Develop Thermoelectric Technology for Automotive Waste Heat Recovery

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Project ID # ace_45_yang

Overview

Timeline

- Start date – May 2005
- End date – August 2010
- Percent complete – 80%

Budget

- Total project funding: $12,779,610
  - DOE share: $7,026,329
  - Contractor share: $5,753,281
- Funding received in

  FY08: $1,293,303

  FY09: $721,701 (10/08-2/09)

Barriers

- Barriers addressed
  - Integrating new advanced TE materials into operational devices & systems
  - Integrating/Load Matching advanced TE systems with vehicle electrical networks
  - Verifying device & system performance under operating conditions

Partners

- Interactions/ collaborations

  GE – subsystem modeling

  ORNL – high Temperature transport and mechanical property measurements

  UM, MSU, BNL, USF – materials development

  Marlow – module
- Project lead - GM

Objectives

Program

- Produce a nominal 10 % improvement in fuel economy without increasing emissions
- Prove commercial viability

FY 2008

- Finalize TE generator and power electronics design
- Finalize vehicle thermal management and integration
- TE module construction
- Improve material ZT and thermo-mechanical properties

Milestones

2008

- **Provide the initial TE waste heat recovery subsystem design -- April 30, 2008**
- **Provide initial lab test data for TE modules -- July 31, 2008**
- **Finalize TE waste heat recovery subsystem design -- September 30, 2008**

2009

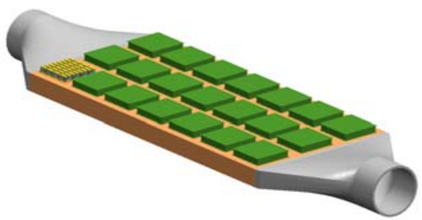
- **Provide initial production ready TE modules for application-based testing -- March 31, 2009**
- **Complete the initial subsystem prototype construction –Oct. 31, 2009**

Approach

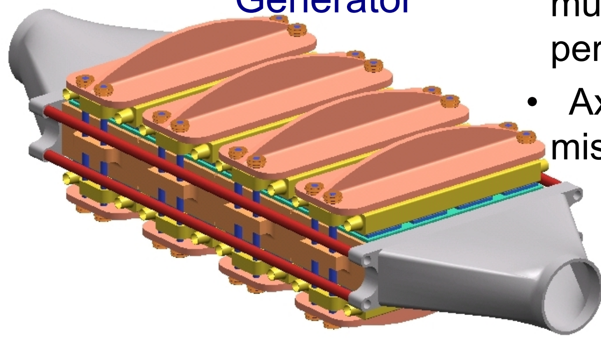
- Developed several models and computational tools to design TE generators which include heat transfer physics at heat exchanger and interfaces; TE materials properties; and mechanical reliability
- Developed power electronic design for power conditioning and vehicle control
- Developed control algorithm for improved thermal-to-electrical conversion efficiency
- Based on the concept of phonon engineering, improved ZT in skutterudites, ZT = 1.6 at 850 K, and ZT_{ave} = 1.1

