U.S. Department of Energy
Energy Efficiency and Renewable Energy

Automotive Waste Heat Conversion to Power Program- 2010 Vehicle Technologies Program Annual Merit Review

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BSST Program Overview

Timeline

Program Start Date:	Oct '04
Program End date:	Oct '10
Percent Complete:	80%

Budget

Total Project funding:	$ 8,934,479
DOE Share:	$ 6,700,859
Contractor Share:	$ 2,233,620
FY09 & FY10 Funding Received:	$ 1,759,876

Barriers

Economic manufacture of TE engines and TEG subsystem

Thermal cycling robustness of TE engines and assemblies

Vehicle TEG system on-cost

Targets

FE Improvement: 10%

Partners

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

Phase 4 Objectives

- Develop a TEG subsystem architecture that improves the manufacturability of TE engines and assemblies
- Evaluate and optimize TE engine interfaces to improve performance by modeling and thermal cycle testing.
- Simplify the Vehicle TEG system, reduce overall size and weight

BSST 2010 Program Milestones

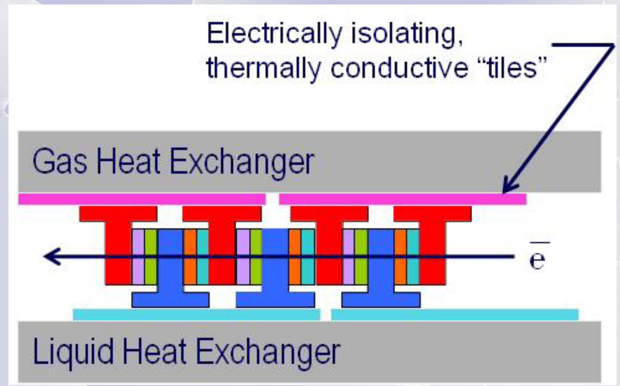
Date	Milestone
May 7	Complete TEG build and test at BSST
June 11	Complete engine/TEG dyno testing at NREL
August 15	Deliver TEGs for BMW and Ford Vehicle installations
October 15	Substantially complete TEG system evaluation in BMW and Ford vehicles

Approach: Improve TEG Subsystem Manufacturability

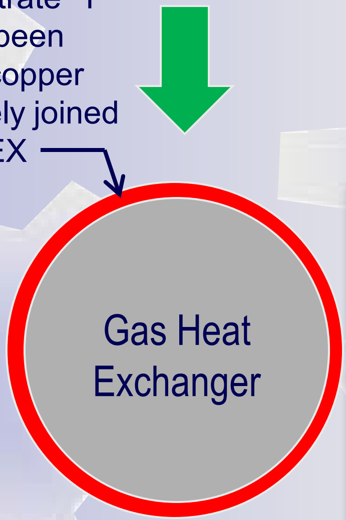
The planar arrangement of TE engines between flat plate heat exchangers requires an electrically isolating, thermally conductive interface.

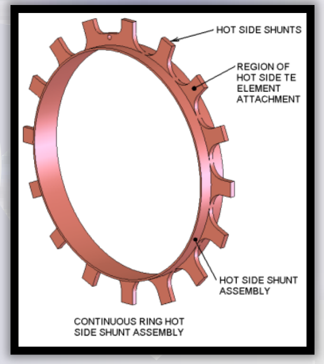
- The interface between the hot gas heat exchanger and TE engines must accommodate temperatures from automotive cold start to (potentially) 800^0 C
- Effective thermoelectric performance requires that all TE engines be effectively coupled to the heat exchangers, i.e. near perfect flatness and parallelism

Proposed solution: Arrange the TE engines around a tube through which the exhaust gas passes. Use rings that are electrically isolated from the tube but thermally conductive as the hot side substrates



