
Performance Measures and Accomplishments

Full Scale, 500 Watt BiTe TEG



Performance Measures and Accomplishments

Full Scale BiTe TEG Test Results



Performance Measures and Accomplishments

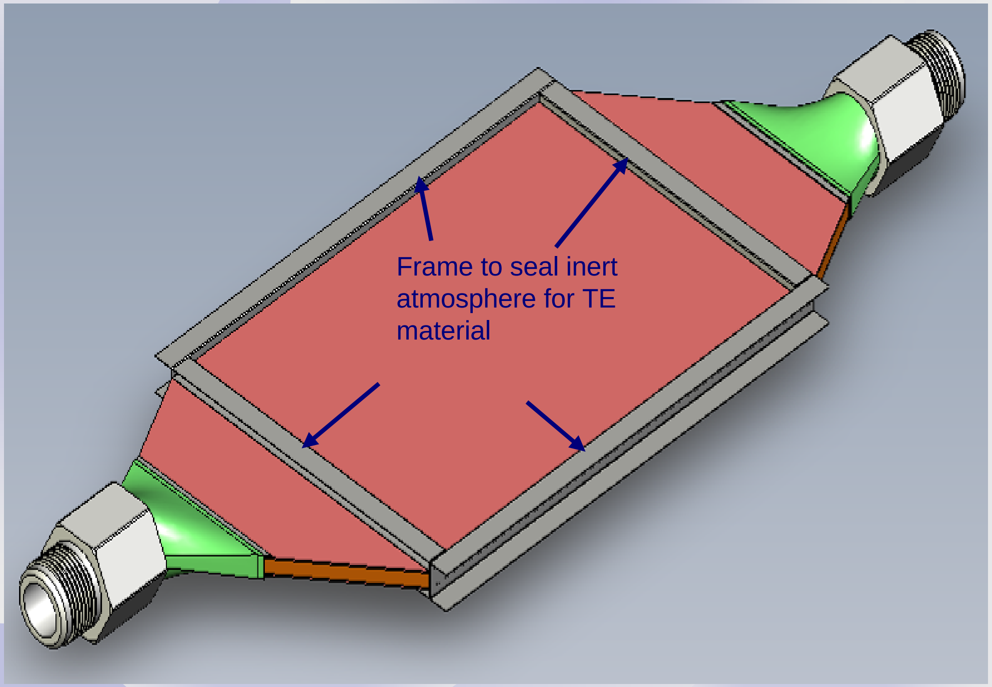
Hot Hx Layer

A stainless steel flat plate heat exchanger is designed for the full scale TEG

Wavy stainless steel fin is used to minimize fouling

