Thermoelectric Waste Heat Recovery Program for Passenger Vehicles

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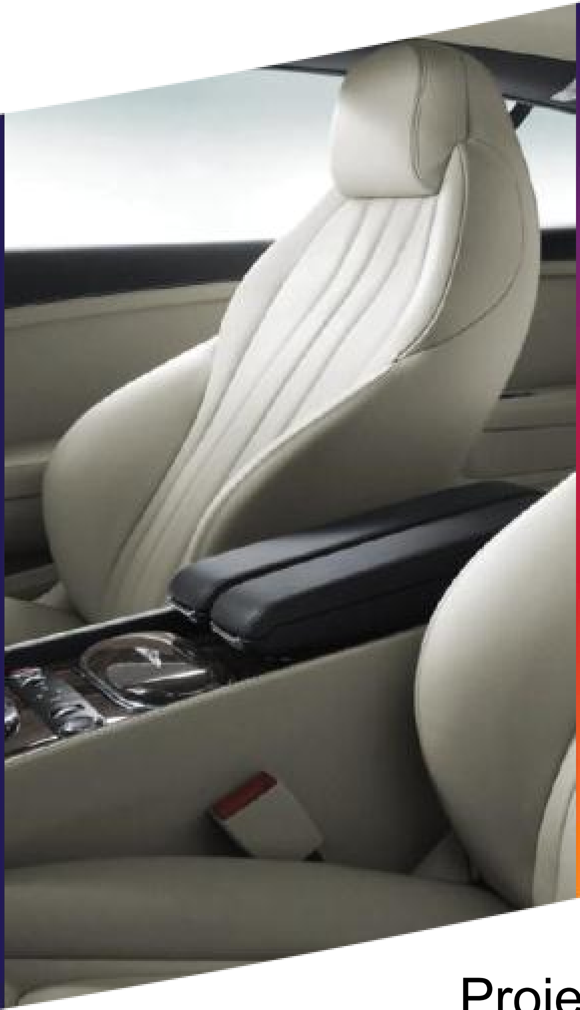
Gentherm Inc.

06/19/14



INSPIRING EFFICIENCY

Project ID # ACE080

GENTHERM PROGRAM OVERVIEW

Timeline

- Project start date: Oct. '11
- Project end date: Sept. '15
- Percent complete: 60%

Budget

- Total project funding: $15,041,393
  - Government share: $8,991,953
  - Contractor share: $6,049,440 (40%)
- Funding received in FY11: $97,974
- Funding received in FY12: $1,688,898
- Funding received in FY13: $2,366,319
- Funding in FY14: $4,019,851
- Funding in FY15: $818,911

Barriers

- Economic manufacture of TE materials and engines and TEG subsystem
- Environmental withstanding and robustness
- Vehicle level integration

Partners

- Interactions/collaborations

OEM Partners:	BMW & Ford
Tier 1 Partner:	Tenneco
University:	Caltech
Fed partners:	NREL

- Project lead: Gentherm (formerly BSST/Amerigon)

Project objectives:

- Detailed production cost analysis for volumes of 100,000 units per year and a discussion of how costs will be reduced in manufacturing.
- Five (5) percent fuel economy improvement by direct conversion of engine waste heat to useful electric power for light-duty vehicle application. For light duty passenger vehicles, the fuel economy improvement must be measured over the US06 cycle.
- Confirmatory testing of the hardware to verify its performance in terms of fuel economy improvement.
- Scale up the TEG designed for passenger vehicles from 500W to 1kW-2kW for the Bradley Fighting Vehicle (TARDEC).

OBJECTIVES/RELEVANCE – MARCH '13–APRIL '14

Objective:

Develop design of a compact / low cost Thermoelectric Power Generation device with integrated hot side and cold side heat exchangers. Develop TEG system level models. Select vehicle for TEG integration.

Addressing commercialization issues:

Historically, high cost and low power conversion efficiencies have been obstacles for implementation of TE technologies. With limited opportunities to significantly improve material properties (ZT) we focus on architectural solutions which would reduce cost and increase the efficiency.

Specific solutions (material – device –vehicle)

- Materials manufacturing focused on production of net shaped TE elements.
- Device packaging capable of compensating large differential expansions.
- Package flexibility – ability to provide solution to wide range of applications.

GENTHERM 2013/2014 PROGRAM MILESTONES

Month / Year	Subtask	Description	Status
Mar-13		Cartridge test at TARDEC lab	Delayed at TARDEC
Sep-13	2.3	Improve SKU performance	On schedule
Sep-13	2.4	TE material sealing (encapsulation and sublimation control) developed	Closed
Dec-13		TARDEC TEG system mock-up	Completed
Mar-14	2.9	TE Engine durability testing	Initiated
Mar-14	2.13	Scale up TEG fabrication concept	50% completed
Sep-14	2.6	TE Engines scalability and power form	Initiated
Dec-14		TEG Assy/test complete, delivery to TARDEC	On schedule

APPROACH – REDUCING TE MATERIALS COST

Objective:

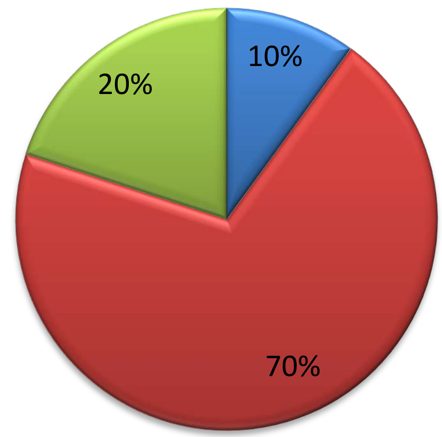
Develop manufacturing process which would enable low cost manufacturing of TE materials.