Technical Accomplishments – Generator Design

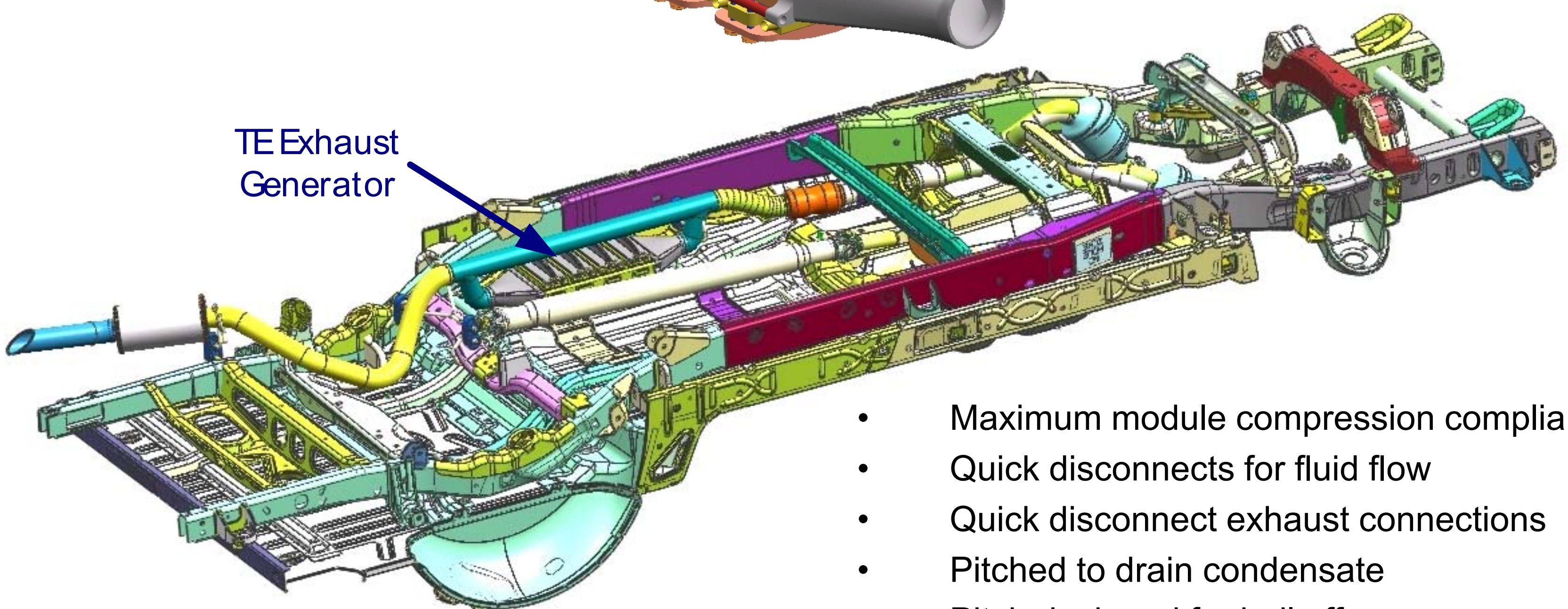
Interior View (module mounting)



TE Exhaust Generator

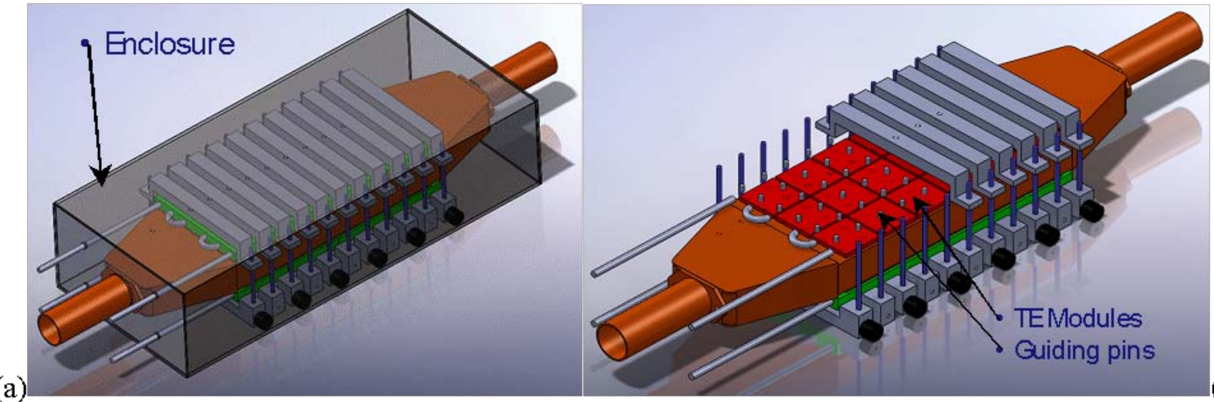


- Located where current muffler is placed; new muffler will be located behind the axle perpendicular to vehicle axis
- Axially compliant for thermal expansion mismatch

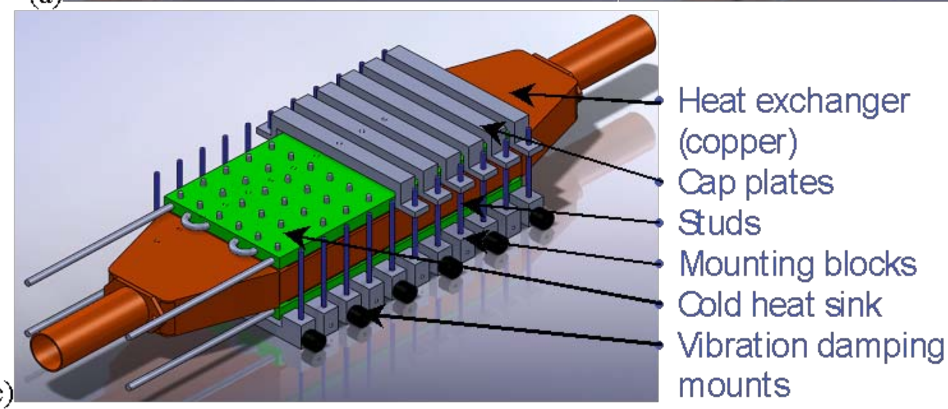


- Maximum module compression compliance
- Quick disconnects for fluid flow
- Quick disconnect exhaust connections
- Pitched to drain condensate
- Pitch designed for boil off
- Sealed electronics

