



Thermoelectric Generator (TEG) Fuel Displacement Potential using Engine-in-the-Loop and Simulation

Neeraj Shidore , Ram Vijayagopal, Andrew Ickes, Chuck Folkerts,
Thomas Wallner, Aymeric Rousseau
Argonne National Laboratory

Michael Reynolds
General Motors Research Laboratories

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Research Objective

To evaluate the fuel economy impact of thermoelectric devices on a conventional vehicle, using engine-in-the-loop testing and simulation studies

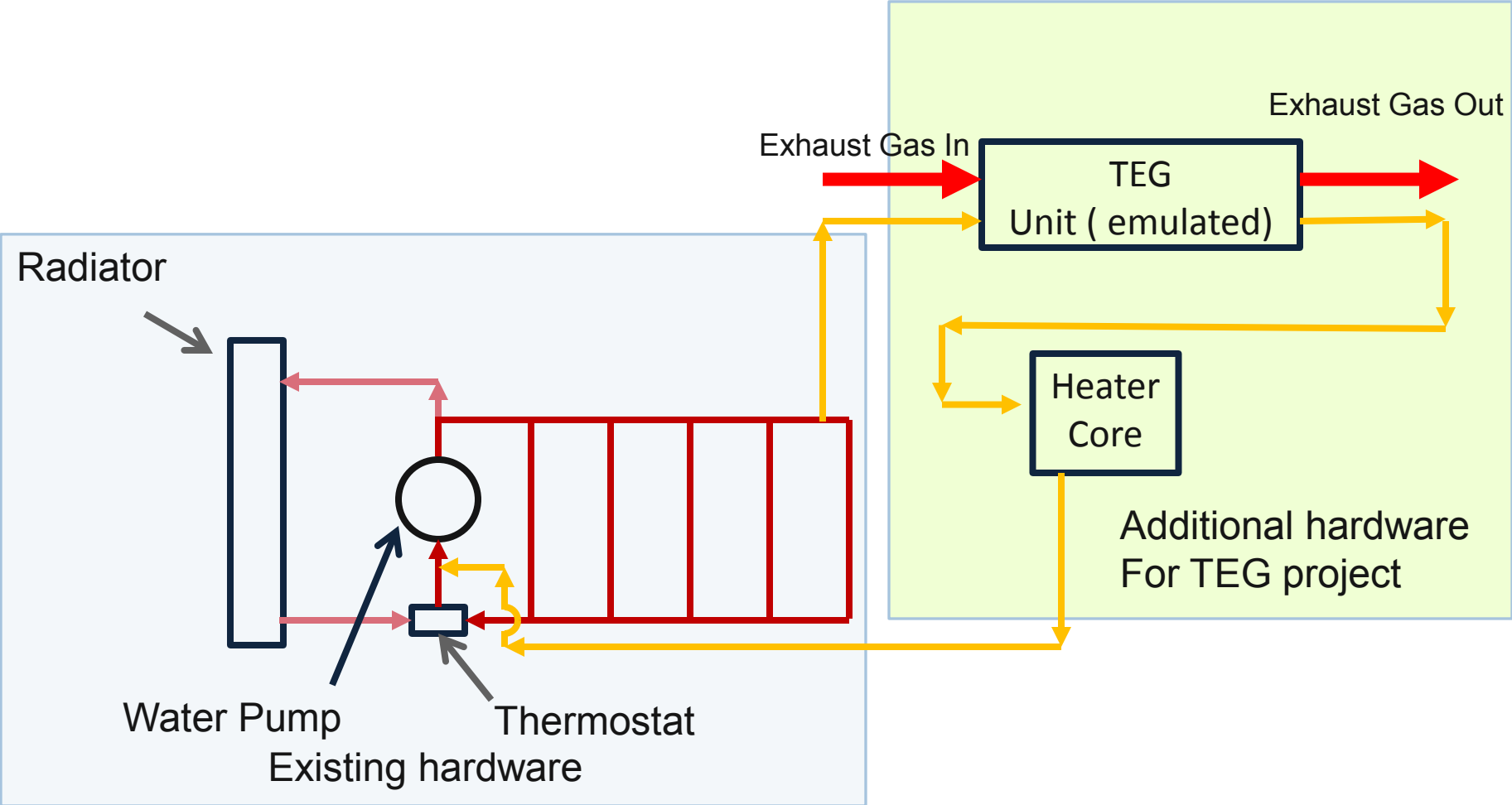


Approach to TEG Evaluation

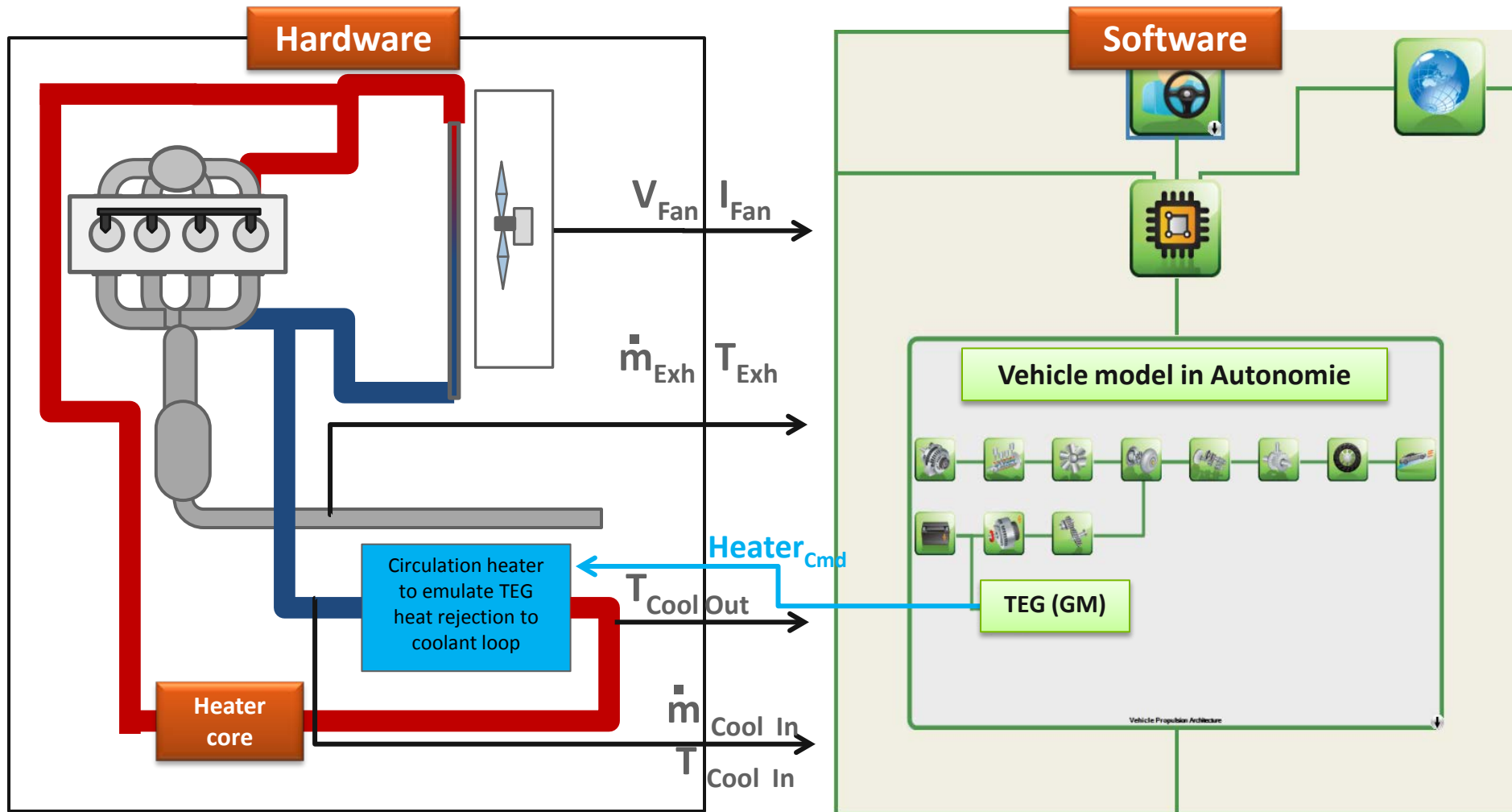
- Engine in the loop (EIL) setup
- Engine in the loop on a US06 cycle:
 - Cold and hot start – thermal and electrical effects.
 - Use engine coolant and exhaust data to drive simulation study.
- Autonomie modeling and simulation:
 - Overview of Autonomie model
 - Simulated benefits of TEG on US06
 - Effect of temperature constraints
 - Comparing effect of TEG to that of reduced electric load
 - Sensitivity to Drive cycles
 - What can we expect from TEGs
- Conclusions



TEG Device Located in the Heater Core Loop



TEG Study Using EIL - TEG Model in Autonomie with Feedback from Real Engine.



Circulation heater, heater core loop, radiator fan are hardware modifications for this project.

m = mass flow rate, T = temperature, V = Voltage, I = current.

Hardware Implementation

Radiator with engine's cooling fan.