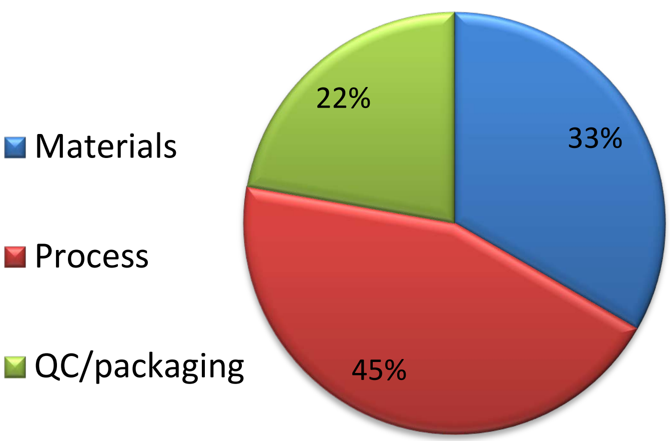
Approach:

- Select low cost starting materials (i.e. eliminate or minimize use of Hf, Zr, Te, rare earth and noble metals)
- Reduce number of operations required to produce single TE element.
- Increase the yield by reducing scrap and implementing true net shape manufacturing.

Supporting tests and modeling

- Detailed analysis of manufacturing process.
- Development of process cost model.
- Production and testing of TE materials to confirm cost/performance.





% values are shown as illustration and might vary as a function of element geometry.

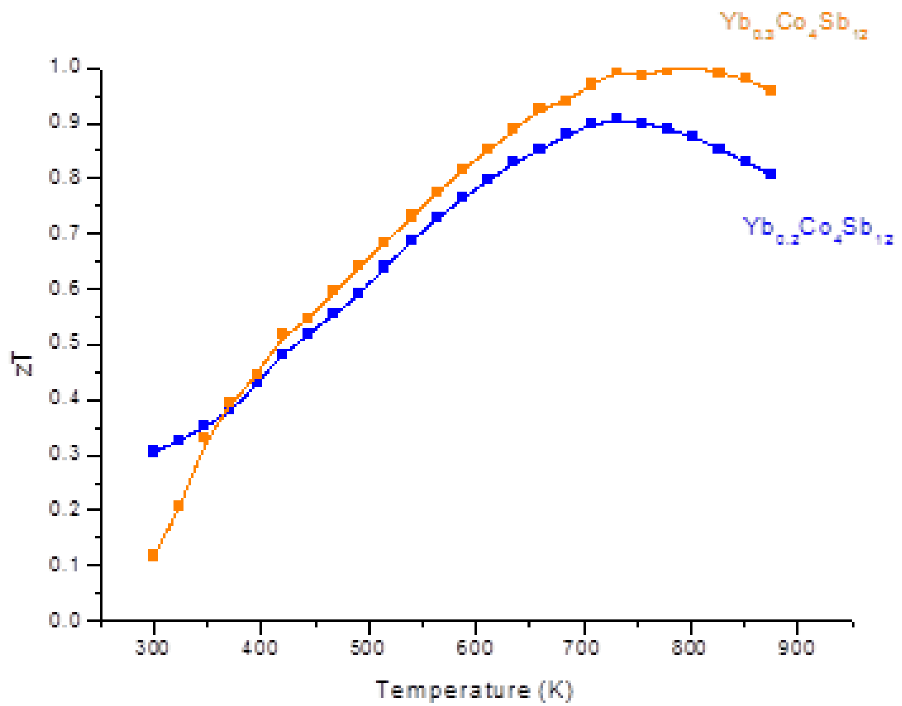
APPROACH – IMPROVE TE MATERIAL PROPERTIES

Objective:

In collaboration with our academic partner Caltech explore opportunities for improvement of material properties.

Approach:

Systematic study of TE material properties as a function of chemical composition.



Supporting tests and modeling

- Sample preparation and testing.
- Development of phase diagrams.
- Development of analytical models describing structure of materials.

APPROACH – TEG DEVICE PACKAGING

Objective:

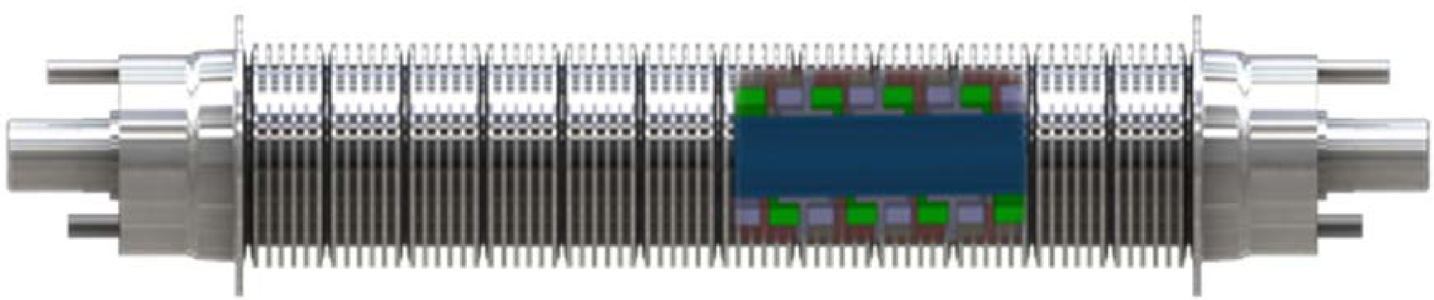
Develop low cost device packaging capable of compensating large differential expansions.