The brazed assembly includes a TE subassembly sealing ring

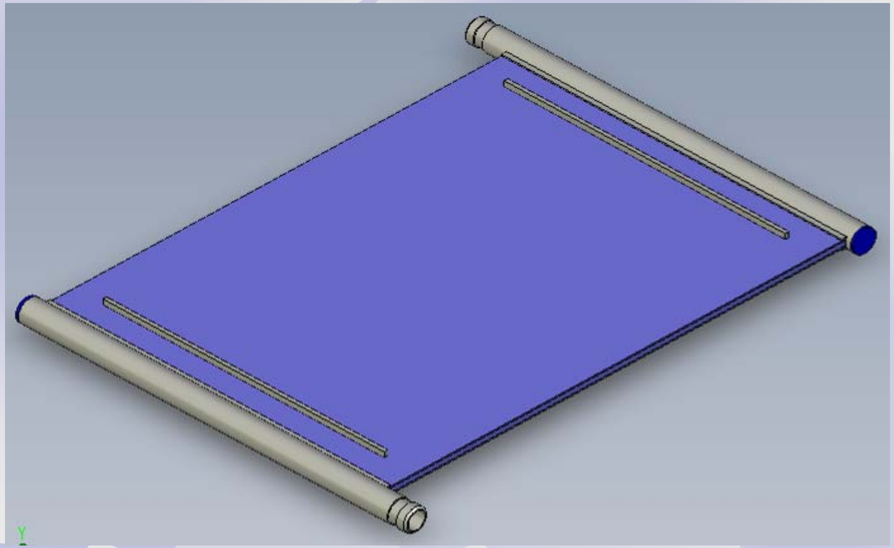
Parts are in fabrication



Performance Measures and Accomplishments

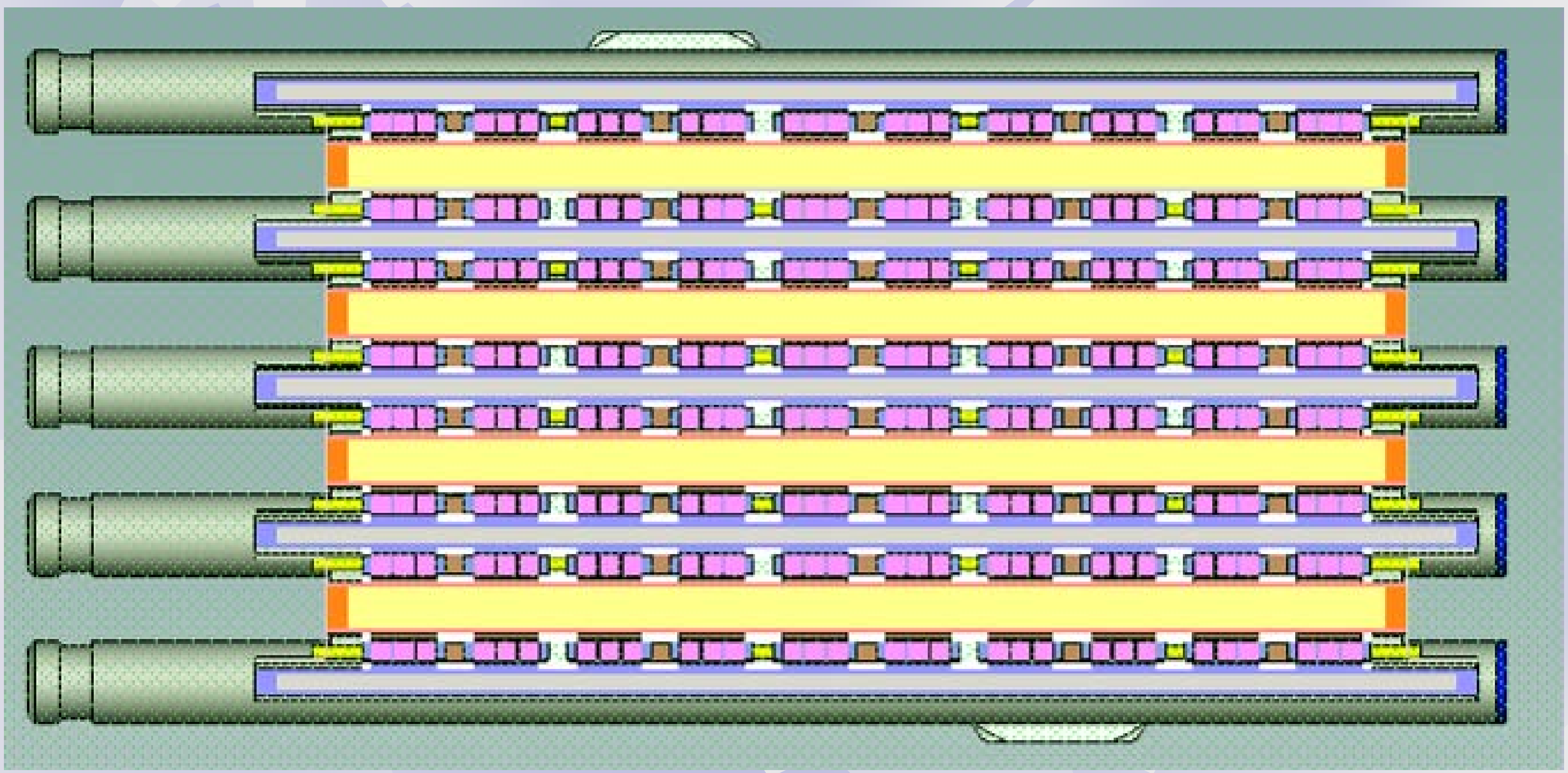
Cold HX Layer

- An aluminum flat plate heat exchanger is designed for the full scale TEG
- Lanced offset aluminum fin is used
- The brazed assembly includes retention features for TE subassemblies
- Parts are in fabrication