External constant velocity fan

Heater core

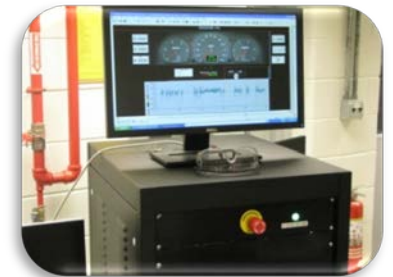
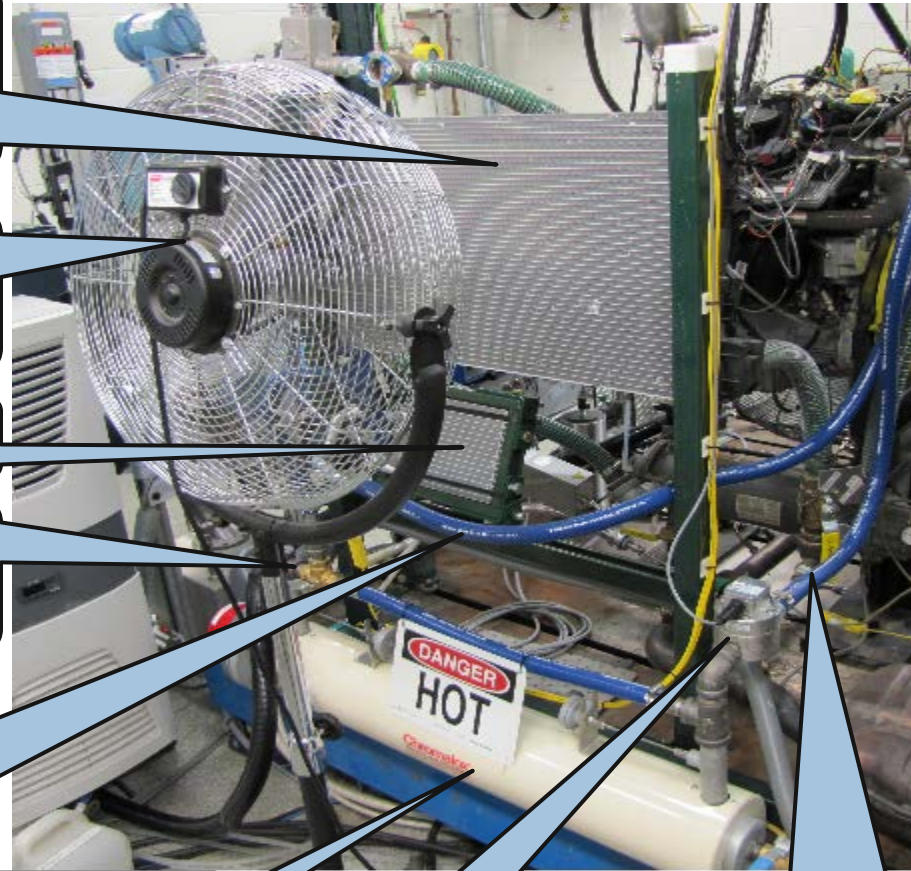
Bypass valve to test no TEG scenario

Coolant looping back from heater core to engine block

Circulation heater

Coolant flow meter

Coolant into the circulation heater from the engine block



Rest of the Vehicle Modeled

AUTONOMIE

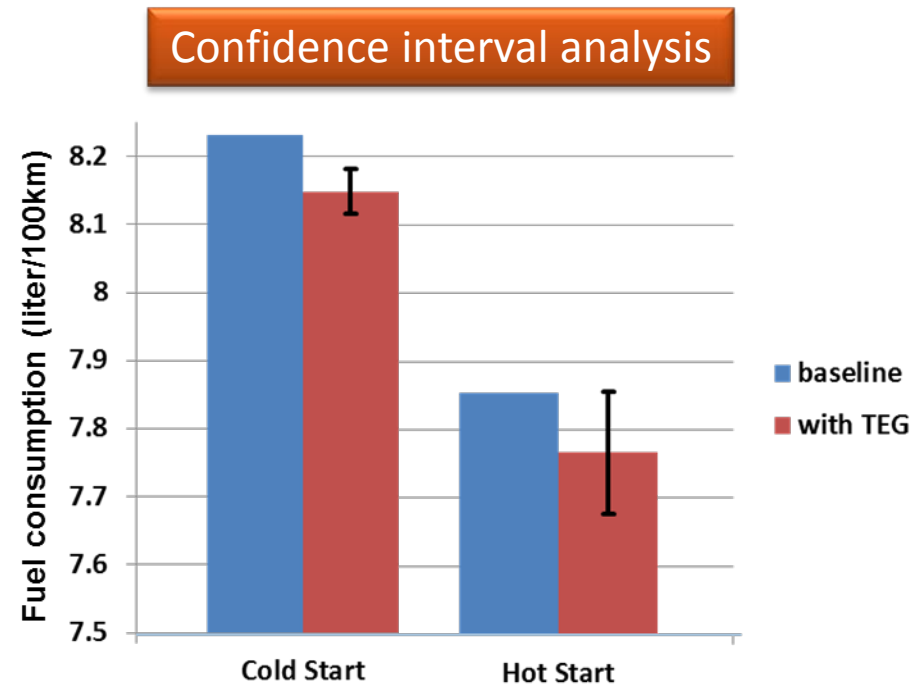
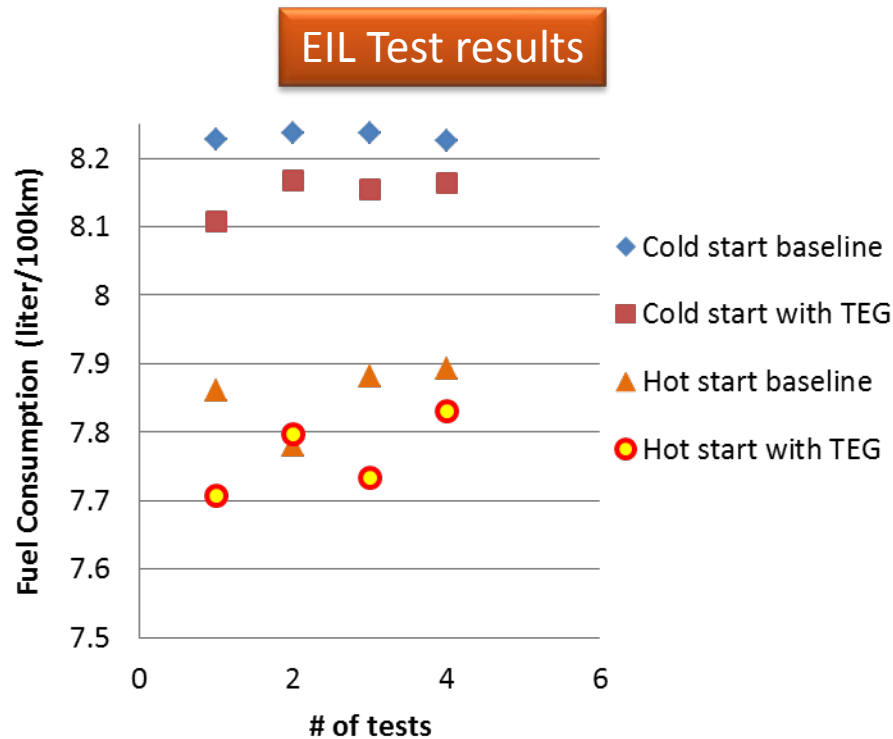


