Automotive Waste Heat Conversion to Power Program- 2011 Vehicle Technologies Program Annual Merit Review

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Project ID # ACE051

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BSST Program Overview

Timeline

Program Start Date:	Oct ‘04
Program End date:	June 2011
Percent Complete:	90%

Budget

Total Project spend:	$10,856,667
DOE Share:	$6,700,859
Contractor Share:	$4,155,808 (38%)
FY09 & FY10 Funding Received:	$1,114,484

Barriers

Complex manufacture of TE engines and the TEG subsystem

Environmental withstanding of TE engines and assemblies in an underfloor exhaust system

Vehicle TEG system on-cost

Targets

FE Improvement:	10%

Partners

Project Lead:	BSST/Amerigon
OEM Partners:	BMW & Ford
Tier 1 Partner:	Faurecia
University/Fed’l Lab Partners:	Caltech, JPL, NREL

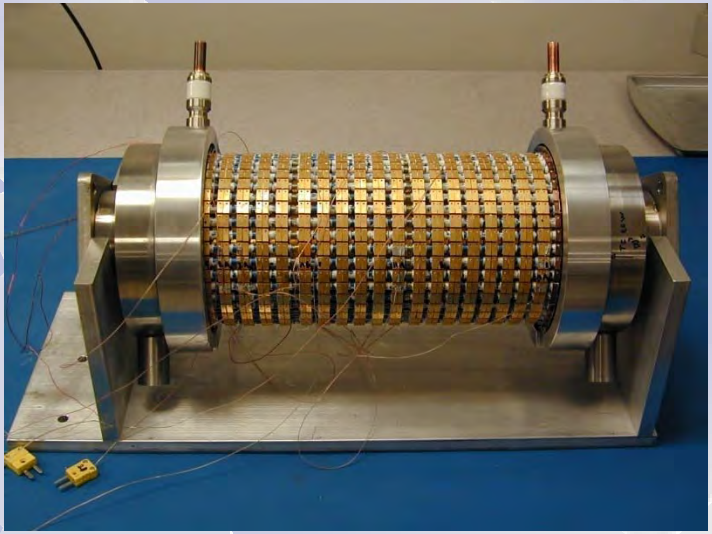
BSST 2011 Program Milestones

Date	Milestone
May 3	Complete TEG S/N 1 build and test at BSST
June 1	Complete BMW X6 TEG system installation, begin vehicle level evaluation
July 1	Complete TEG S/N 2 build and test at BSST
July 11	Begin Dyno test with TEG S/N 2 at NREL using BMW engine
Aug 1	Complete TEG S/N 2 Dyno testing, install in Ford vehicle. Begin vehicle level evaluation