Technical Accomplishments – Generator Design



(a) (b)

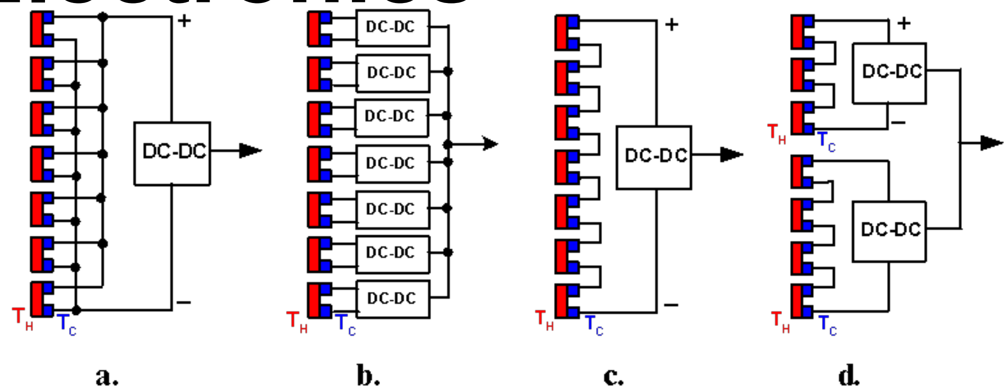


(c)

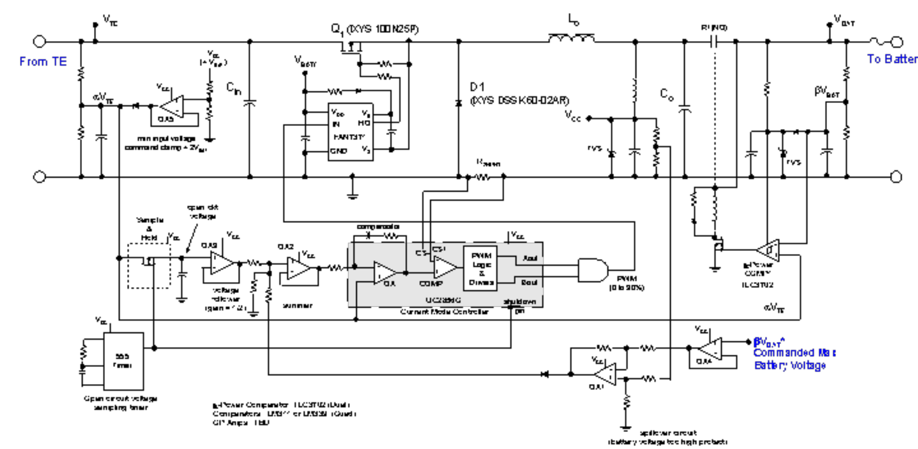
- The generator core is mounted to the enclosure through a series of isolation mounts to isolate harsh shock and vibration
- The enclosure will provide a sealed environment for the generator.
- The enclosure will be stiff in the vertical axis of the generator, so as to provide rigidity