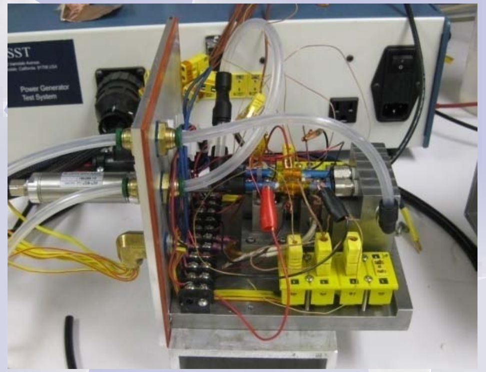
The hot substrate “T” shunts have been replaced by copper rings intimately joined to the gas HEX



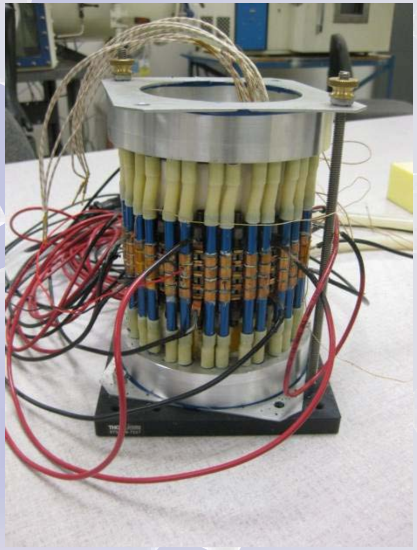


Approach: Validate Robustness of Thermal and Electrical Interfaces

- 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

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

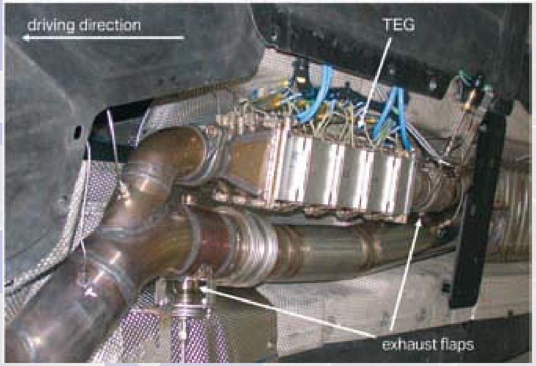
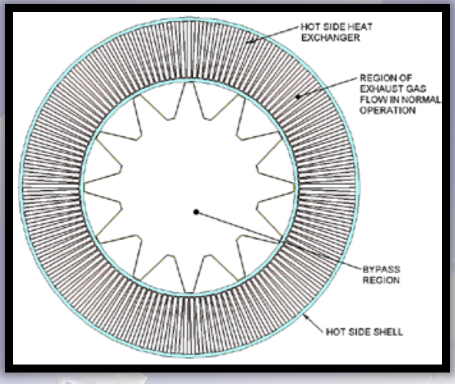