EIL Design of Experiment

| | |
|------------------|--|
| Drive Cycle | US06 |
| Vehicle platform | Conventional compact (Ford Focus) |
| Engine | 2.2 L SIDI ECOTEC GM Opel Vectra |
| Test conditions | Cold start @ 20°C Hot start – after 10 min soak |
| # test cases | 4 cold start tests 4 hot start tests |
| Accessory load | 150 W |



EIL Results Show Improvements in Fuel Consumption With Consistent Improvement During Cold Starts



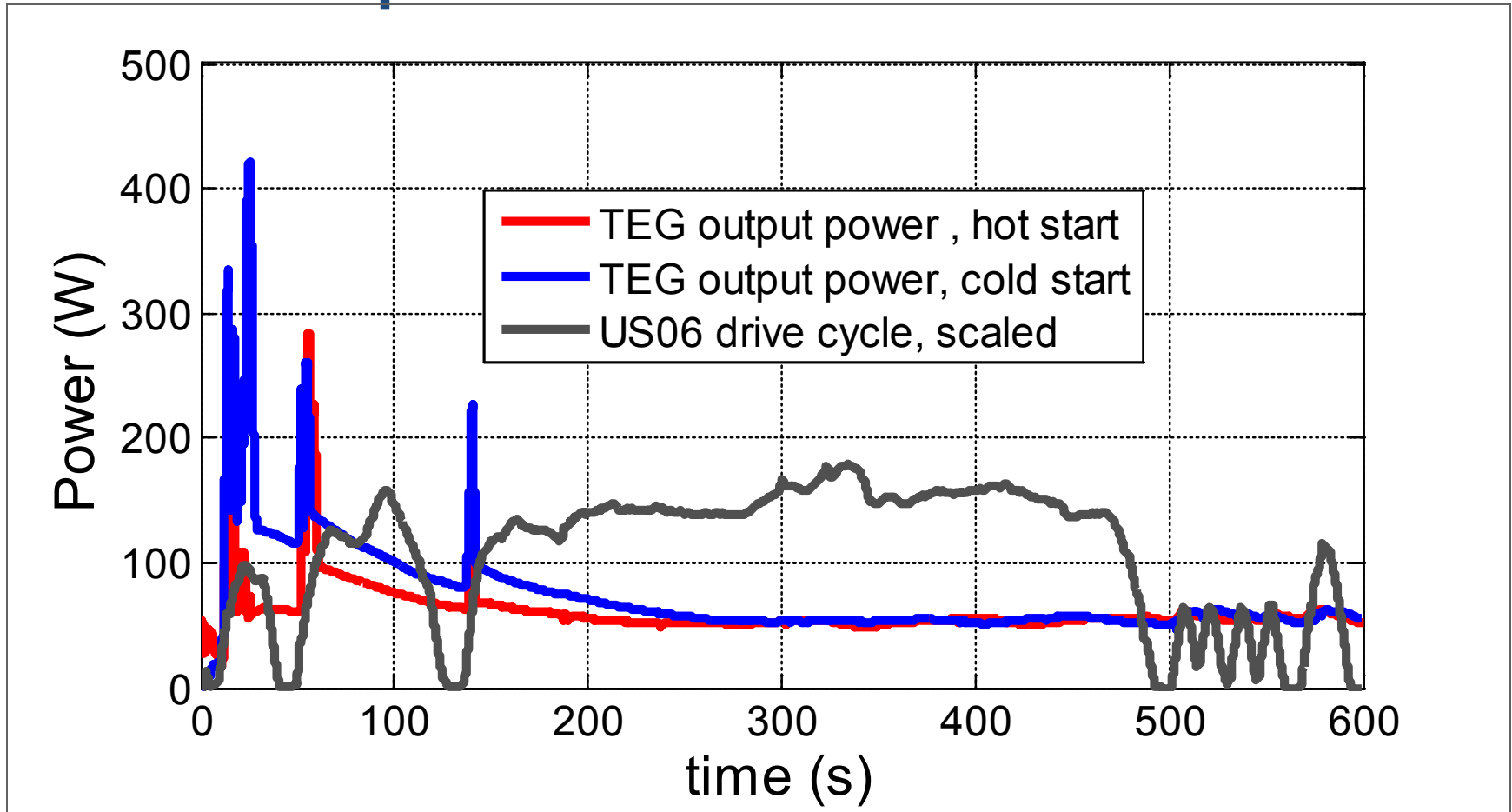
Cold start improvements $\rightarrow 0.08 \pm 0.033$ liter/100km