Technical Accomplishments – Power Electronics

Four alternative TE power conversion architectures

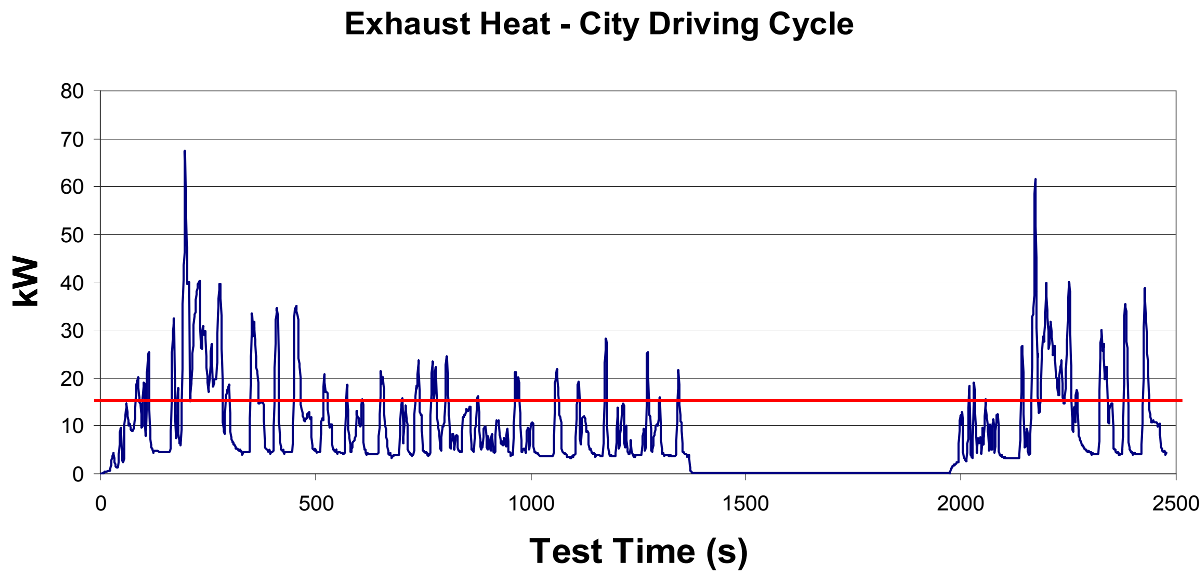


Functional control block diagram



- Completed a trade-off study to determine the electrical topology of the generator and the DC-to-DC converter architecture
- Selected the design that maximizes reliability & efficiency over the driving cycles and minimizes system cost.