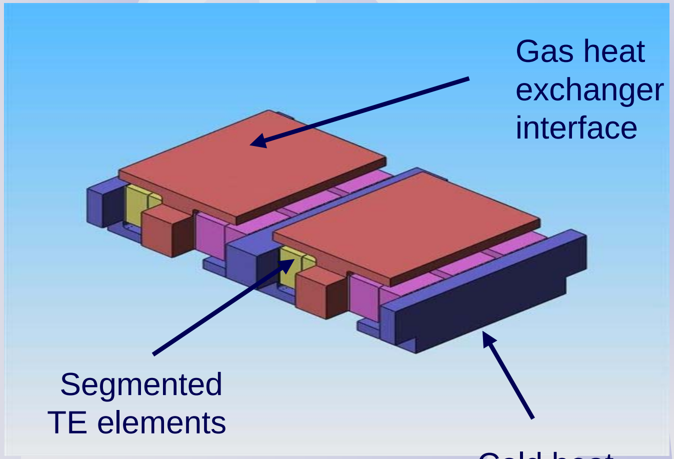


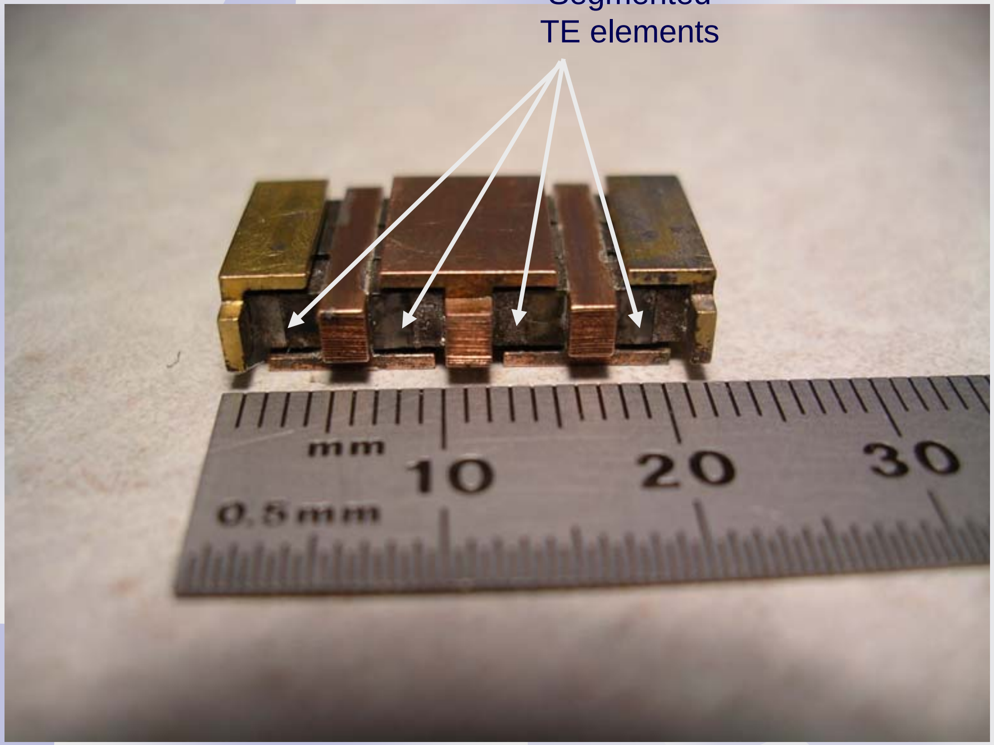
Performance Measures and Accomplishments