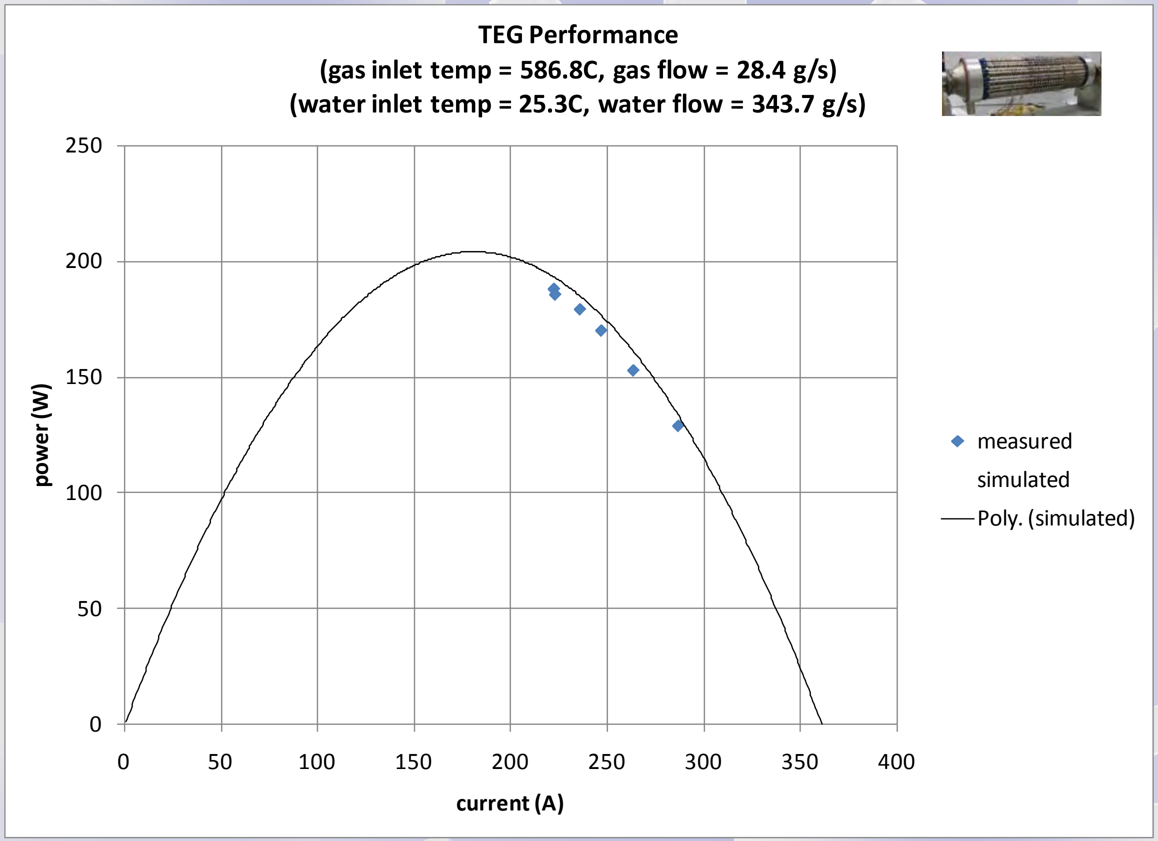
Approach: Improve the manufacturability of TE engines and the TEG subsystem

In Phase 4, a full scale Cylindrical TEG was built and tested. While the power produced was significantly higher than the planar configuration TEG, and the performance repeatable, this TEG underperformed by 60% (model prediction) due to poor interfaces.

In Phase 5, an approach was taken that involved redesign and improved tooling to improve thermal and electrical interfaces so that the power produced would be closer to the model prediction.



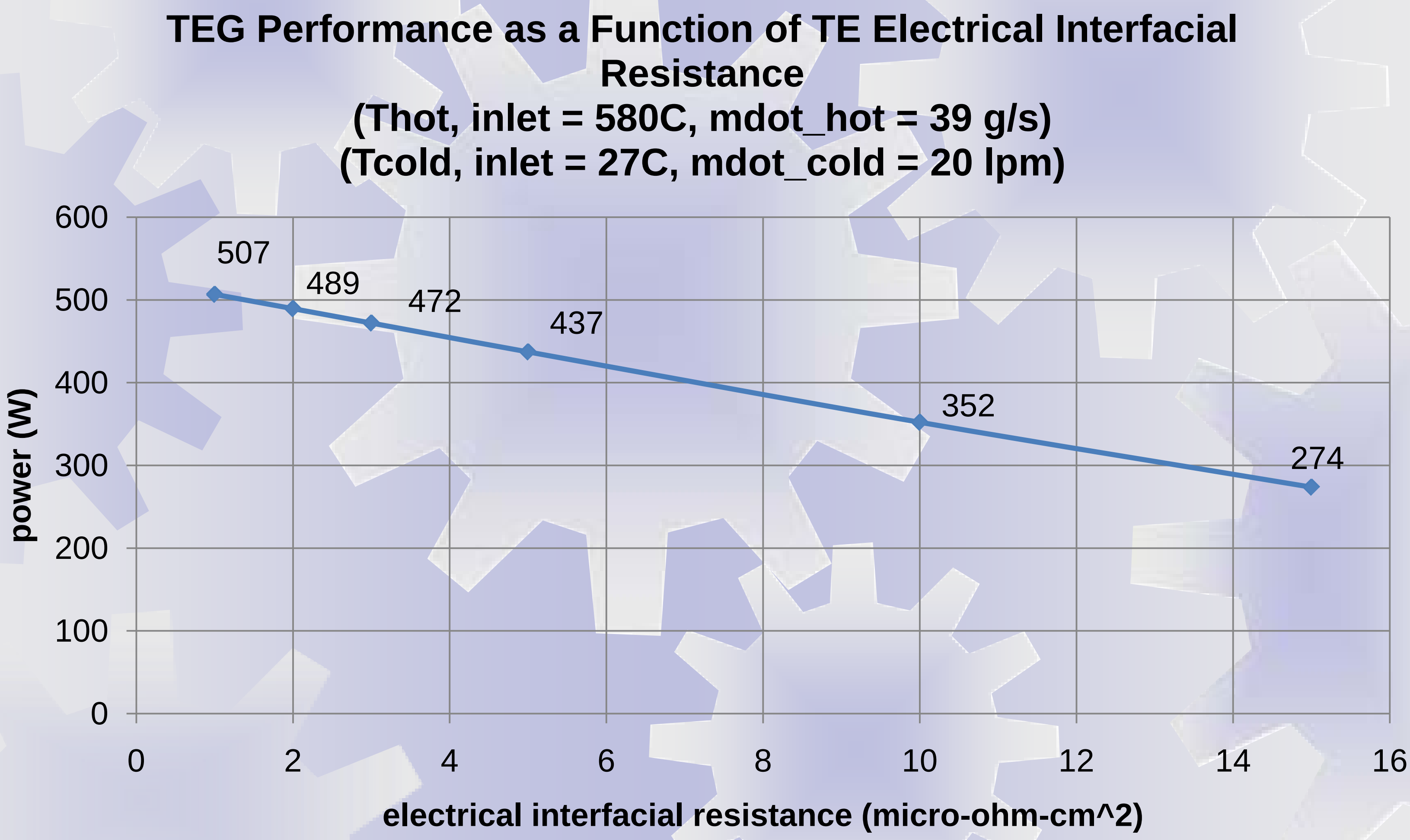
Achievements: Phase 4 TEG Measured Performance