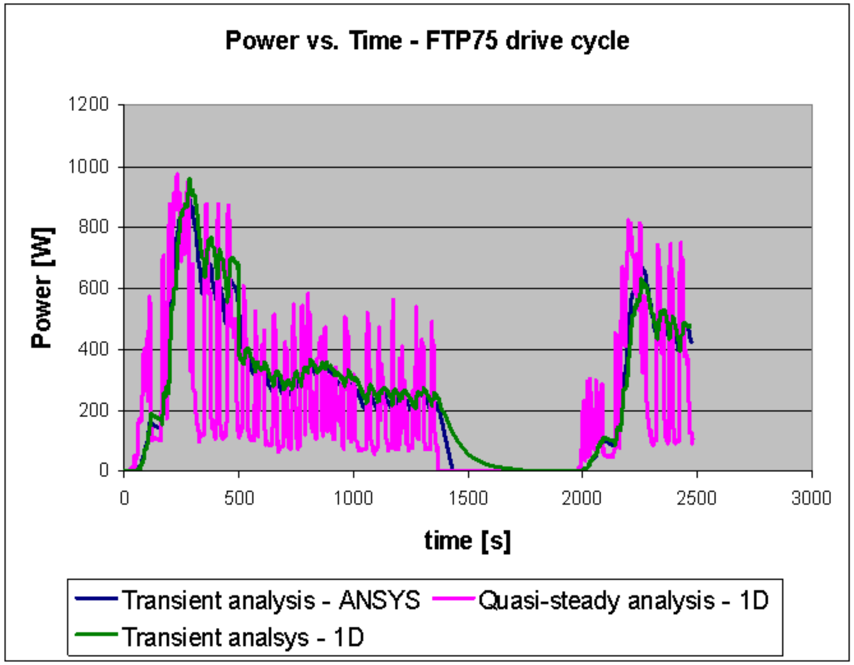
Vehicle Selection – Chevy Suburban

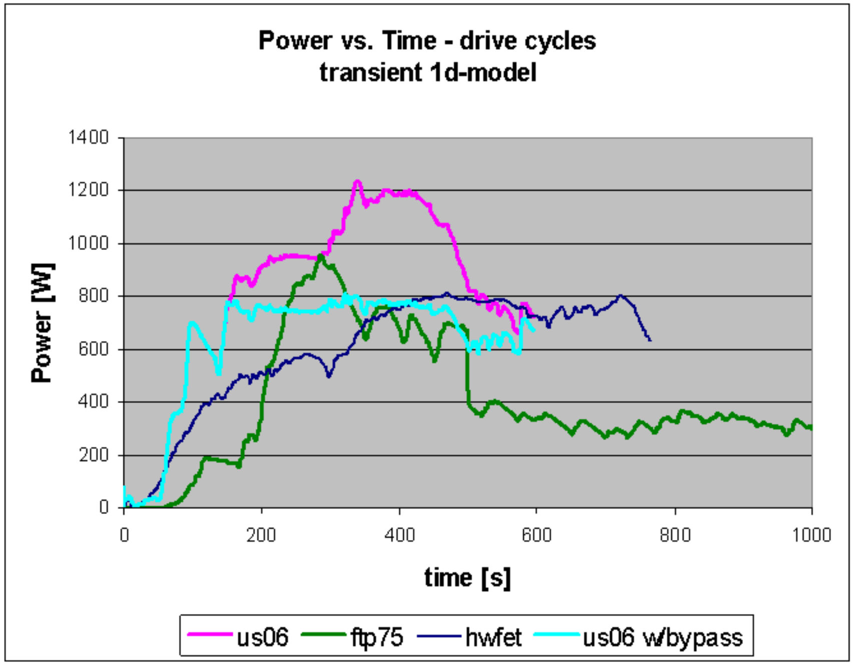


- The Suburban was selected as a test vehicle because it simplified the modifications and installation of the prototype.

- Since electrical loads are a larger percentage of the engine output on smaller vehicles, there is greater opportunity for the TEG to displace electricity generated by the engine and thereby improve fuel economy.