Hot start improvements $\rightarrow 0.08 \pm 0.089$ liter/100km

Conducting more tests can narrow the margin of error



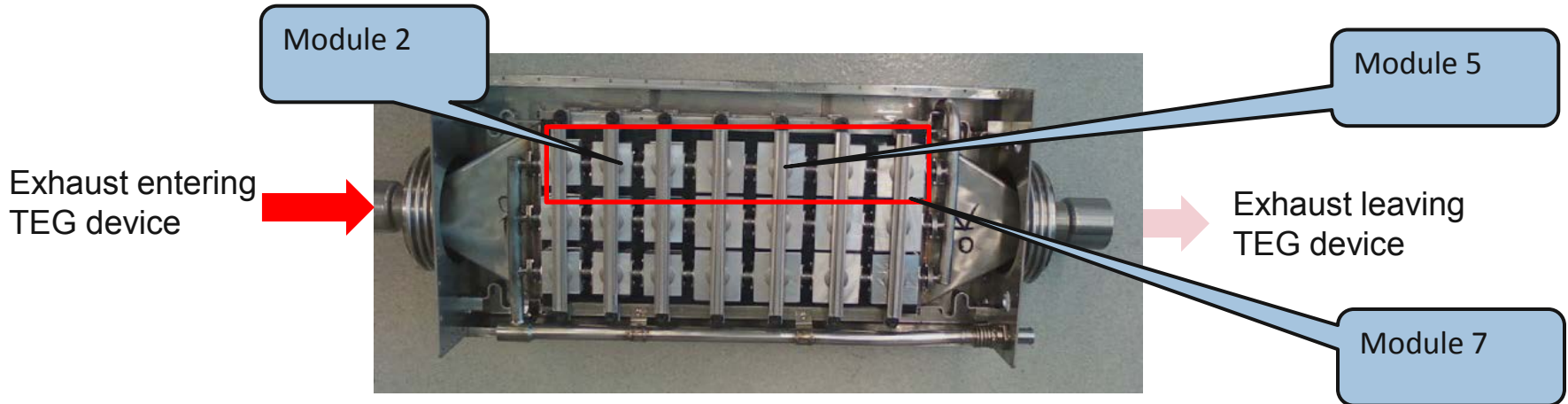
TEG Provided ~50W Average Electrical Power Output



1. Initial spikes are due to the higher exhaust flow rates due to initial acceleration.
2. Spikes fade away as modules 'downstream' get to a stable higher temperature.