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

Interfacial Resistance Analysis

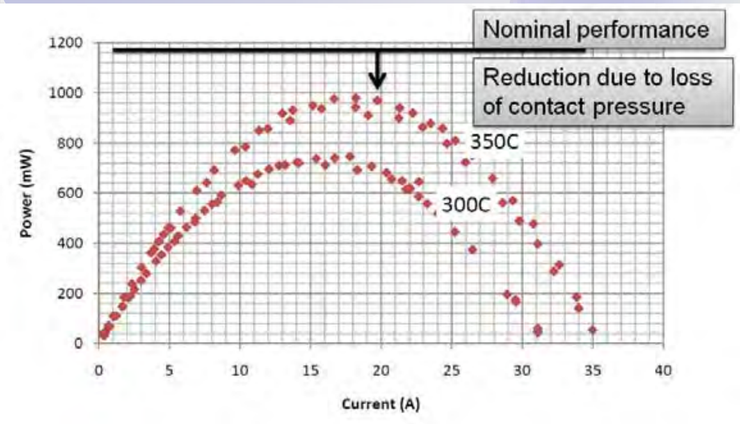


Interfacial Resistance- Countermeasures

The registration of engines with respect to the hot side rings is enhanced through several process and assembly tooling improvements:

- Careful machining of the gas heat exchanger to achieve a consistent diameter. This enables uniform axial ring positioning so that TE engines mate properly with the heat exchanger contact surface. The Phase 4 TEG had total indicator runout of 1.5 mm, the Phase 5 TEG TIR has measured 0.05 mm.
- The TE elements are soldered to the hot shunts, and make contact with the ring over an uninterrupted surface through 360^0. This makes the position of the TE elements less sensitive to the relative XY plane position of the cold/hot shunt interface.
- In addition, the number of elements/shunt has been reduced from 4 to 2 to reduce thermal shear stresses and parasitic thermal losses.