Technical Accomplishments – Generator Output

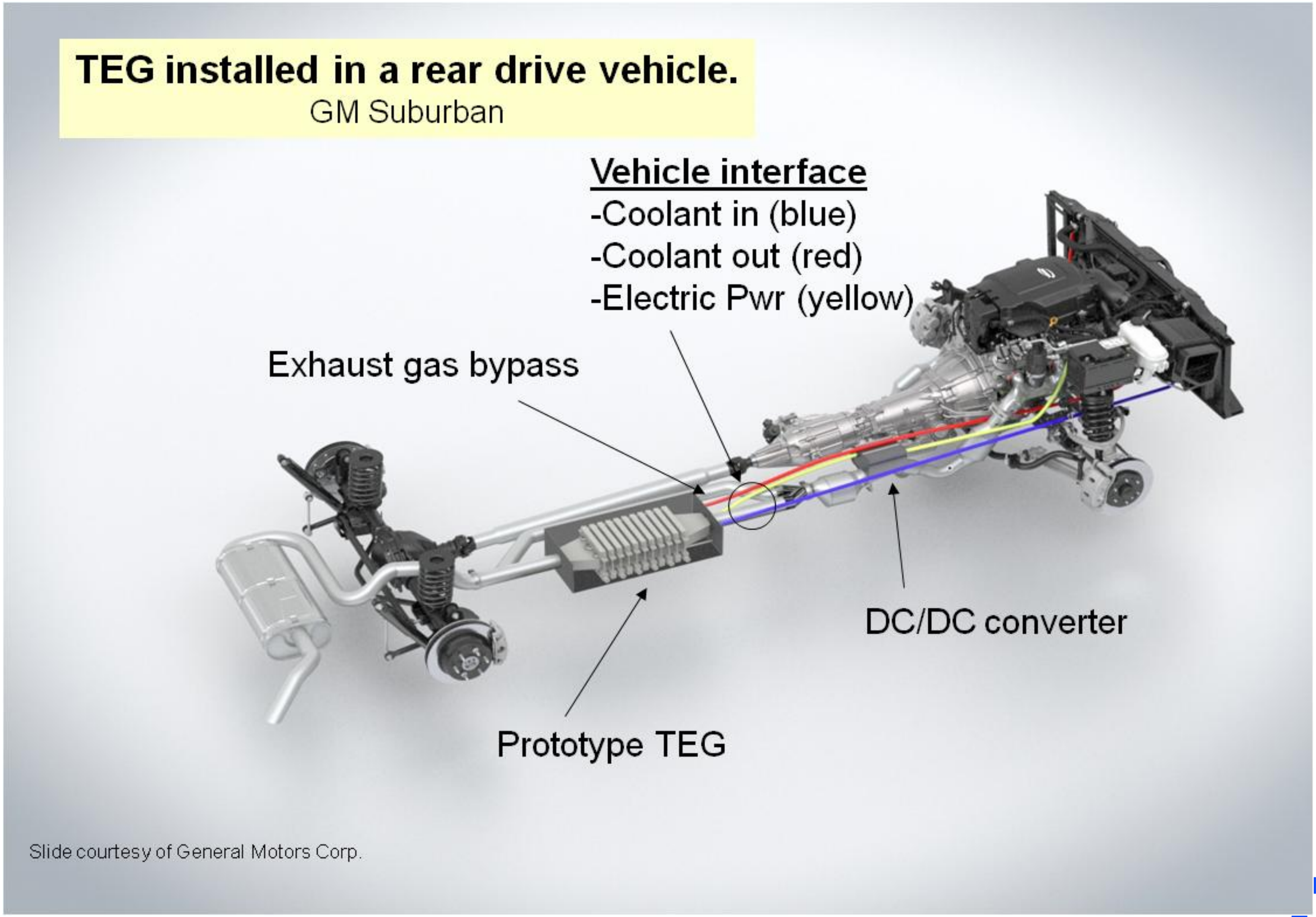




- We expect ~ 1 mpg (~ 5 %) fuel economy improvement for Suburban (average 350 W and 600 W for the FTP city and highway driving cycles, respectively.)

- This technology is well-suited to other vehicle platforms such as passenger cars and hybrids.

GM TE Generator on a Chevy Suburban



Generator Animation

TE Generator Thermal Management

Diagram 1. – Coolant & Exhaust Flow Paths

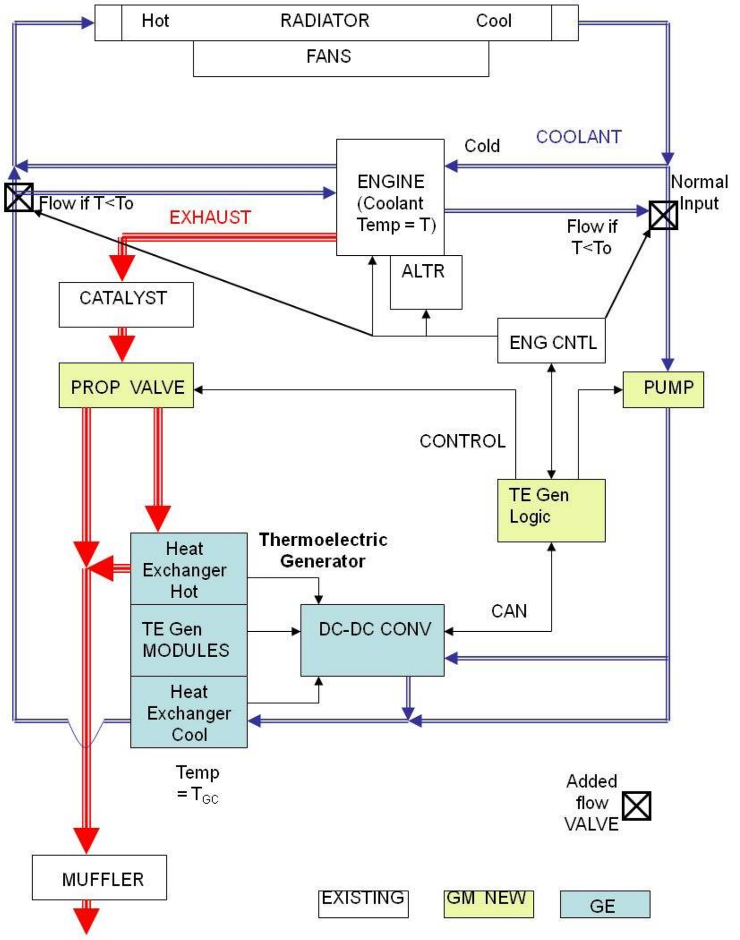
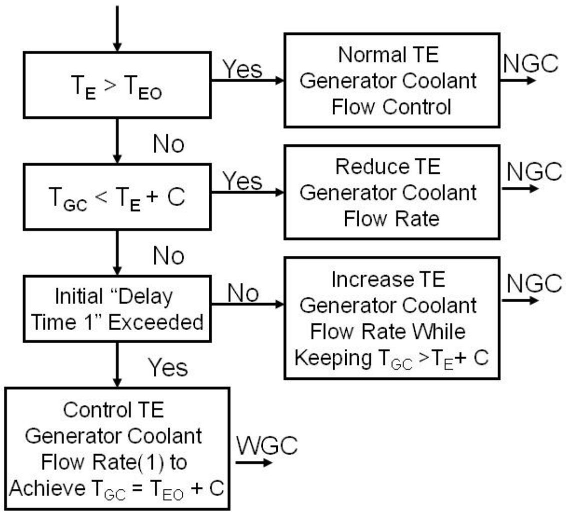