Approach development of TE cartridge:

- Close integration of cold side heat exchanger, hot side heat exchanger and TE device.
- Hermetically sealed packaging.
- Applying Gentherm patented Y-shunt approach to maintain constant external loads on TE elements.
- Controlling differential thermal expansion between cold and hot heat exchangers by segmenting hot side heat exchanger.

Supporting tests and modeling

- Analysis of product manufacturability to confirm cost.
- Development of performance model 1D/3D CFD.
- Production and testing of cartridges to confirm cost/performance.



APPROACH- VEHICLE INTEGRATION

Objective:

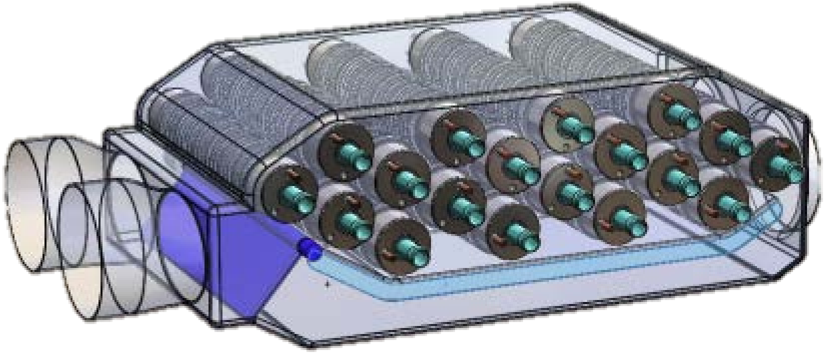
Perform system level analysis for a wide range of vehicles.

Approach development of TE cartridge:

- OEM's Ford and BMW define the thermodynamic parameters under which the TEG system will operate.
- TIER 1 Tenneco designs the exhaust components, electrical and water connections and the exhaust gas bypass line.
- Based on the specific vehicle size select the number of cartridges for the specific design and develop the exhaust package solution.

Supporting tests and modeling

- Analysis of product manufacturability.
- Development of performance models 1D/3D CFD.
- Stress analysis modeling CFD/FEA.
- Prototype build and testing.