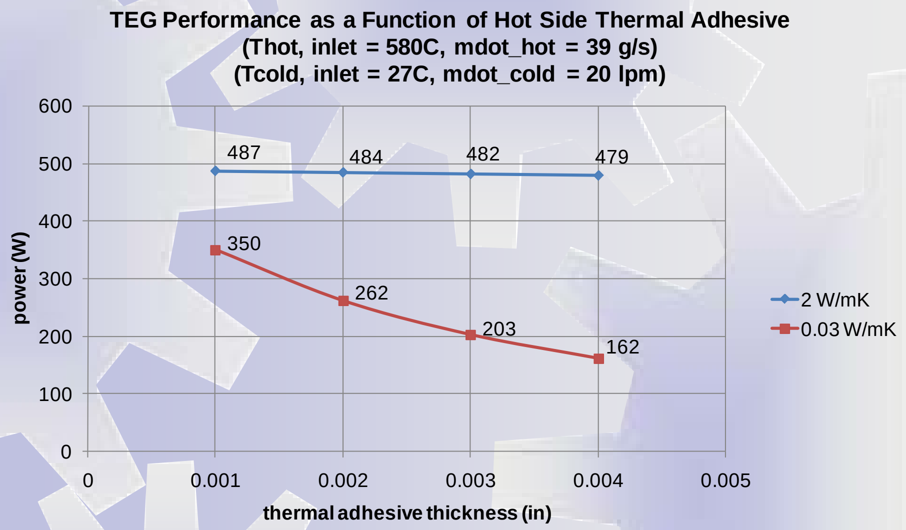
The compression of the TE elements shunts is made uniform and consistent over the wide operating temperature range through redesign of the cold shunt to accommodate a new lower spring rate flexure. In addition, a spacer ring is added between the hot shunts to maintain uniform spacing and compression.



Thermal Interface, Hot Side Analysis & Countermeasures

Heat transfer between the hot side rings and SS tube was poorer than expected. The thermal resistance across the interface was higher than anticipated due to several factors:

- The fit between the rings and SS tube was such that the adhesive was porous and cracked, increasing thermal resistance. This was due to inadequate braze fixtures and tube uniformity
- Early experiments with thermal interface materials provided a solution that had excellent electrical resistance but provided significant room for improvement in thermal conductivity.



Countermeasures include:

- Tight dimensional control of the gas heat exchanger finished OD (previously described).
- Replacement of the Phase 4 interface material system with an improved material system for Phase 5.

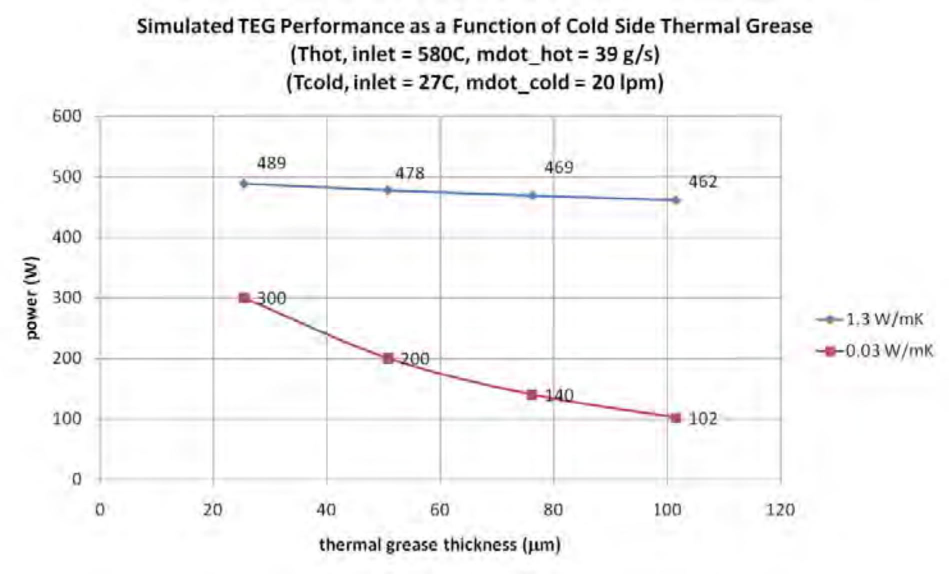
Thermal Interface, Cold Side Analysis & Countermeasures