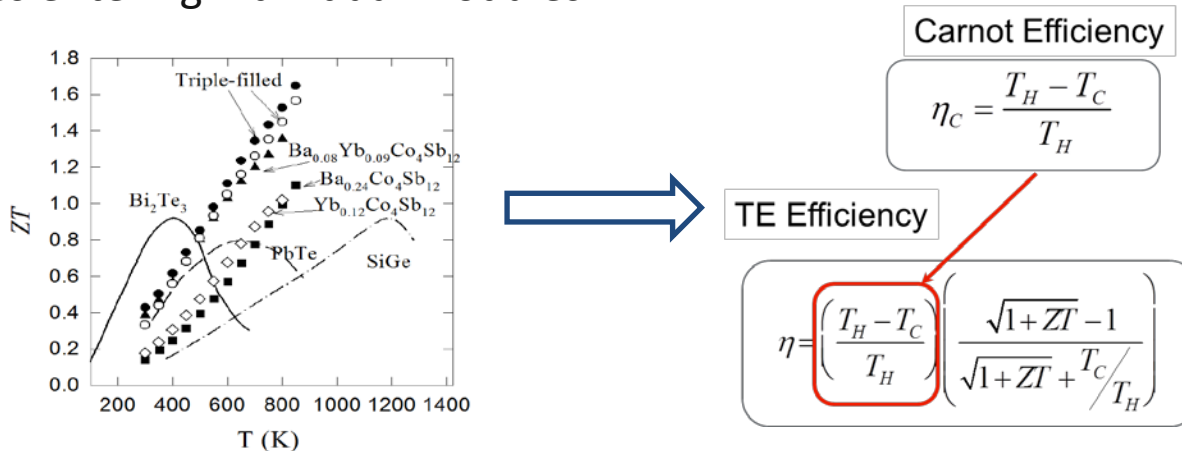


TEG Device and Module Efficiency Calculation



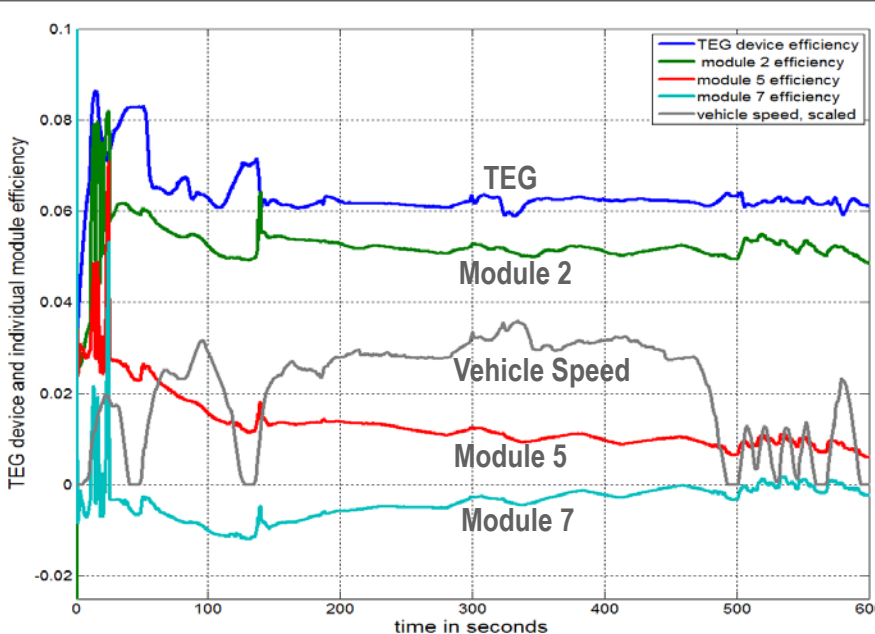
From John W Fairbanks, 'Automotive Thermoelectric generators and HVAC', presented at the DOE internal meeting, Washington DC, Nov 2011

Module efficiency for module 2, 5, and 7 calculated by recording exhaust and coolant temperatures entering individual modules.

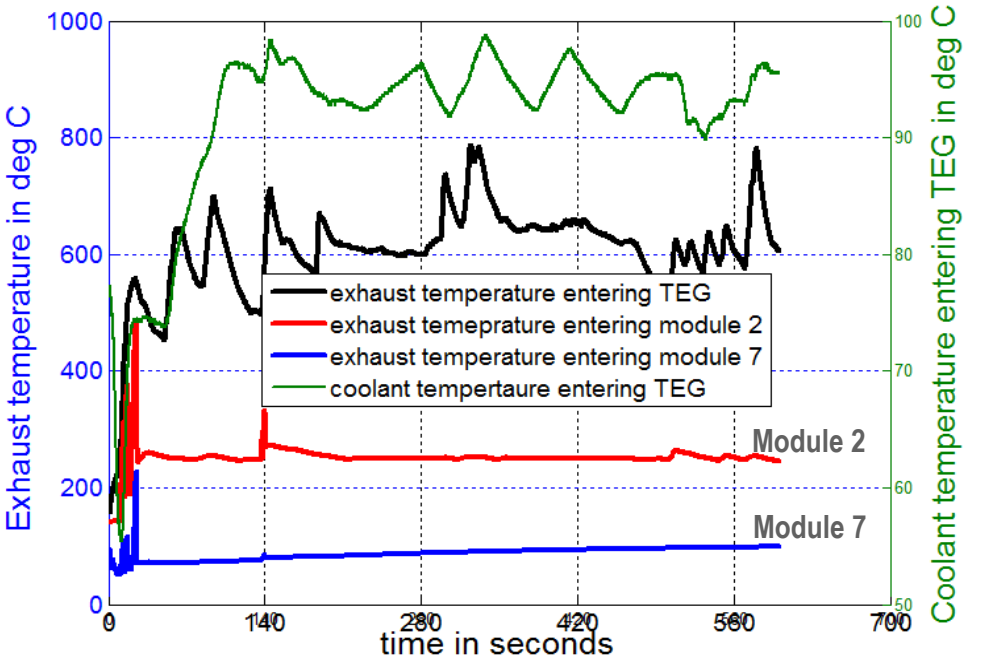


ZT is the figure of merit for the TEG Material.

'Down Stream' Modules: Lower Thermal Potential Results In Lower Efficiency



Efficiency drops as modules are farther from Inlet, due to lower exhaust temperatures.