Cross section view – full scale TEG

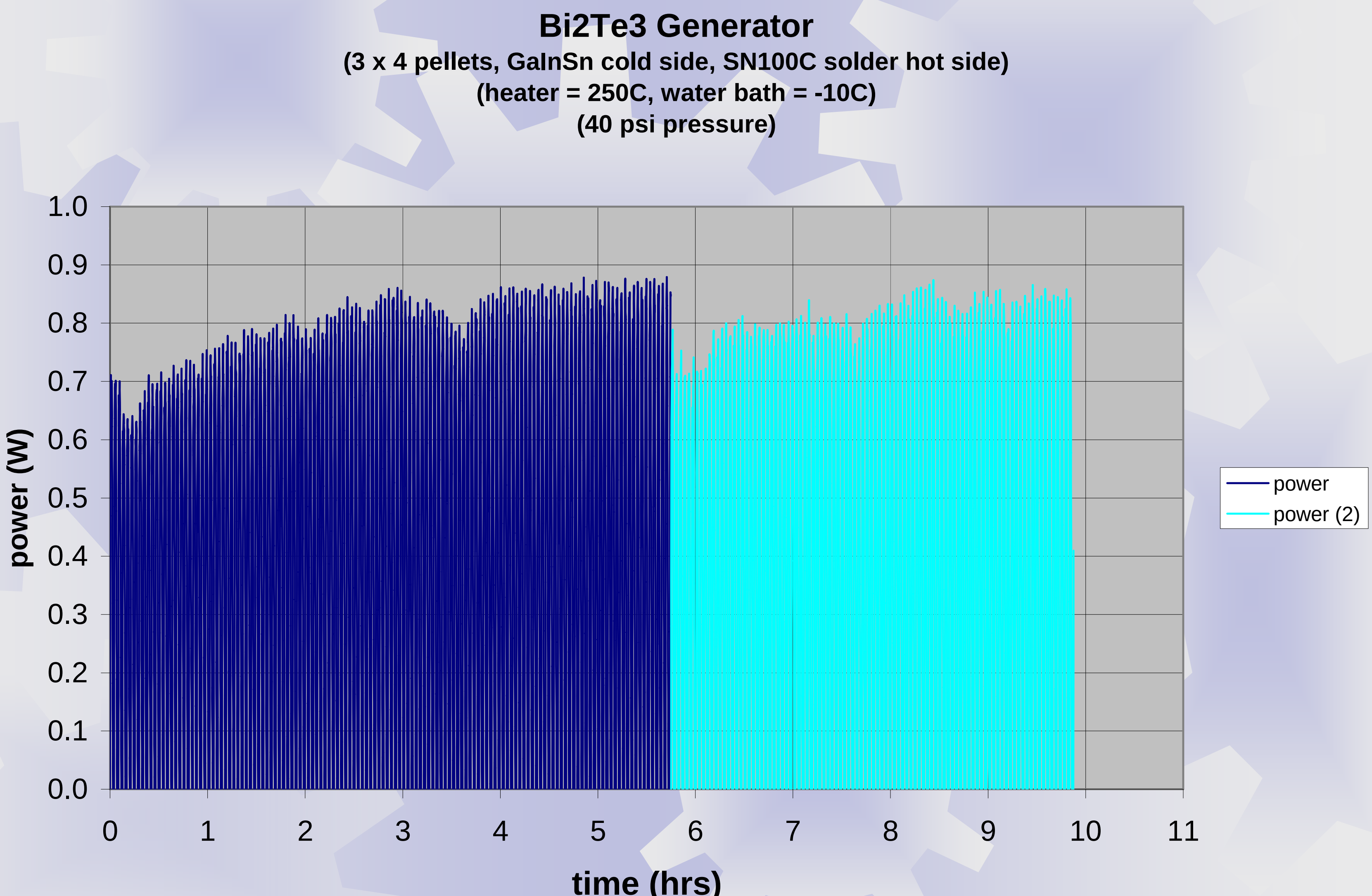


High Temperature Section 2-Stage Segmented Element Subassembly

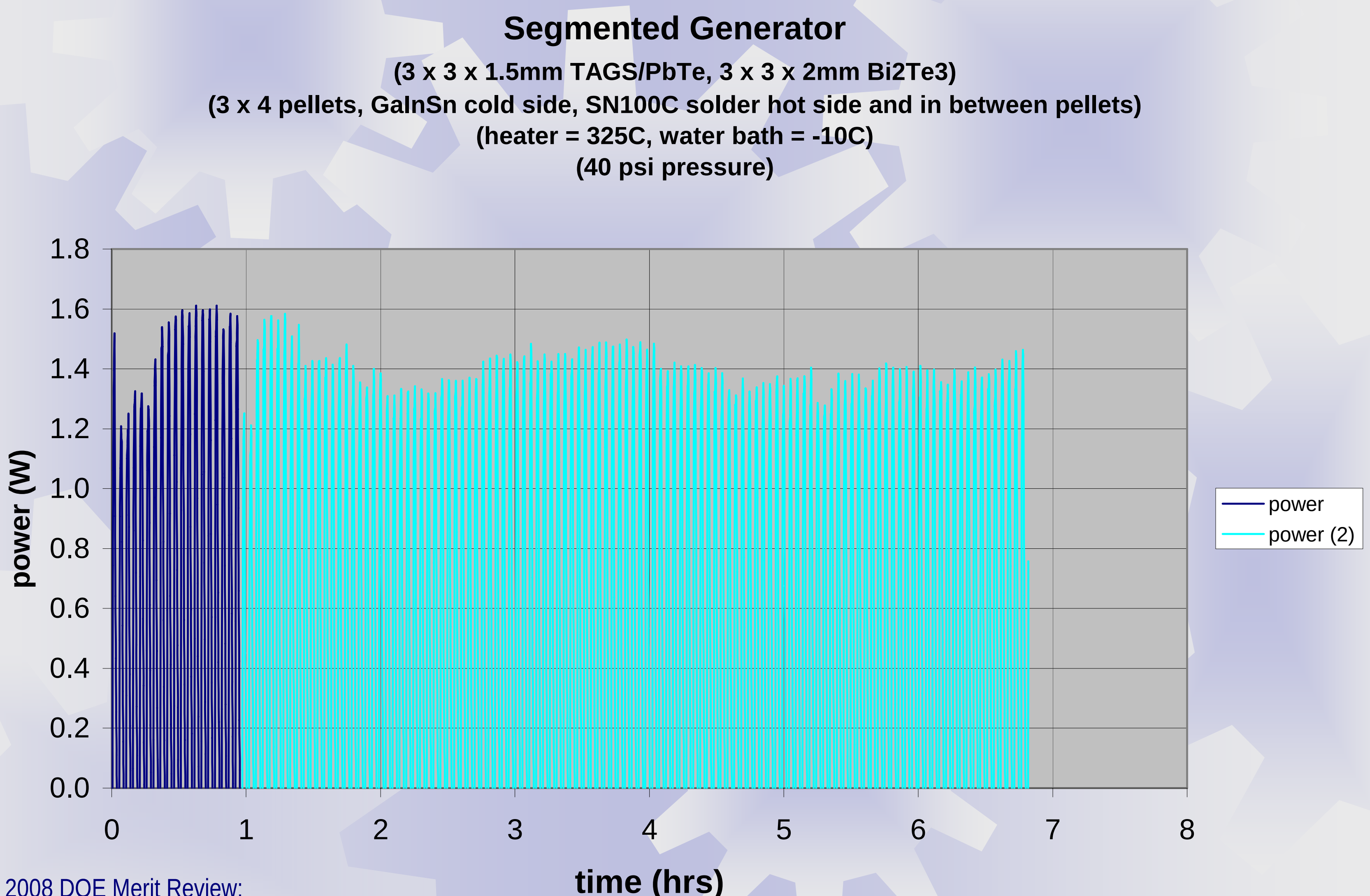




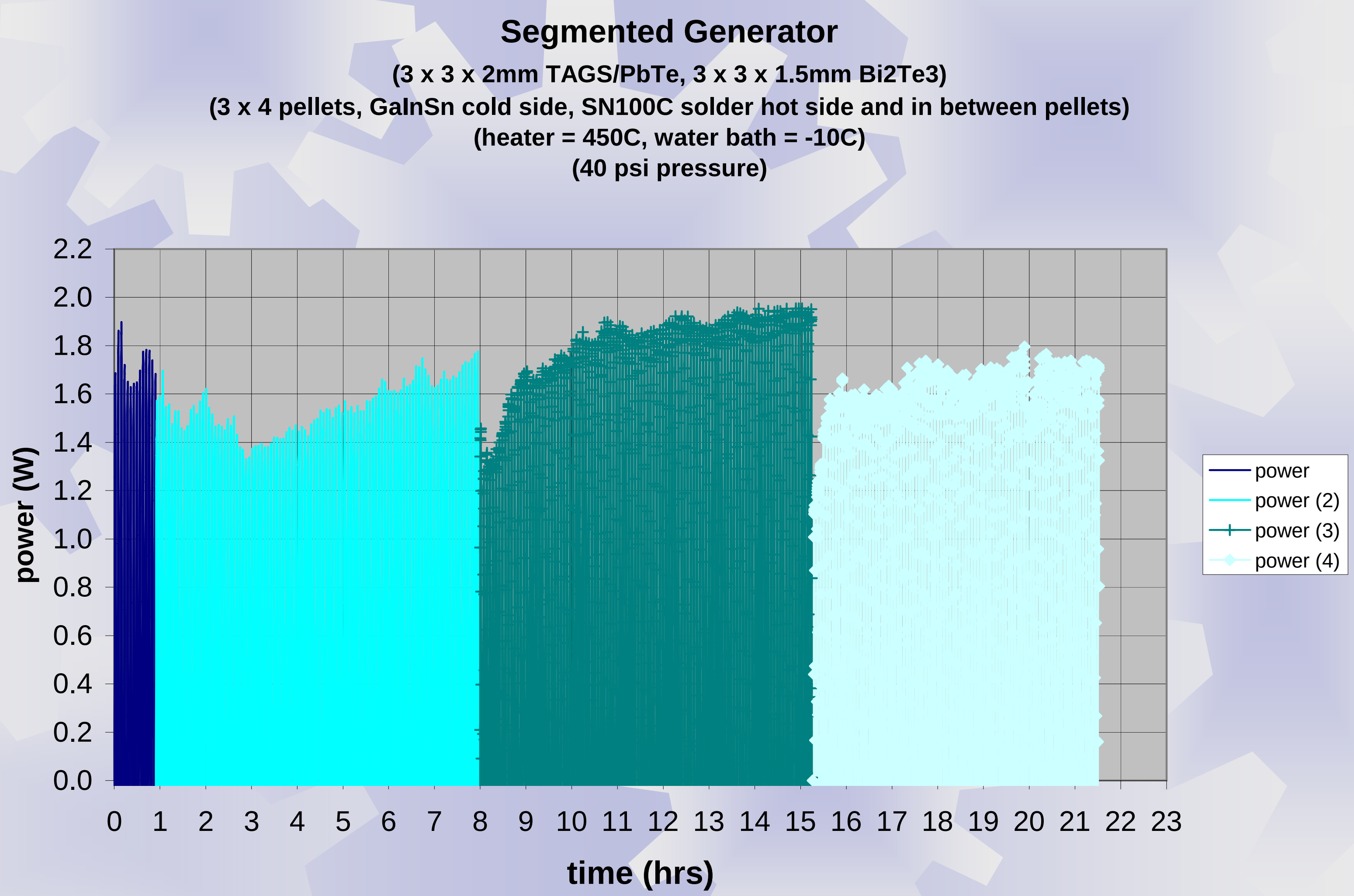
Low Temperature Section
(296 cycles)



Medium Temperature Section
(136 cycles)



High Temperature Section
(322 cycles)



150 Watt TGM Converter Integrated Buck/Boost Power Topology

The PCS is capable of producing a positive output voltage that is greater than, equal to or less than the input voltage in a single stage.

Minimizes cost, size and weight while maximizing power conversion efficiency.

Supports the implementation of Maximum Power Point Tracking.