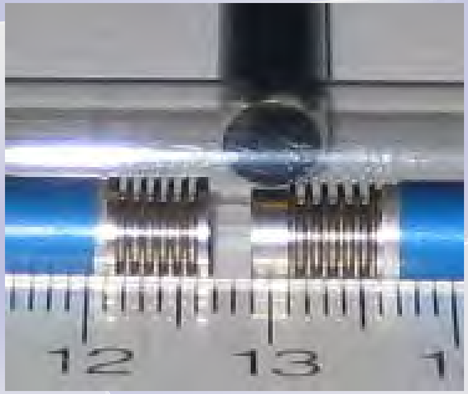
Heat transfer between the cold shunt and aluminum tube was inadequate. The thermal resistance across the interface was higher than anticipated due to several factors:

- Misalignment of the hot rings with the SS tube prevented alignment of the cold shunts. The resultant fit of the aluminum tube was too tight to permit adequate thermal grease application at the cold shunt /tube interface.
- The design of the shunt required heat transfer from groups of 4 n and p TE couples across a large area inducing further parasitic thermal losses.

Countermeasures include:

- Improved dimensional control of the gas heat exchanger as previously described. This will enable effective greasing at the aluminum tube/cold shunt interface. A grease filling hole has been added to promote uniform application of thermal grease.
- Pre-installation of the aluminum tubes with the cold shunt sleeves to provide improved alignment.





Final Assembly Fixture

Assembly fixture role and benefits

- Positions the heat exchanger vertically and allows the stacking of the hot rings, the TE engine crowns and the spacers.
- Compresses uniformly the TE elements.
- Assures a precise positioning of cooling tube and TE engines.
- Completes and lock up the compressed assembly steps of the TEG's active core.

Approach: Simplify the TEG Vehicle System, Reduce Size and Weight

The current approach is to use a split tube (“Y) to bypass the TEG in high exhaust gas mass flow conditions:

- Avoid excessive pressure drop which degrades fuel efficiency
- Protect temperature sensitive TE material

Proposed solution: Incorporate the bypass within a cylindrical “coaxial” form factor to reduce weight and subsystem volume

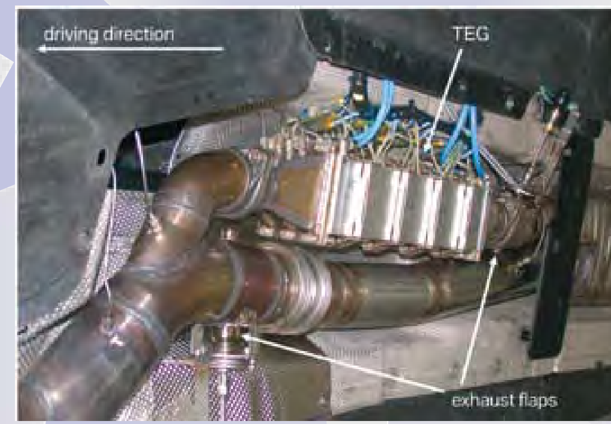
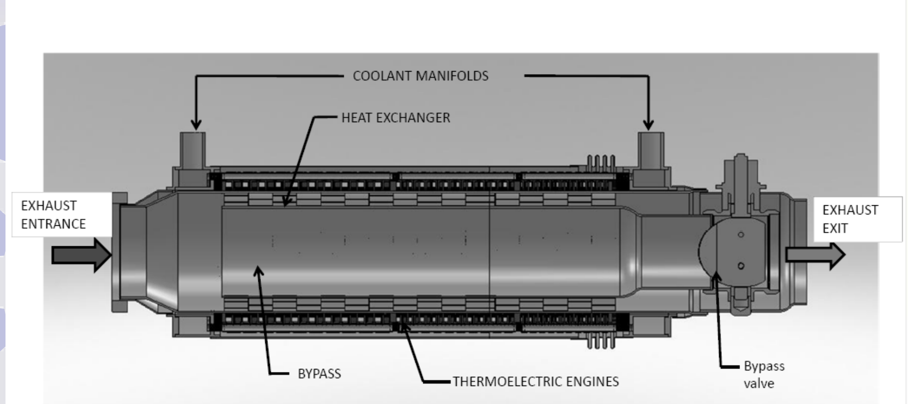