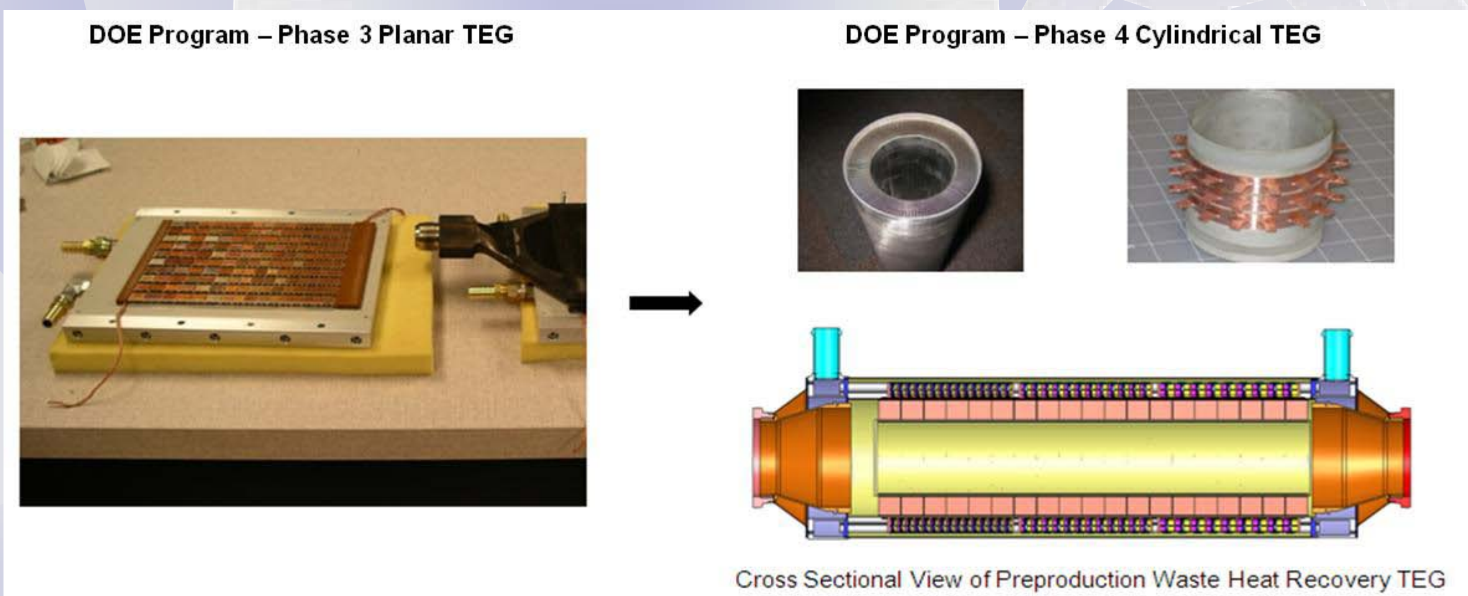
Image courtesy of the BMW Group



Accomplishment: Development of a Manufacturable TEG Subsystem

The Phase 3 TEG (planar form) was redesigned for Phase 4 into a cylindrical form to improve manufacturability

- The cylindrical form eliminates the requirement to maintain hot and cold flat plate heat exchangers parallel, in compression, equidistant and flat over large areas
- Heat transfer is improved by mechanical attachment of hot side substrates to the gas heat exchanger in the cylindrical TEG
- The stack design is carried through from Phase 3 and modified to accommodate thermal expansion induced stresses

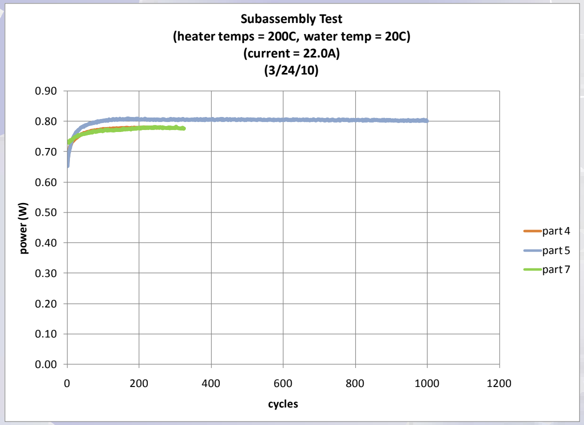


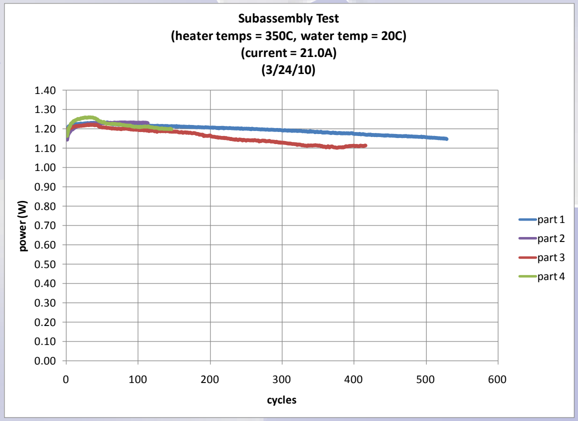
Cross Sectional View of Preproduction Waste Heat Recovery TEG