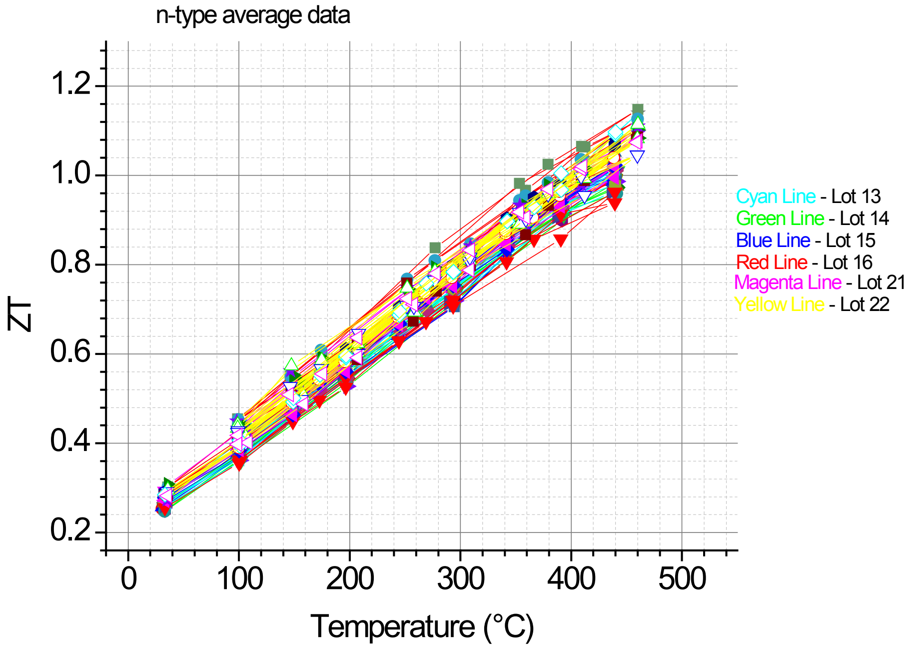


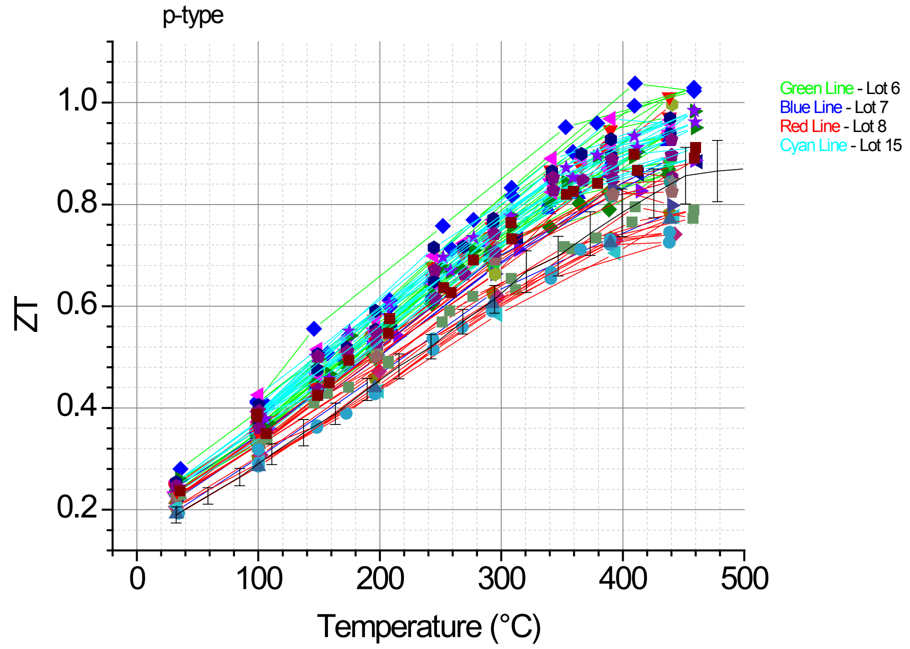
ACCOMPLISHMENT: PRODUCTION OF TE MATERIALS

<u>Demonstration of process stability.</u>

Production and testing of net shaped TE elements:

QC at the material level confirm performance at average peak ZT ~1



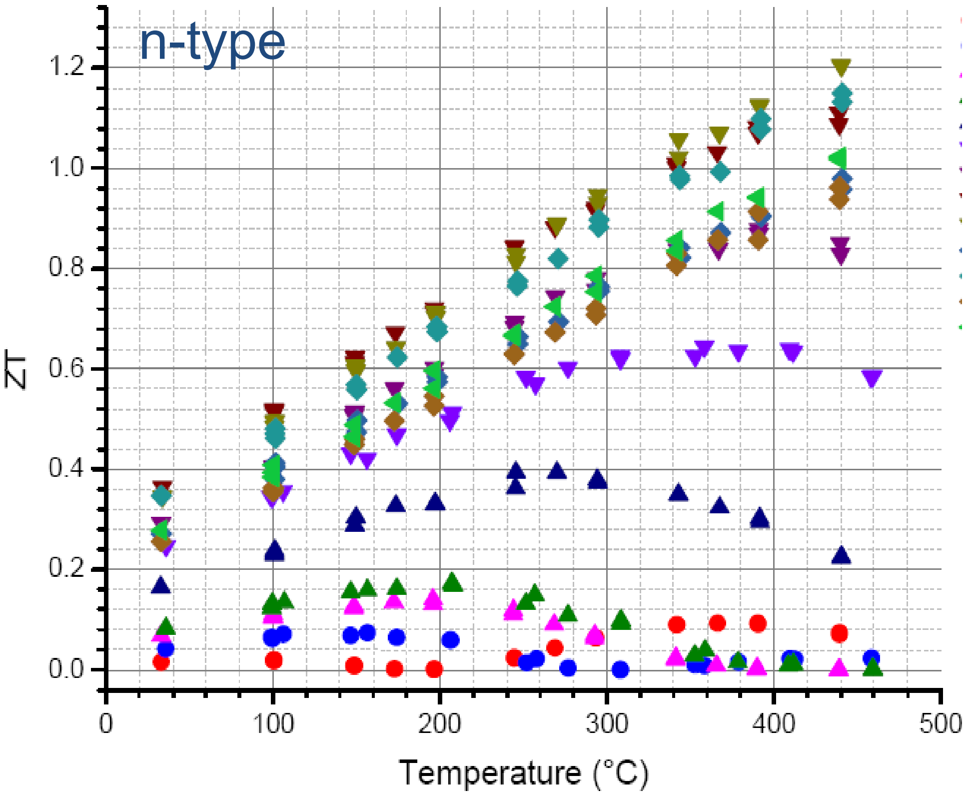


Data collected over period of 2 years.

Methods of improving Skutterudite performance

Careful control of chemical composition and impurity levels will result in improved material performance.

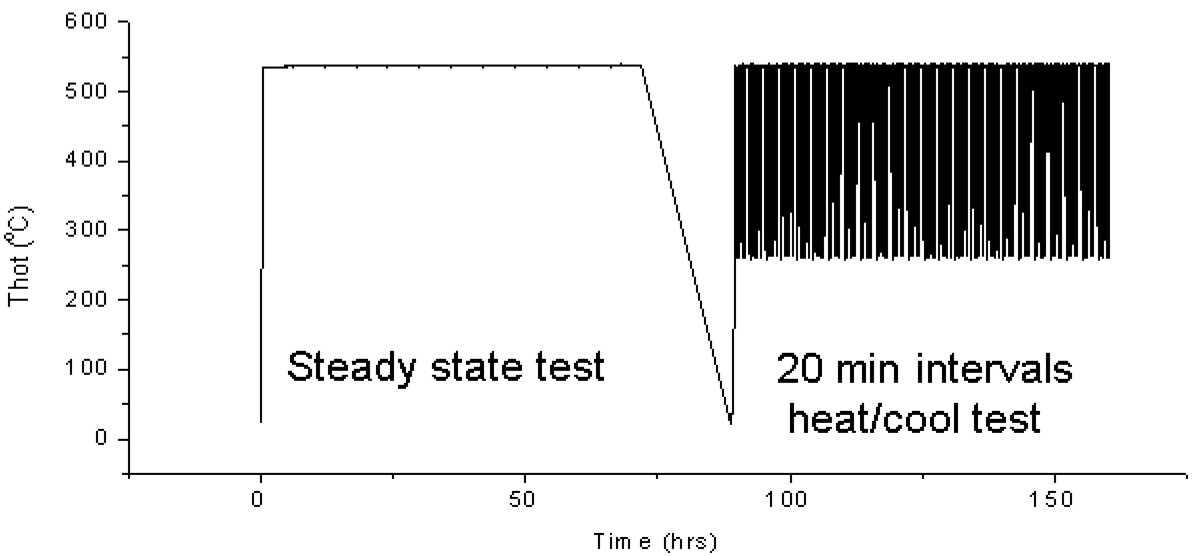
Development of phase diagrams! First in this family of materials.