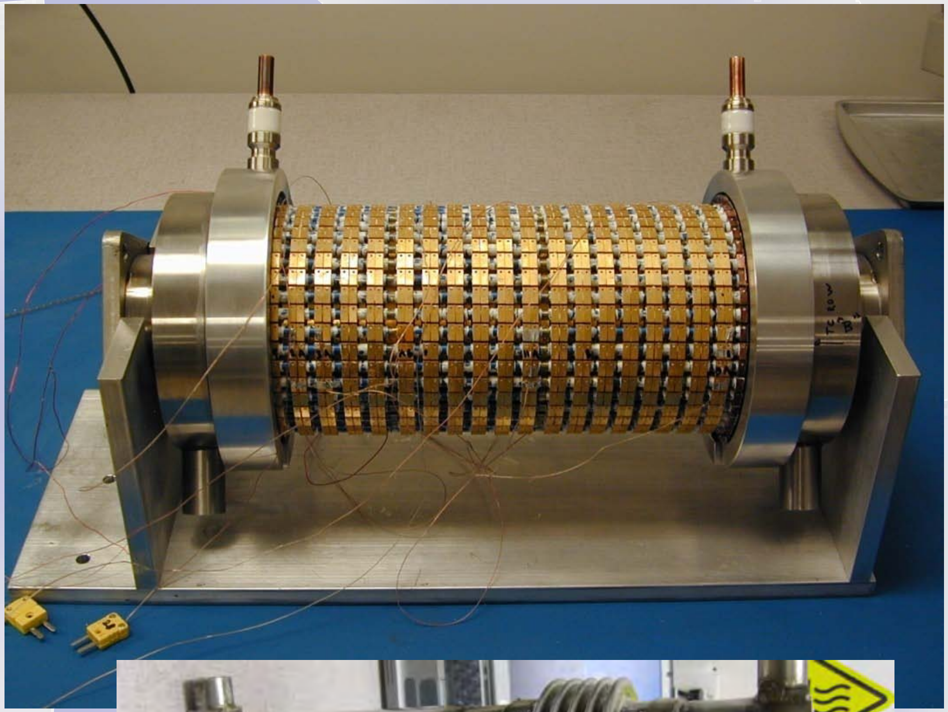
Image courtesy of the BMW Group



Accomplishment: Development of a Manufacturable TEG Subsystem

Manufacturing improvements to the Phase 4 cylindrical TEG for Phase 5 vehicle installations included:

- Fixing TE elements to the rings for hot, medium and low temp sections,
- Reducing cold shunt pellet interface from 4 to 2
- Truing the gas heat exchanger tube surface and match-machining ID of hot rings
- Reducing liquid tube bellow diameters to improve cold side heat transfer
- Improving the interfacial barrier material between the hot rings and SS gas tube