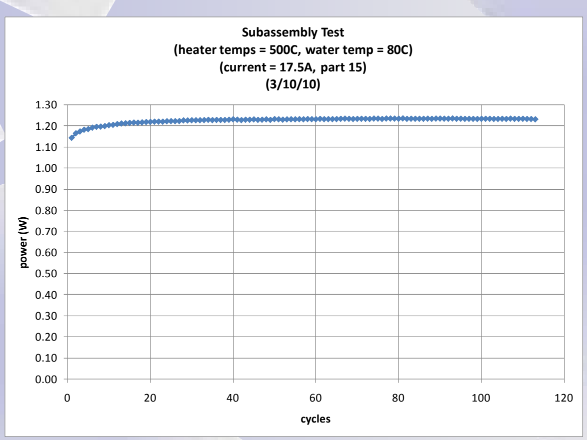
Accomplishment: Thermal Cycling Robustness of TE Engines and Assemblies

Thermal cycling performed by cycling electric power to cartridge heaters to reach temperature

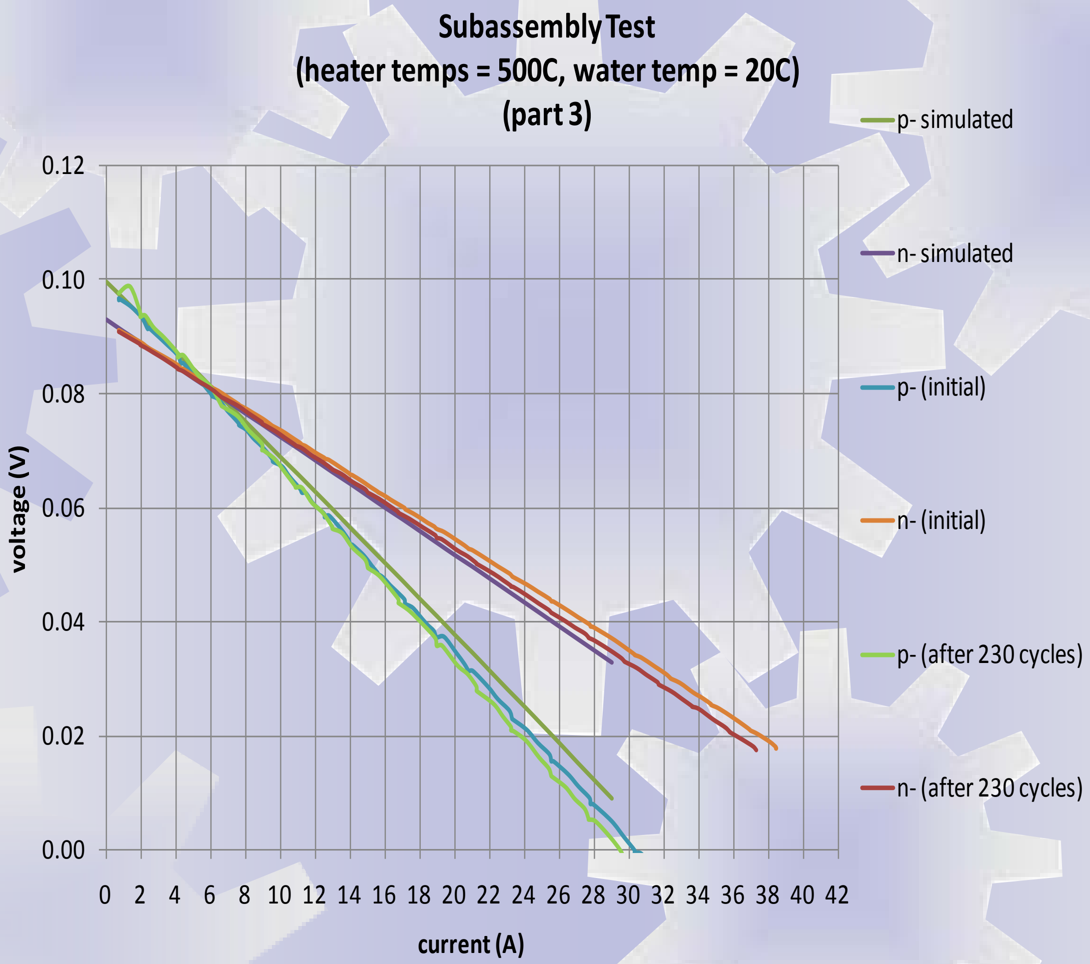
Cycle time ranges from 14 minutes for the high temperature devices to 4 minutes for the low temperature devices.