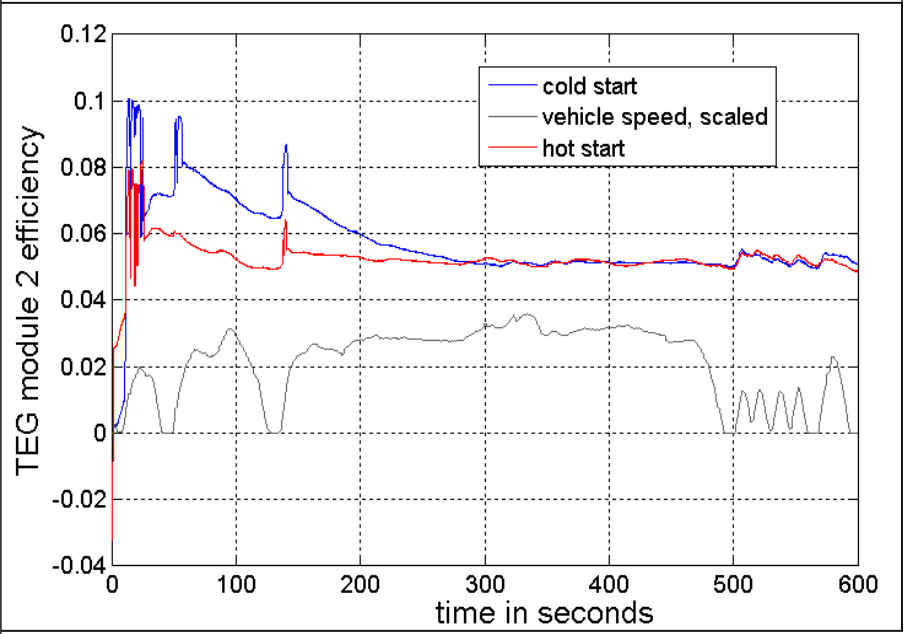
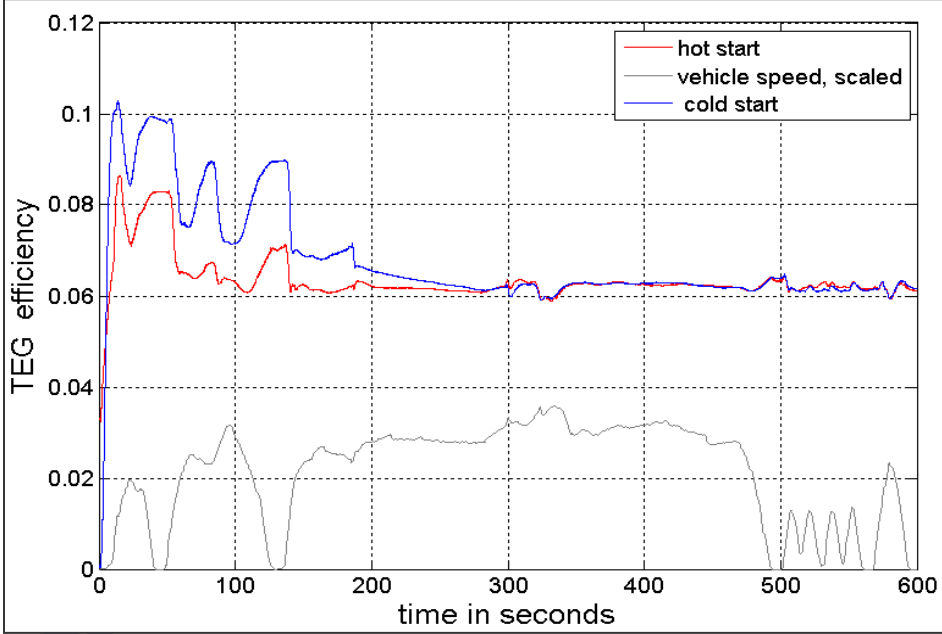
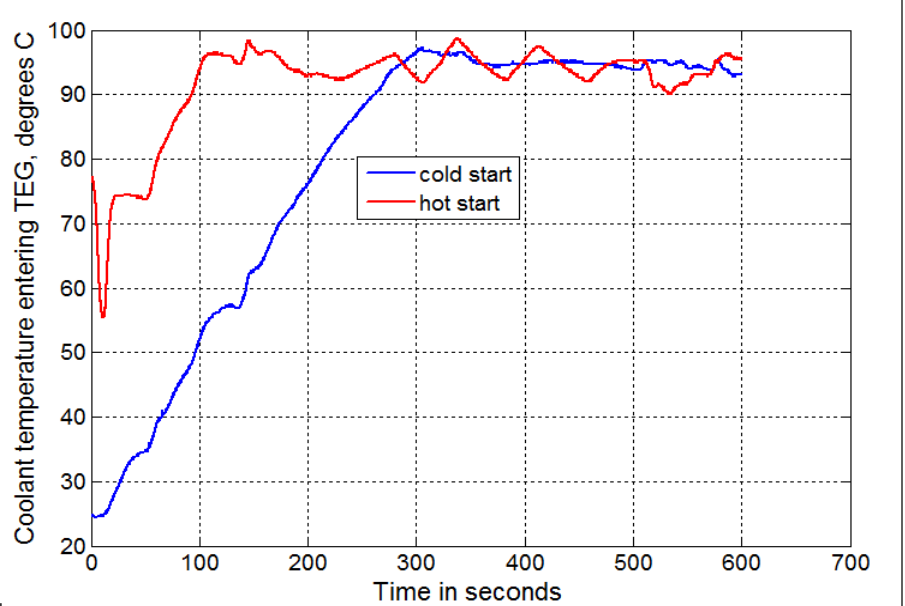
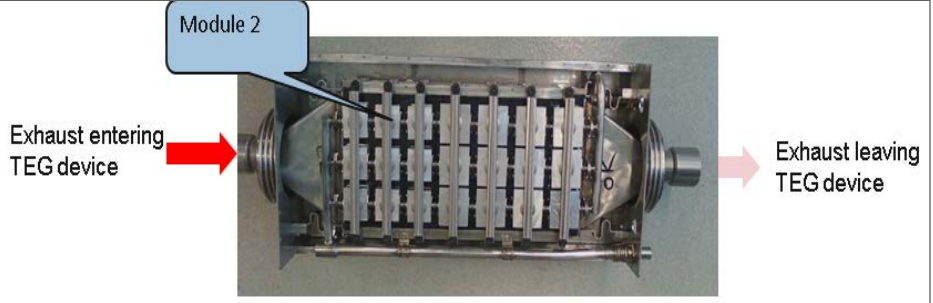