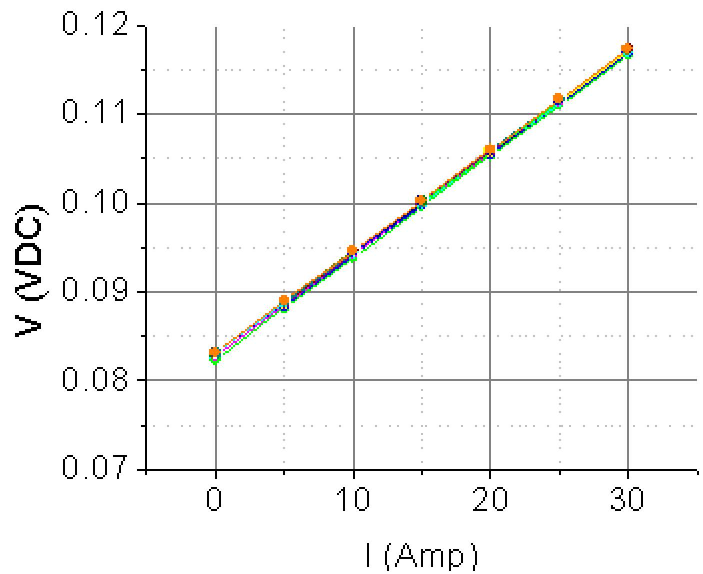


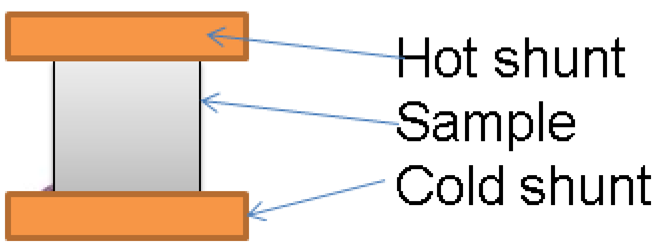
Performance improvements achieved by control of impurity levels.

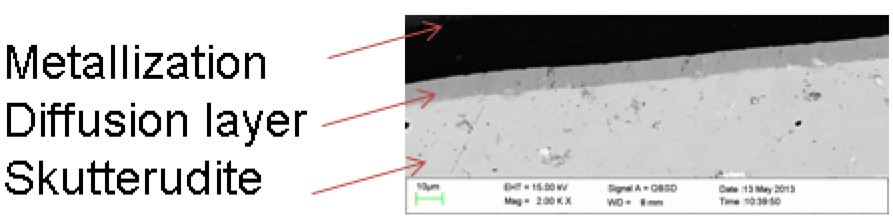
ACCOMPLISHMENT: DEVELOPMENT OF DIFFUSION BARRIER

Stability of diffusion barriers for both p and n-type materials is demonstrated in 150 hrs thermal soak tests.
Materials characteristics (IV curves) are measured during test process.