Accomplishment: Model Vs Experimental Voltage and Current Measurements



N and p type measured voltage and current (initial and post-230 cycles) are plotted Vs simulated values using 2 micro-ohm cm^2 contact resistance.

Accomplishment: Simplifying the Vehicle TEG System

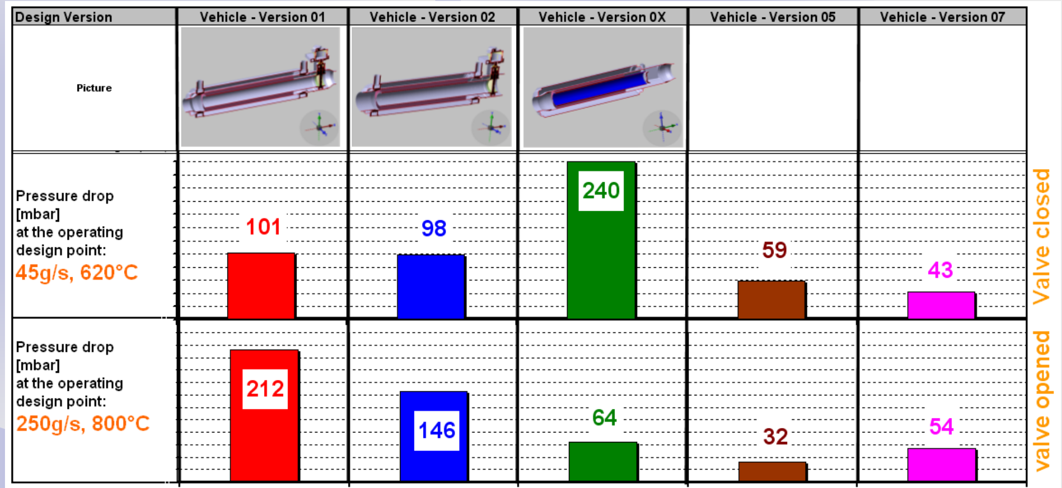
- Exhaust system modeling and design was performed to achieve backpressure design requirements within a coaxial bypass form factor
- Modeling of TEG temperature in the direction of flow was performed in conjunction with pressure drop Vs flow analysis to solve for TEG outside and (internal) bypass diameters simultaneously
- Design options were summarized and a final design selected

Collaborations

Lead by Faurecia, collaborative modeling and design of the TEG was performed by BMW, Ford and BSST for underfloor exhaust system integration

Faurecia is translating engine operating map info (exhaust gas mass flow and temperature) into TEG thermal flux requirements through powertrain cooling and exhaust system performance requirements (back pressure, acoustic quality, etc.)

NREL is developing a dynamometer test for evaluation of the system at Golden Colorado



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.

ZT Plus is on schedule to produce kilogram batches of PbTe (n and p types) with peak ZT's of 1.4 by the end of calendar 2010.