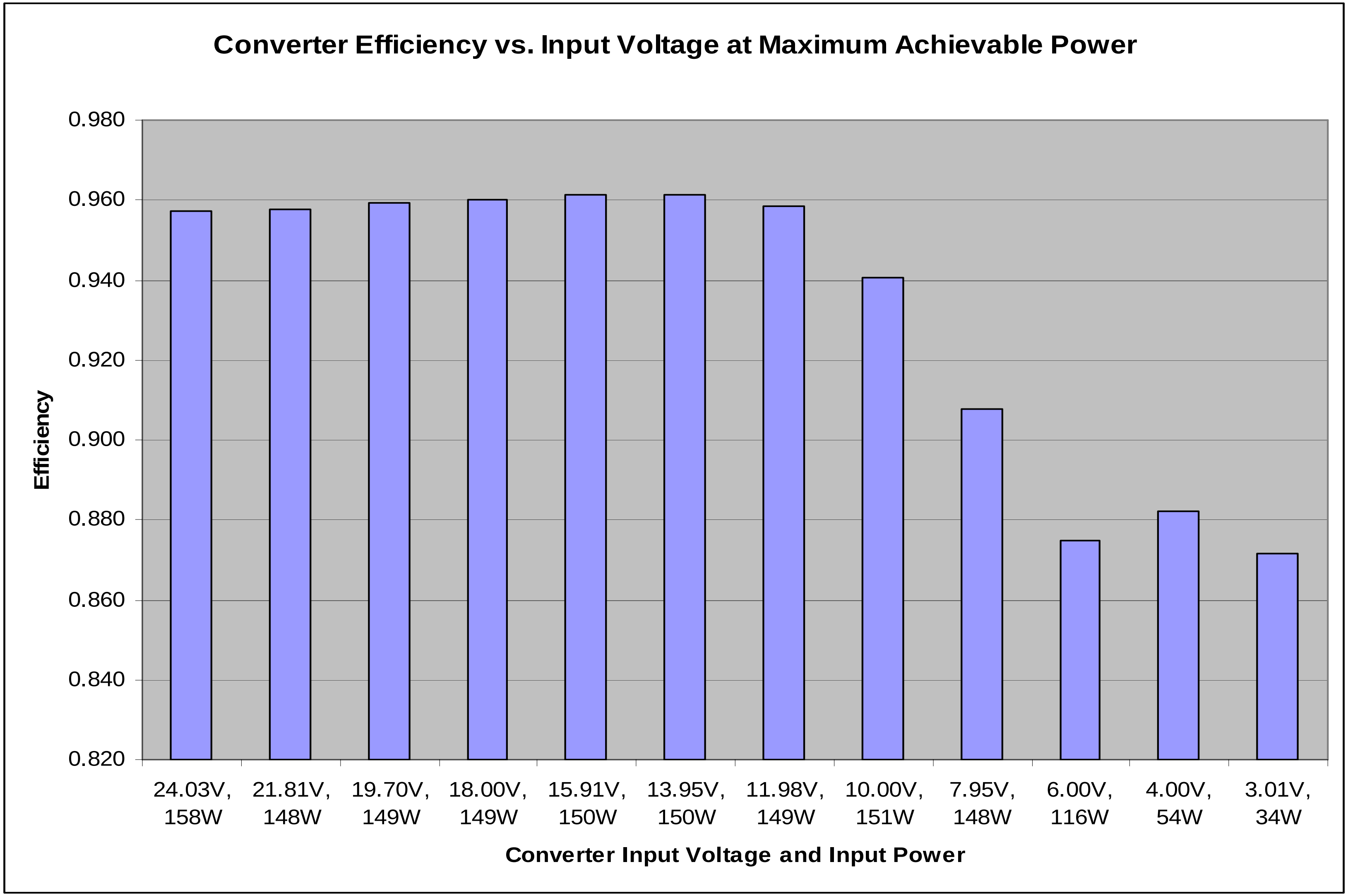
Simplified Maximum Power Point Tracking Algorithm

- Because the TEG is a nearly ideal Thevenin source, the maximum power point occurs when the TEG terminal voltage is equal to ½ the open circuit voltage.

- New algorithm measures the open circuit voltage of the TEG and controls the converter input voltage between 50% and 55% of the TEG open circuit voltage.

- Tracks the TEG maximum power point within 1% while guaranteeing operation on the positive slope of the power curve.

Power Converter Efficiency



Performance Measures and Accomplishments.
System Performance.

System performance ranges from 1% to 8.3% FE improvement over city and highway driving conditions.

Best results are achieved in the after flange position, with an insulated exhaust path to the TEG, boosting powertrain coolant temperature at start up and with an auxiliary radiator to lower cold side temperatures.

Modeling has demonstrated the significant benefit of tailoring TE element, shunt and heat exchanger geometries with respect to thermal flux density.

Modeling continues to further optimize the recovery of energy with trade-offs Vs the amount of TE, shunt, heat exchanger materials and other variables being considered.

Performance Measures and Accomplishments.
System Performance.