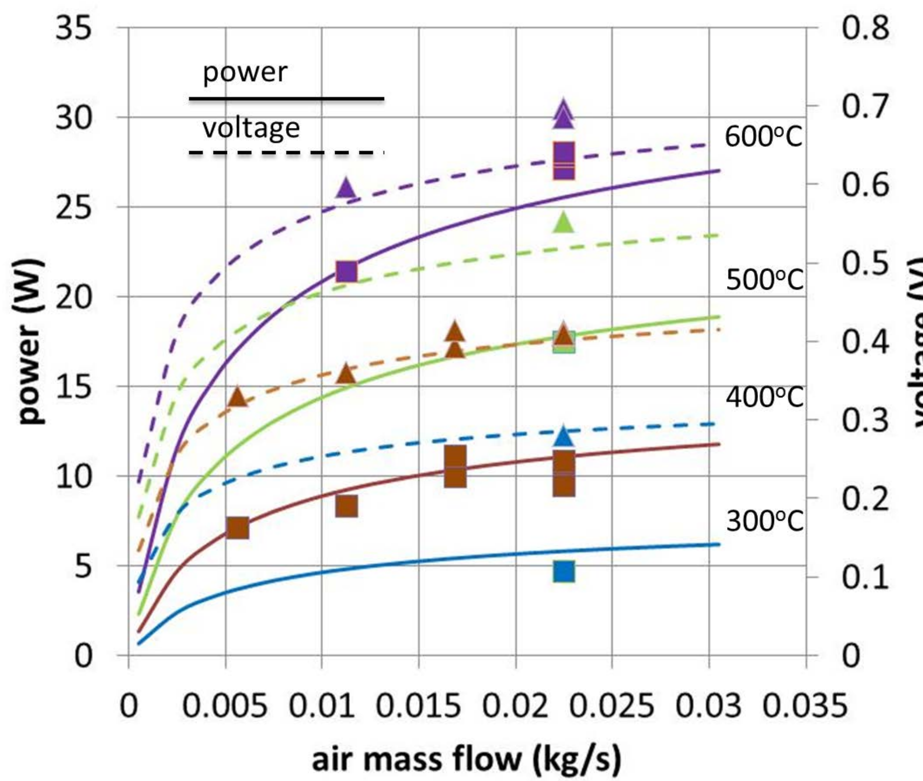






ACCOMPLISHMENT: TEG CARTRIDGE

- TEG cartridge developed - device integrating hot and cold side heat exchanger with thermoelectric device.
- Hermetic packaging is selected to protect TE materials from environmental influences.
- Minimized effects of CTE mismatch to stresses developed in TE materials.
- Performance compared against predictive models:

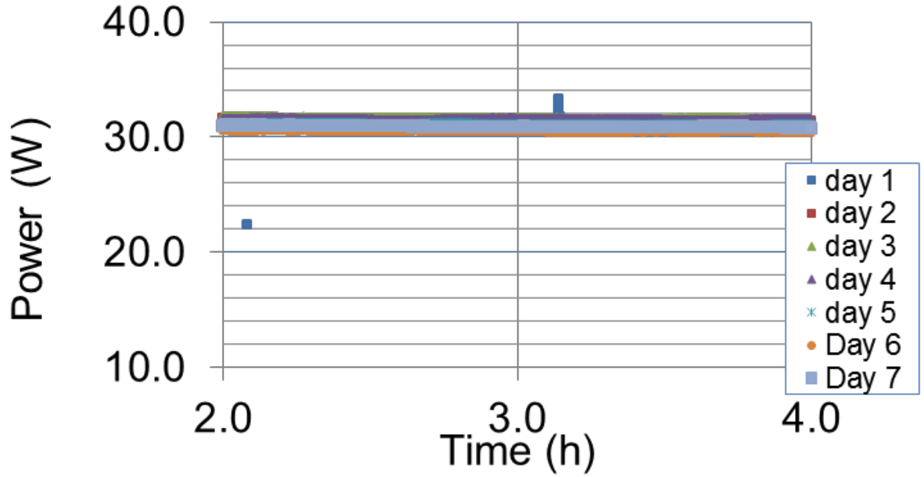


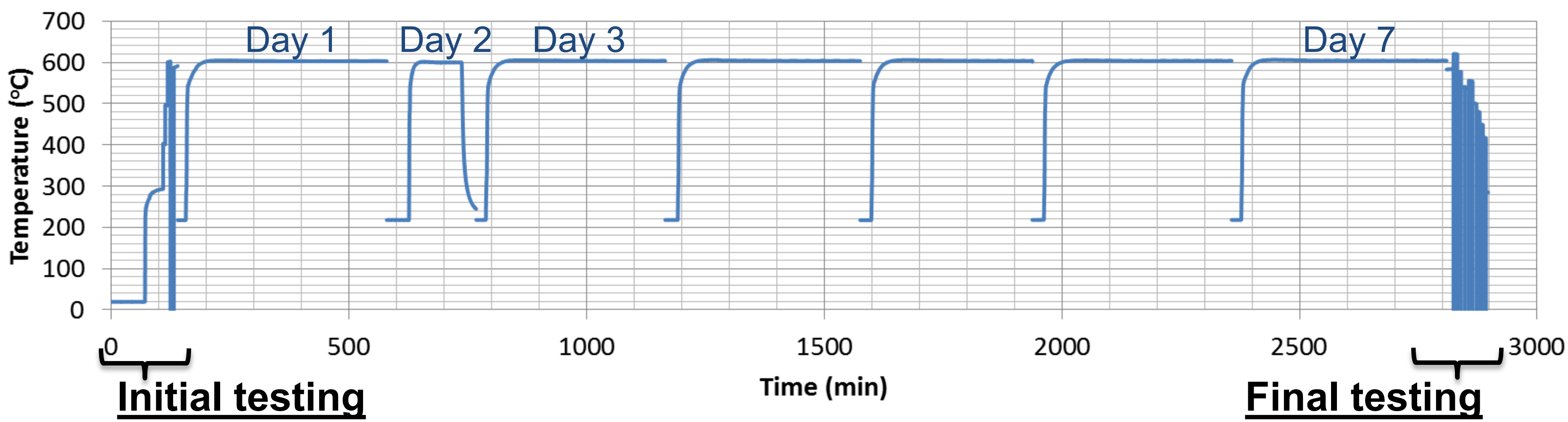
Dots are experimental data points shown against lines indicating model data.

ACCOMPLISHMENT: LONG TERM TESTING AND PERFORMANCE REPEATABILITY

Prolonged testing: cycling - steady state – cycling

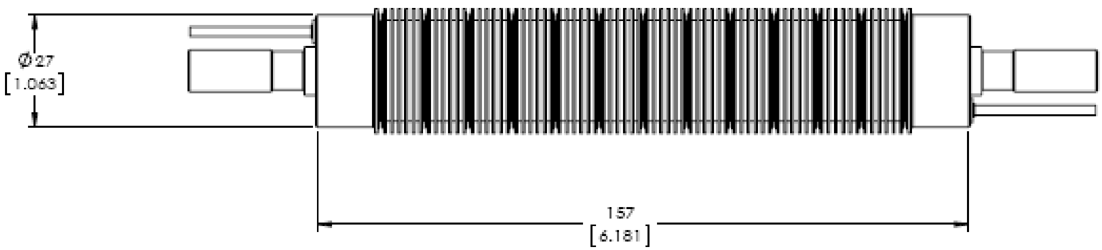
Comparison of test result at the beginning and end of test cycle shows no degradation in measured power output.