Future Work

Future work includes completion of Phase 4 (Dynamometer testing) and Phase 5 vehicle installations

Phase 4 dynamometer testing is being performed with a BMW 6 cylinder engine and exhaust system at NREL

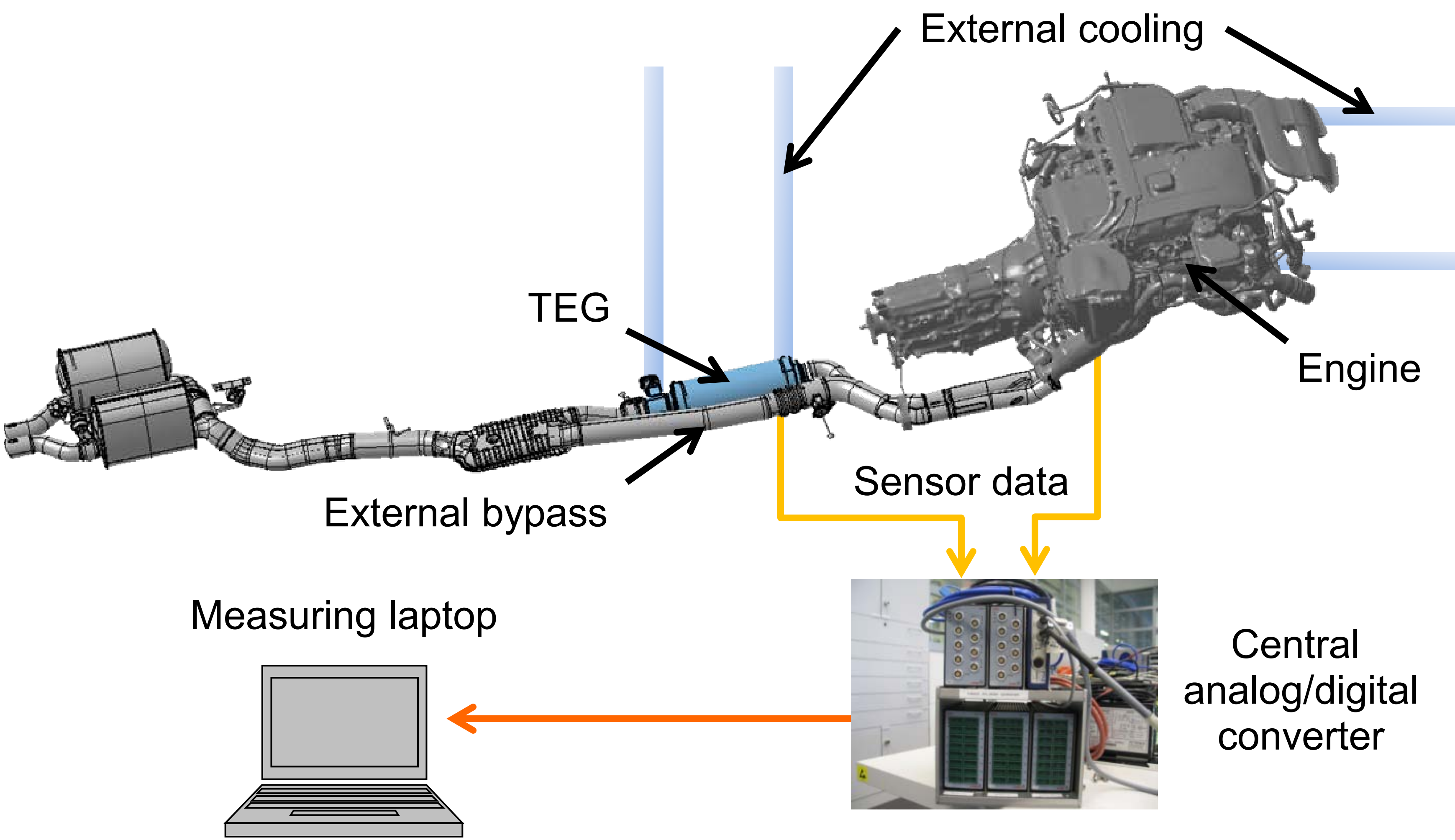
Phase 5 objectives include:

- TEG installation and evaluation in BMW X6 and Ford Fusion vehicles
  - Exhaust system design and integration of the TEG subsystem by Fourecia
  - 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.