Diagram 2. - Coolant Flow Logic

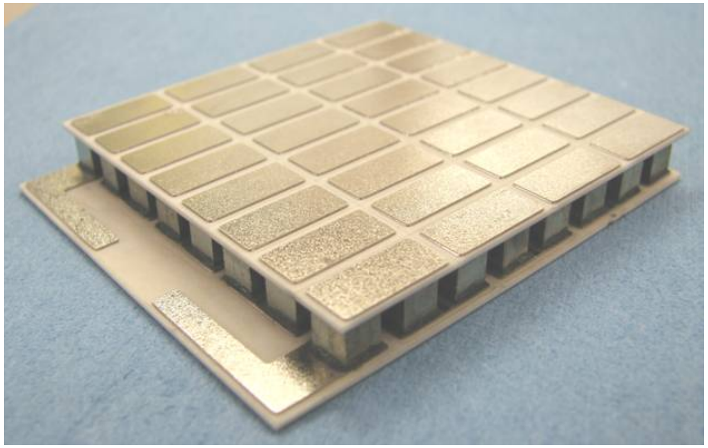


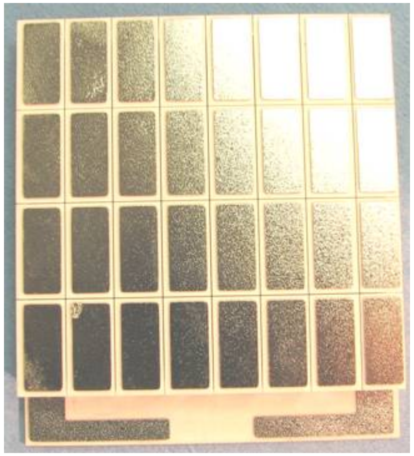
- T_E = Engine Coolant Temperature
- T_{EO} = Optimum Engine Coolant Temp
- T_{GC} = TE Generator Cool Side Coolant Temp
- T_{GH} = TE Generator Hot side Temperature
- NGC= Normal TE Generator Coolant Flow path = Input from Radiator Cool Side and Return to Radiator Hot Side
- WGC = Warm-up TE Generator Flow path = Input from Engine Out and return to Engine Input
- C = Temperature Delta between Generator and Engine needed to add heat to engine (typically 5° C)
- Delay Time 1 = Time to move warm coolant from TE Generator to Control Valve (reset when $T_E = T_{EO}$)

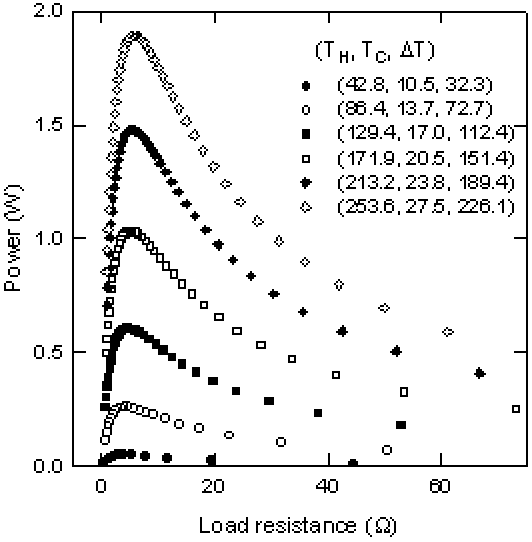
(1) Control flow rate to maintain $T_{GC} > T_E + C$ while increasing T_{GC} over N seconds [function of T_{GH}, TE Generator Heat transfer, and T_{EO}] until $T_{GC} = T_{EO} + C$

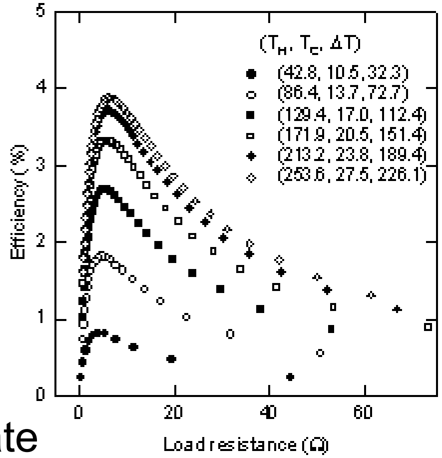
- Developed vehicle level control algorithms to optimize potential fuel economy gains