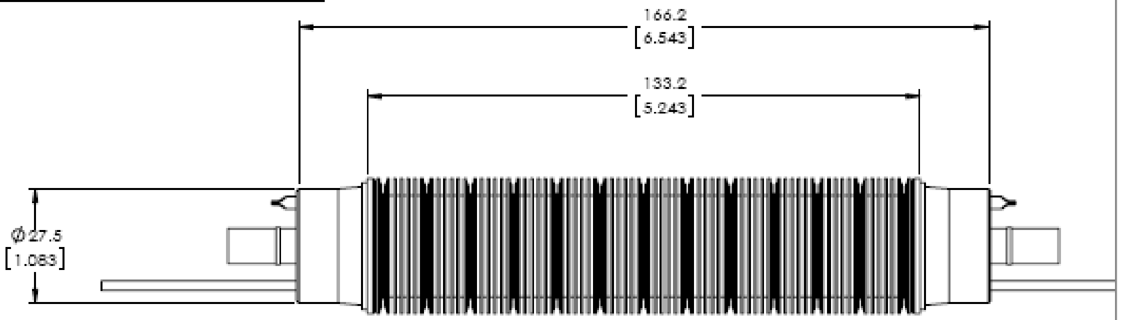


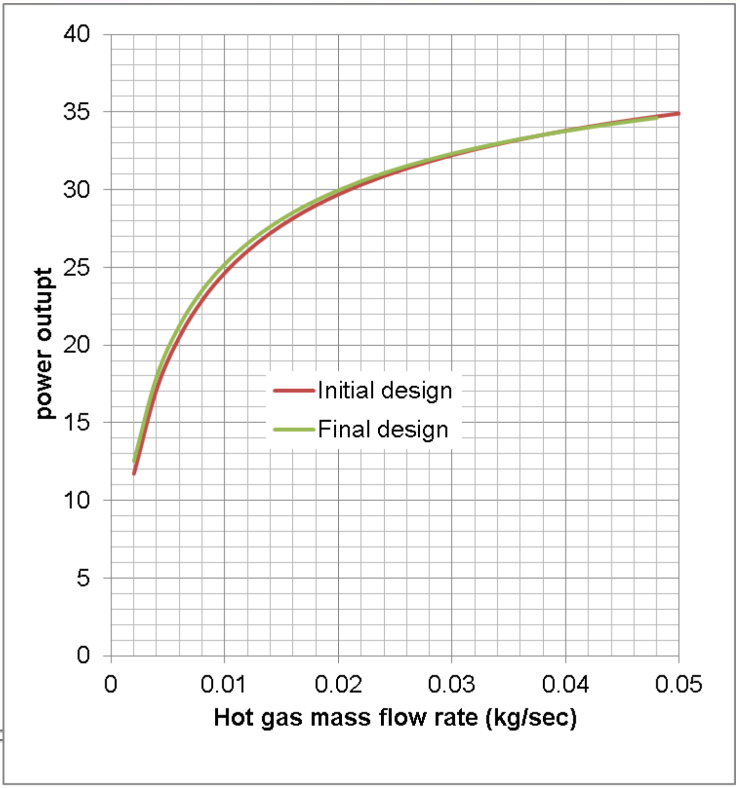
ACCOMPLISHMENT: FINAL CARTRIDGE DESIGN

Initial design:



Final design:

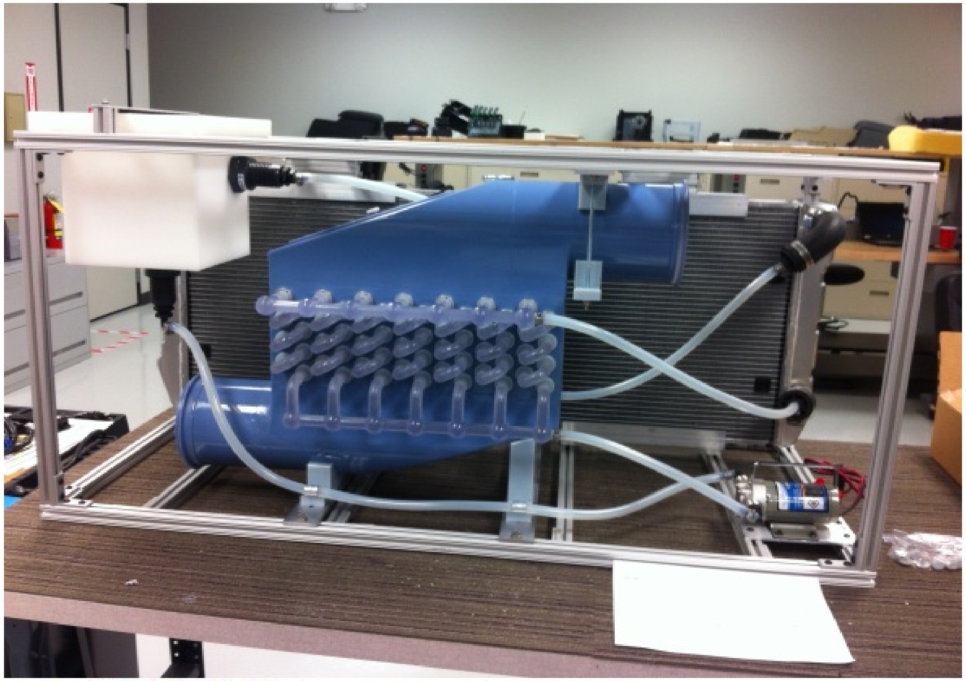


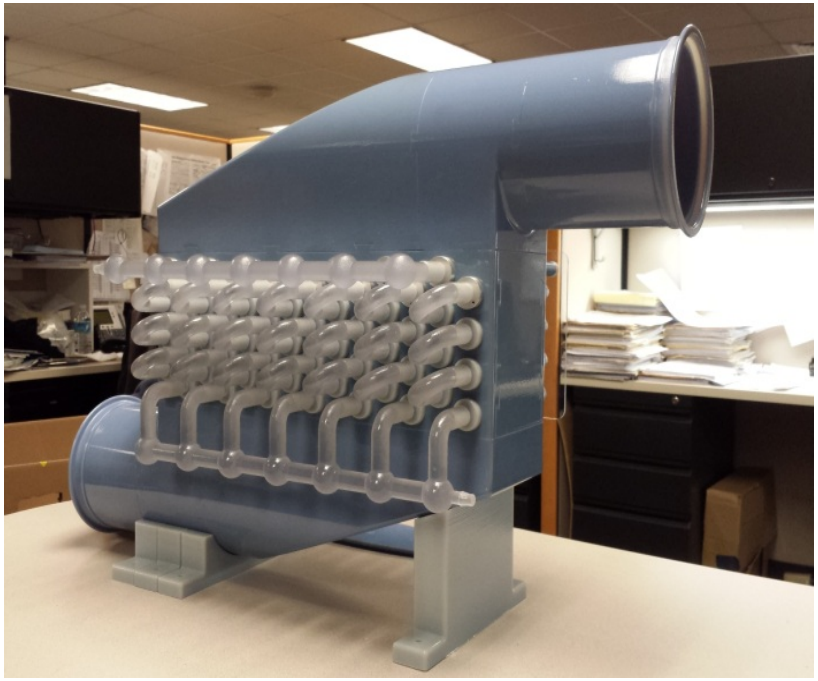


- Following initial trials and package design feedback provided by Tenneco, Gentherm has completed final cartridge design.
- Predictive models indicate no significant performance change.
- Final design prototypes are in the prototype build phase.

ACCOMPLISHMENT: DELIVERY OF BRADLEY VEHICLE TEG MODEL - TARDEC PROGRAM

- Full scale TEG model developed for Bradley fighting vehicle delivered in January of 2014.
- 56 cartridge system is predicted to produce up to 1.5kw of power.
- TEG package developed at TENNECO.
- Cooling system developed at Gentherm.





COLLABORATIONS

Project lead: Gentherm

Expertise in integration of thermoelectric materials and heat exchangers. Development of scalable manufacturing processes for TE materials and device manufacturing.

OEM: Ford and BMW, TARDEC

Definition of vehicle level requirements. Integration of TEG system on vehicle. Vehicle level testing and prediction of FEI.

Tier 1: TENNECO

Design of the TEG canning and integration with exhaust components. Electrical and coolant connections. Development of gas flow control strategy.

Academic partner: Caltech

Deepening understanding of material structure – basis for future process control and improvements in material performance.

National laboratory: NREL

Provides independent confirmation of the TEG-level and vehicle-level performance.

FUTURE WORK

Material level work:

Complete development of net shape manufacturing process and tooling. Define long term material stability.

TEG cartridge level work:

Produce 200-300 cartridges. Develop process cost models.

TEG system level work:

Complete TEG system design. Refine 1D and 3D performance predication models. Build TEG systems (3-5 units).

Vehicle level work

Integrate and test TEG. Define TEG effect on vehicle performance. Define fuel efficiency improvement.

Define cost to manufacture 100,000 TEG systems per year.

FUTURE WORK - DOE PROGRAM SCHEDULE

2014

Q2	• Complete design of TEG system • Initiate manufacturing of TE cartridges
Q3	• Manufacturing of Bradley vehicle TEG
Q4	• Manufacturing of Ford/BMW TEG system

2015

Q1	• Vehicle level integration and testing
Q2	• Confirmatory testing • Cost analysis
Q3	• Final report due

SUMMARY

Material level work:

Development of net shape material processing and development of metallization is completed. Efforts on developing encapsulation at the material level are abandoned. Process cost models are developed. Resolving issues related to process scale up are ahead of us.

TEG cartridge level work:

TEG cartridge is developed. Hermetic sealing is achieved at the cartridge level as a substitution to material level encapsulation. Manufacturing of larger number of cartridges is initiated. Durability testing is ahead of us.

TEG system level work:

Initial TEG system level models are developed. Packaging studies are underway.

Vehicle level work

OEM's have selected vehicles for TEG integration. US06 and other drive cycle data is collected and made available to team. OEM's are providing guidance in the TEG system level design process.

ACKNOWLEDGEMENTS

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