TEG component testing.

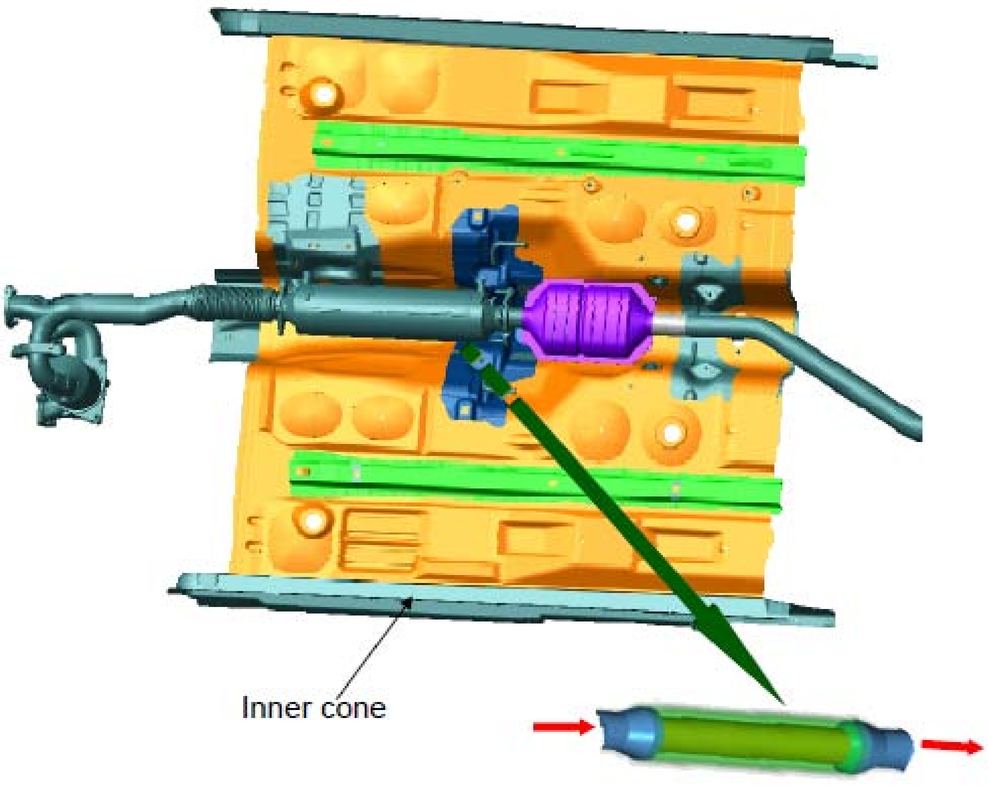
Phase 4 system setup on test bench.



TEG component testing.
Phase 4 comprehensive measuring program.