Prototype Modules



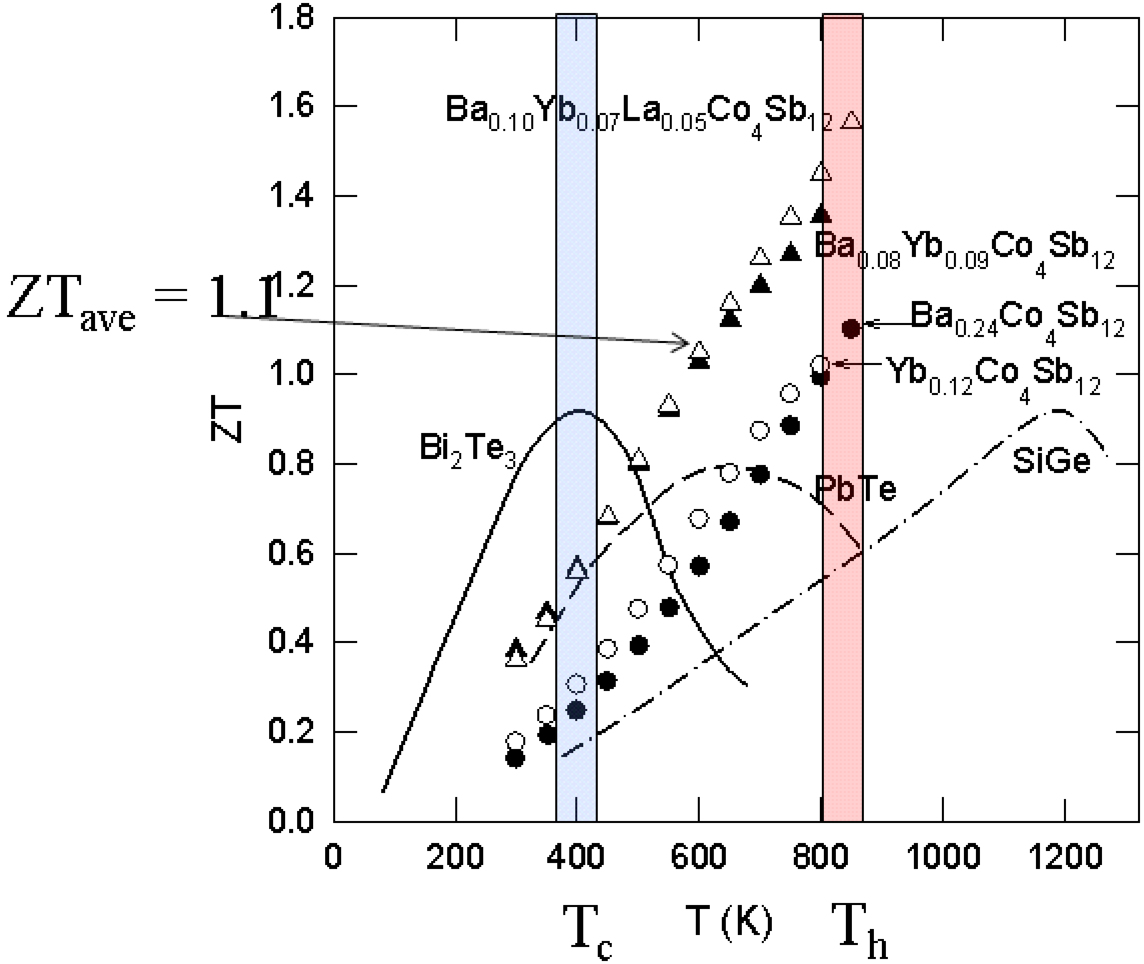






- Developed a novel solid-phase diffusion bonding process to fabricate thermoelectric modules
- Measured performance of some initial modules at various temperature gradients

Results – Highest ZT Achieved in Triple-filled Skutterudites



Future Work

2009

- Skutterudite-based TE module construction
- Complete the initial subsystem prototype construction

2010

- Provide test data for initial TE subsystem
- Finalize advanced modeling and upgrading based on design
- Finalize vehicle integration with TE waste heat recovery system and the necessary vehicle modification
- Carry out dynamometer tests and proving ground tests for vehicle equipped with TE waste heat recovery subsystem
- Demonstrate fuel economy gain using TE waste heat recovery technology

Summary

- Completed TE Generator design
- Completed power electronics design
- Skutterudite-based module in process
- Prototype construction and installation in process
- Record ZT_{max}=1.6 and ZT_{ave}=1.1 achieved

	Average Output [W]	Maximum Output [W]
FTP-75	349	957
HWFET	595	813
US06	808	1233
US06 w/bypass	628	809