Heat Flux	Radiator	ZT	Insulation	Position	NEDC	FTP75	US-Comb.	BSST 1	BSST 2	BSST 3	BSST 4	Cons. 1	Cons. 2	Cons. 3	Cons. 4	Cons. 5	Cons. 6
								30 kph	70 kph	120 kph	160 kph	10 kph	40 kph	50 kph	90 kph	100 kph	135 kph
with	Main	0.85	without	after Flange	1.27	1.35	1.64	-	-	-	-	-	-	-	-	-	-
			with	after Flange	1.51	1.66	2.00	-	-	-	-	-	-	-	-	-	-
				Pretube	1.00	1.22	1.65	-	-	-	-	-	-	-	-	-	-
		1.25	without	after Flange	1.46	1.69	2.04	-	-	-	-	-	-	-	-	-	-
			with	after Flange	1.78	2.04	2.51	-	-	-	-	-	-	-	-	-	-
				Pretube	1.25	1.55	2.07	-	-	-	-	-	-	-	-	-	-
		2	without	after Flange	1.84	2.27	2.69	-	-	-	-	-	-	-	-	-	-
			with	after Flange	2.21	2.75	3.24	-	-	-	-	-	-	-	-	-	-
				Pretube	1.56	2.10	2.76	-	-	-	-	-	-	-	-	-	-
without	Main	0.85	without	after Flange	1.00	1.10	1.51	1.03	1.81	3.61	4.23	0.53	1.10	1.31	1.80	2.88	4.65
			with	after Flange	1.22	1.41	1.87	1.48	2.24	4.16	4.49	0.77	1.34	1.78	2.16	3.48	5.15
				Pretube	0.87	1.07	1.59	1.16	2.34	4.03	4.45	0.64	1.38	1.62	2.05	3.23	5.04
		1.25	without	after Flange	1.22	1.47	1.92	1.08	2.24	4.25	5.65	0.54	1.22	1.46	2.07	3.29	5.58
			with	after Flange	1.52	1.80	2.39	1.25	2.87	4.81	5.82	0.84	1.71	2.02	2.51	4.03	6.19
				Pretube	1.13	1.42	2.01	1.28	2.58	4.64	5.82	0.66	1.50	1.75	2.32	3.80	6.06
		2	without	after Flange	1.68	2.11	2.61	1.14	2.47	5.08	5.82	0.84	1.39	1.78	2.61	4.23	6.50
			with	after Flange	2.03	2.58	3.15	1.86	3.50	5.67	5.82	1.00	2.07	2.49	3.15	5.06	6.96
				Pretube	1.48	2.01	2.72	1.53	3.16	5.52	5.82	1.12	1.80	2.22	2.94	4.80	6.88
without	Aux.	0.85	without	after Flange	1.15	1.42	1.84	1.41	2.32	3.94	4.24	0.78	1.59	1.76	2.15	3.24	4.98
			with	after Flange	1.39	1.76	2.28	1.58	2.74	4.50	4.62	1.10	1.77	2.28	2.63	3.88	5.48
				Pretube	1.01	1.39	1.98	1.43	2.89	4.35	4.50	0.93	1.62	2.00	2.40	3.65	5.42
		1.25	without	after Flange	1.45	1.81	2.39	1.47	2.84	4.64	5.27	0.84	1.74	1.89	2.53	3.72	6.01
			with	after Flange	1.81	2.34	2.95	2.01	3.42	5.26	5.27	1.38	2.11	2.55	3.06	4.67	6.52
				Pretube	1.31	1.87	2.52	1.57	3.34	5.10	5.27	1.15	1.89	2.21	2.92	4.43	6.43
		2	without	after Flange	2.10	2.80	3.34	2.36	3.54	5.76	5.27	1.88	2.05	2.56	3.36	5.13	7.00
			with	after Flange	2.48	3.35	3.99	2.62	4.76	6.48	5.27	2.58	2.91	3.38	4.00	5.98	8.29
				Pretube	1.89	2.69	3.47	2.31	4.41	6.28	5.27	2.22	2.49	2.94	3.79	5.55	8.18

FE improvements in % for different driving conditions.
Reference vehicle: 530i (MY 2006) with increased electrical load of 750W.

Collaborations- Interactions

BSST is working with leading Universities, Laboratories and Companies worldwide to commercialize advanced TE material for the Waste Heat Recovery Program

Key Program partners include BMW and Visteon Automotive

University partners include:

- Virginia Tech is developing high efficiency power conversion and control electronics
- Cal Tech is characterizing advanced TE materials from Marlow and others
- The Ohio State University is developing advanced TE materials
- The University of Texas at Dallas is characterizing contact interfaces

Related Publications and Patents

Publications

- Diesel Engine Emissions Reduction (DEER) Conference (presentation) – 'Development of a Scalable 10% Efficient Thermoelectric Generator' (August 15, 2007) Authors: Douglas Crane, John LaGrandeur, and Lon Bell
- ASME Energy Sustainability Conference (paper ES2007-36210) – 'Design to Maximize Performance of a Thermoelectric Power Generator with a Dynamic Thermal Power Source' (June 27 – 30, 2007) Authors: Douglas Crane and Lon Bell
- Crane, D.T. and Bell, L.E., Progress Towards Maximizing the Performance of a Thermoelectric Power Generator, Proceedings of the 25th International Conference on Thermoelectrics, Vienna, Austria, August 2006
- LaGrandeur, J, et. al, Automotive Waste Heat Conversion to Electric Power Using Skutterudites, TAGS, PbTe and BiTe, Proceedings of the 25th International Conference on Thermoelectrics, Vienna, Austria, August 2006
- LaGrandeur, J, et. al, Proceedings of the 12th Diesel Engine Emissions Reduction (DEER) Conference, Detroit, MI, August 2006
- LaGrandeur, J, et. al, Vehicle Fuel Economy Improvement Using Waste Heat Recovery, Proceedings of the 11th Diesel Engine Emissions Reduction (DEER) Conference, Chicago, IL, August 2005