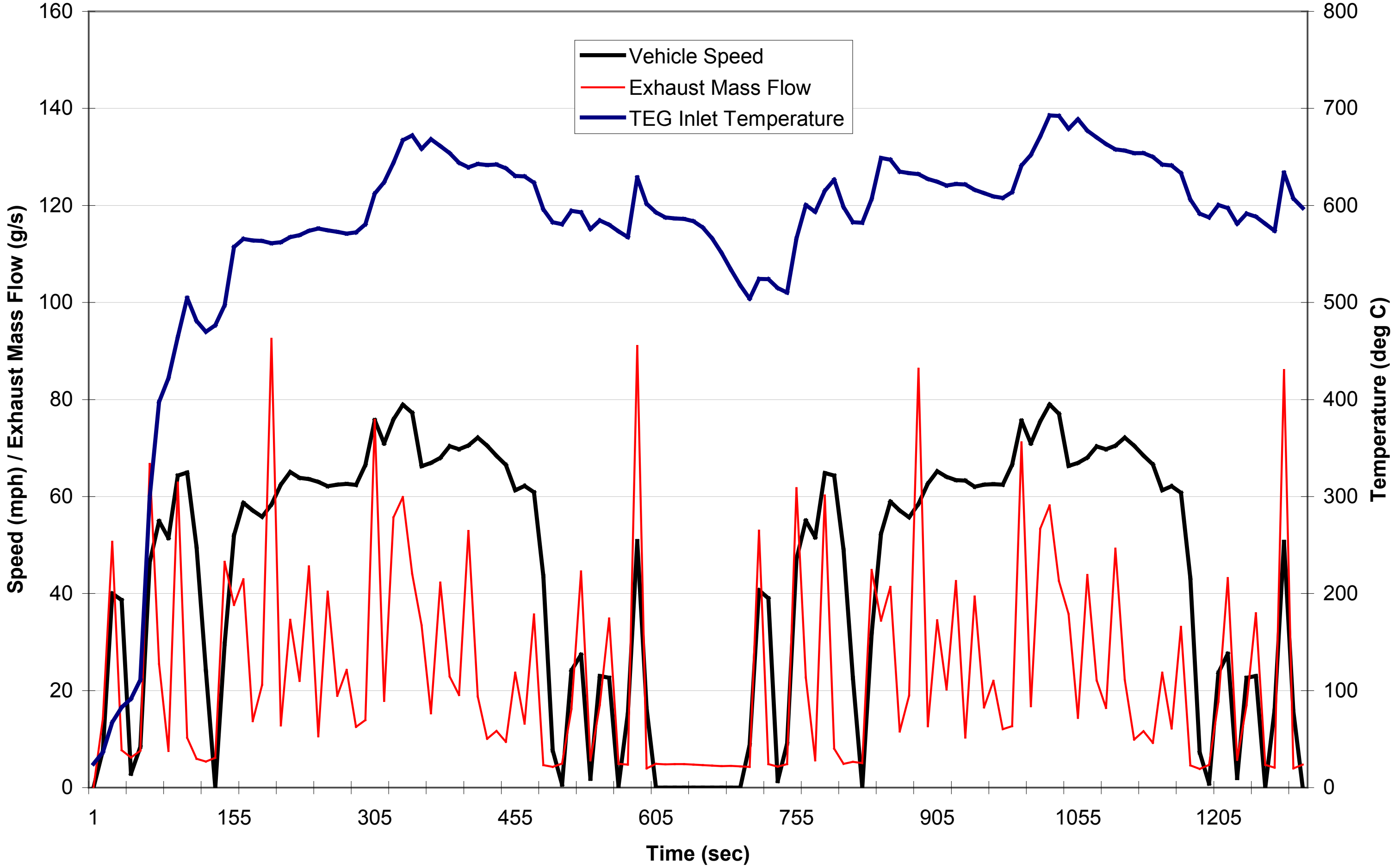
- 29 temperature, 6 voltage, 2 differential pressure,
  1 current , 1 volume flow rate sensor and > 20 engine data
- Test matrix consists of 47 different load points
- Exhaust temperature varries from 340°C up to 850°C
- TEG exhaust mass flow ranges from 40 $^{kg}/_{h}$ to 140 $^{kg}/_{h}$
- The total test duration will be app. 40h
- Similar setup will be used in the phase 5 prototype vehicle

TEG In-Vehicle Packaging Study



- Packaging before mid-bed catalyst improves available heat
- Coolant loop connected to heater core for energy dissipation

Exhaust Conditions for US06



Average mass flow 25 g/sec; Average inlet temperature 600°C

Excursions exist that require bypass valve strategy

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.

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

- Phase 4 concludes with dynamometer testing at NREL combining the TEG subsystem with BMW’s 6 cylinder engine. In Phase 5, TEG systems will be integrated into the exhaust systems of BMW X6 and Ford Fusion vehicles.