Outer cover

Accomplishment: 500 watt High Temperature TEG Build/Test Results

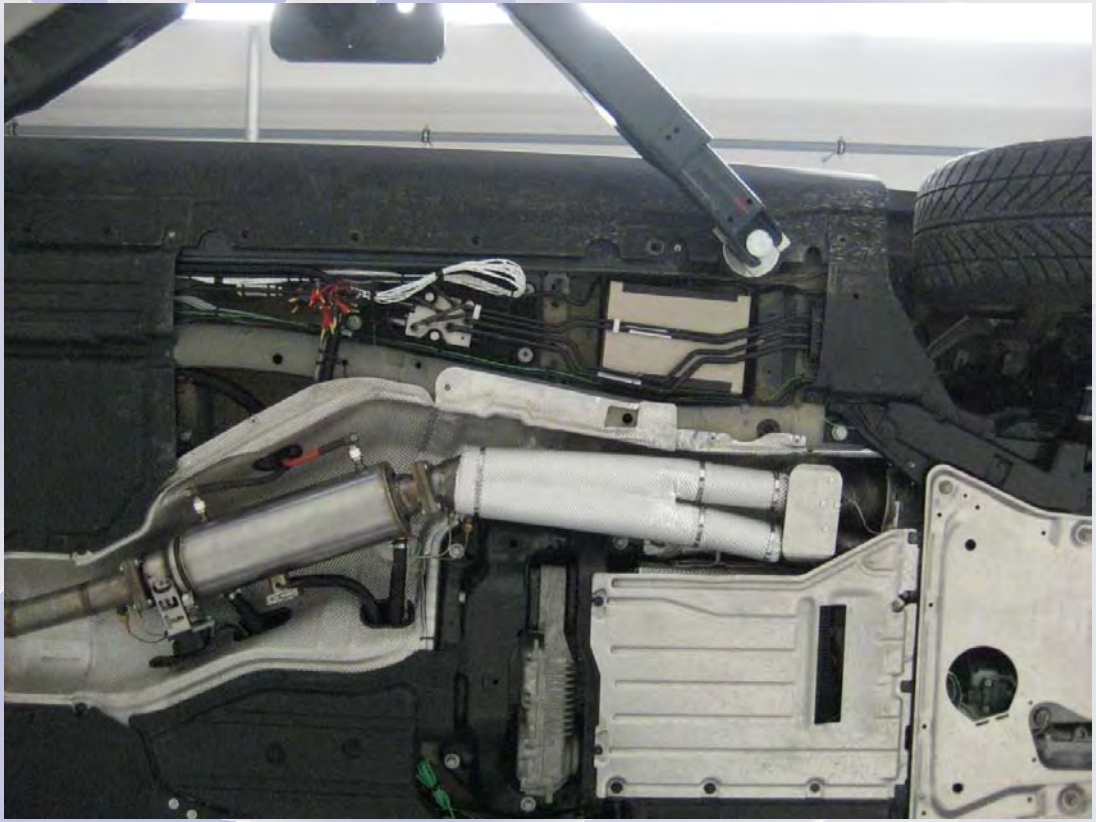
To be presented at the May 13 review

Accomplishment: Simplifying the Vehicle TEG System

A solenoid operated bypass valve was designed and built by Faurecia

The valve operates proportionally to vary flow according to closed loop algorithmic control

Phase 5 TEGs and vehicle installations will include this valve



Collaborations

- OEM led vehicle system engineering and architecture is performed by BMW and Ford
- Tier 1 level underfloor exhaust system design/build and vehicle installation is led by Faurecia
- The Jet Propulsion Laboratory and CalTech are contributing TE material synthesis and characterization support
- NREL is managing the instrumentation and test set up for Dynamometer testing of the system with BMW’s in line 6 cylinder ICE.

Collaborations

In a separately funded, parallel effort to the DOE program Amerigon/BSST has invested in the development of advanced power generation TE materials through collaborations with Ohio State University and Northwestern.

An Amerigon/BSST wholly owned subsidiary, ZT Plus, has been established to lead the pilot production of advanced TE materials including those developed at OSU and Northwestern Universities.

Future Work

Phase 5 objectives include:

- Dynamometer testing of a high temperature TEG at NREL
- TEG installation and evaluation in BMW X6 and Ford Fusion vehicles
  - Exhaust system design and integration of the TEG subsystem by Faurecia
  - Vehicle performance testing by BMW and Ford
- Commercialization preparation including TE material and waste heat recovery key subsystem production roadmaps
  - TE material source needs to be made production ready
  - TE engine scale up for production needs to be performed

Additional work is required to scale up TE materials and engines for production and to ready vehicle systems for the deployment of the technology.

Principle Investigator Succession Plan

Effective January 1, 2011, Dr. Lon Bell has retired from BSST and will no longer serve in the role as Amerigon/BSST's PI.

Dr. Douglas Crane will succeed Lon as Principle Investigator for the current and (pending) future TEG programs.

Summary

Relevance

- Exhaust gas waste heat conversion to electric power reduces fuel consumption and is aligned with the increasing electrification of vehicles.

Approach/Strategy for Deployment

- An approach focused on optimizing vehicle level system performance while reducing the amount of TE material used to facilitate commercialization has been followed. The approach is based upon a proprietary TEG design and construction that tightly integrates TE materials and substrates with gas and liquid heat exchangers in a novel, cylindrical form factor.

Technical Accomplishments and Progress

- A cylindrical TEG design was adopted in Phase 4 to improve manufacturability and the performance of key interfaces. Thermal cycling has been performed on low, medium and high temperature TE engines and assemblies that demonstrates robustness. The vehicle level TEG system has been simplified by means of a coaxial bypass within the cylindrical TEG.