Patents:

Case No.	Title of Invention:	Country:	Status:	Application No.	Filing Date:
BSST.001CP2C1	HIGH POWER DENSITY THERMOELECTRIC SYSTEMS	US	Published	11/136334	5/24/2005
BSST.016A	THERMOELECTRIC POWER GENERATOR FOR VARIABLE THERMAL POWER SOURCE	US	Pending	11/476325	6/28/2006
BSST.022A	THERMOELECTRIC POWER GENERATOR WITH INTERMEDIATE LOOP	US	Pending	11/476326	6/28/2006
BSST.024PR	THERMOELECTRIC POWER GENERATOR	US	Pending	60/834006	7/28/2006

FY 2008 Work Plan

Build and initial testing of the 1st layer of a high temperature TEG is scheduled for March 2008

- Power electronics integration will performed using the Visteon PCS in March 2008

A full scale TEG will be built and test begun by April 2008

Phase 4 activities leading to engine dynamometer testing will begin in June of 2008 and are planned for completion in January 2009

Summary

- Fractional and full scale BiTe TEGs that produced over 500 watts of electric power have been built and tested
- The system model has been updated to reflect real world transient behavior and is being used to optimize system design Vs the trade-offs of weight, volume and cost
- High temperature TEG assemblies are achieving power output and thermal cycling performance in line with Phase 3 expectations
- A full scale system is on track for dynamometer test start by year-end

Acknowledgements

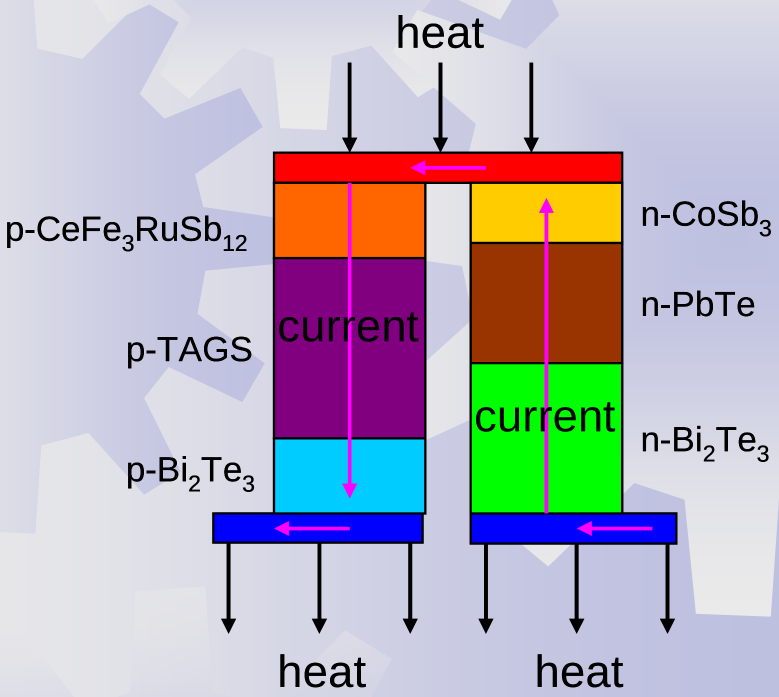
The continued support of the US DOE Freedom Car Vehicle Technologies Office in support of this work is appreciated

Reference Material

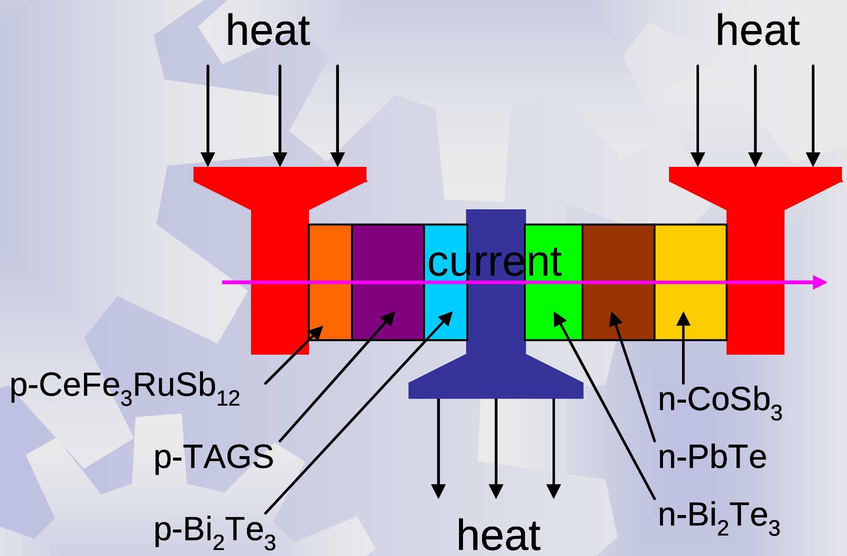
This presentation does not contain any proprietary or confidential information

BSST Technology Approach:

BSST Y Configuration Reduces TE Material Usage



Traditional configuration



BSST “Y” configuration