Collaborations and Coordination with Other Institutions

- Faurecia, a Tier 1 global leader in exhaust systems, has joined BMW, Ford and BSST and is leading the TEG subsystem integration into the exhaust system. In parallel, Amerigon/BSST, through a self funded collaboration with OSU and Northwestern, has developed a pilot production facility ,ZT Plus ,for the manufacture of advanced TE material.

Proposed Future Work/Proposed Future Activities

- In Phase 5, TEG systems will be integrated into the exhaust systems of BMW X6 and Ford Fusion vehicles. Dyno testing will be performed at NREL to further analyze system performance.

Publications

The following documents have been published since the last report (Q2 2010):

- 2010 Diesel Engine Emissions Reduction (DEER) Conference (presentation) – “Status of a Cylindrical Waste Heat Power Generator for Vehicles Development Program”, J. LaGrandeur, L. Bell, D. Crane
- 2010 International Conference on Thermoelectrics, “Status of a Thermoelectric Segmented Element Waste Heat Power Generator for Vehicles, Lon E. Bell, Douglas Crane, John LaGrandeur, C. Ramesh Koripella, Steven Ayres
- 2010 International Conference on Thermoelectrics, Shanghai, China, “An introduction to system level steady-state and transient modeling and optimization of high power density thermoelectric generator devices made of segmented thermoelectric elements”, Douglas T. Crane
- 2010 IAV Conference, Berlin Germany; “Progress Report on Vehicular Waste Heat Recovery using a Cylindrical Thermoelectric Generator “, Lon E. Bell, Douglas Crane, John LaGrandeur,
- 2011 Thermoelectric Applications Workshop (presentation), “Status of Segmented Element Thermoelectric Generator for Vehicle Waste Heat Recovery” Doug Crane, John LaGrandeur, Lon Bell
- 2011 Materials and Manufacturing Engineering Conference, Pune India, “Thermoelectric Materials and Engines for Automotive and Industrial Waste Heat Conversion to Electricity”, John W. LaGrandeur, Doug T. Crane, Lon E Bell

Technical Back-up Slides

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%

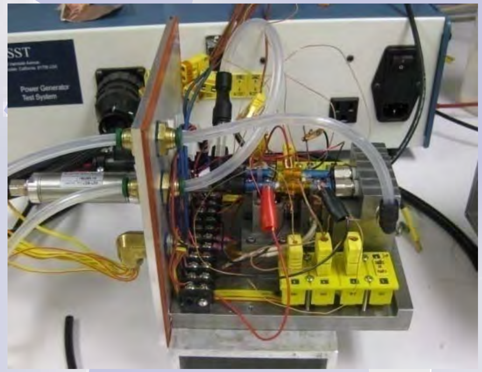
New cooling system integration shows higher benifits during engine warm-up but higher coolant temperatures during constant speeds.

FE results includes the influence of increased weight and exhaust backpressure

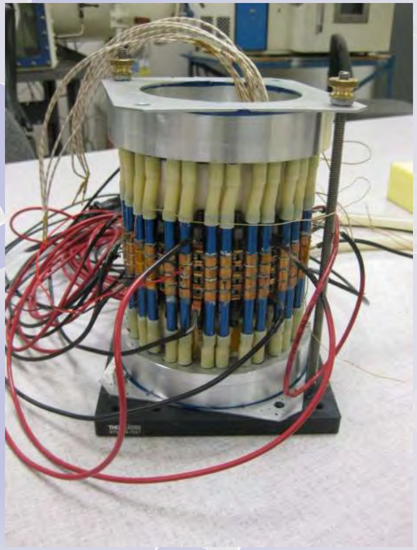
FE results for higher values of ZT do not reflect TEG optimization. For ZT = 2 BSST anticipates FE savings to reach 10%

Approach: Validate Robustness of Thermal and Electrical Interfaces

- Test TE engines using different interfacial materials at the couple, engine and fractional TEG assembly levels
- Thermal cycling using electric heaters to precisely control thermal flux, room controlled temperature liquid baths on the cold side
- Three cycles used based on the TEG's temperature profile in the direction of gas flow



TE Engine level testing



Fractional TEG level testing