Note the slow rise in temperature for module 7

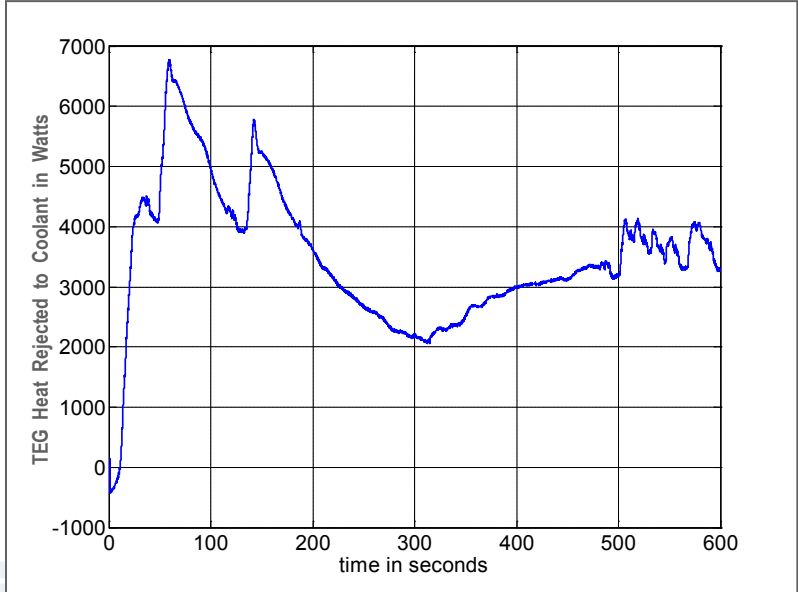
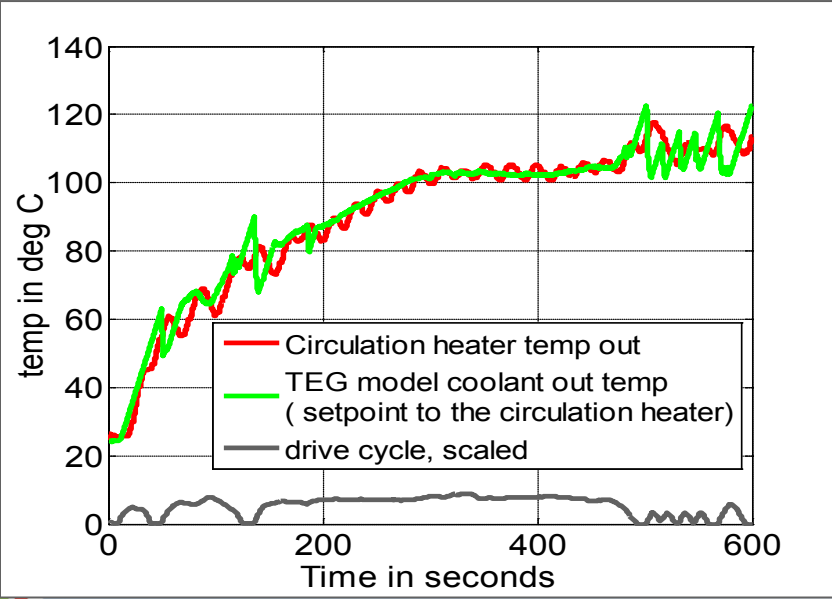
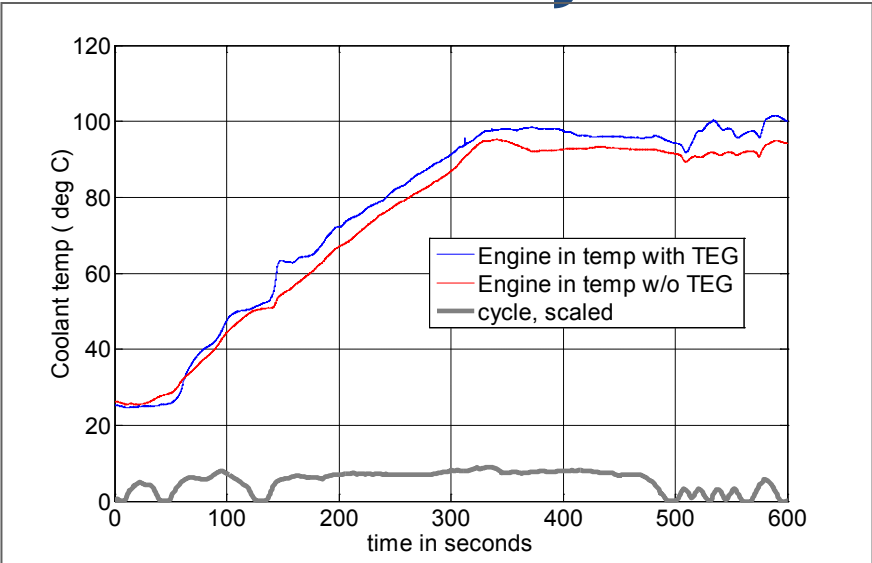
* Hot start results; but, true for cold start also



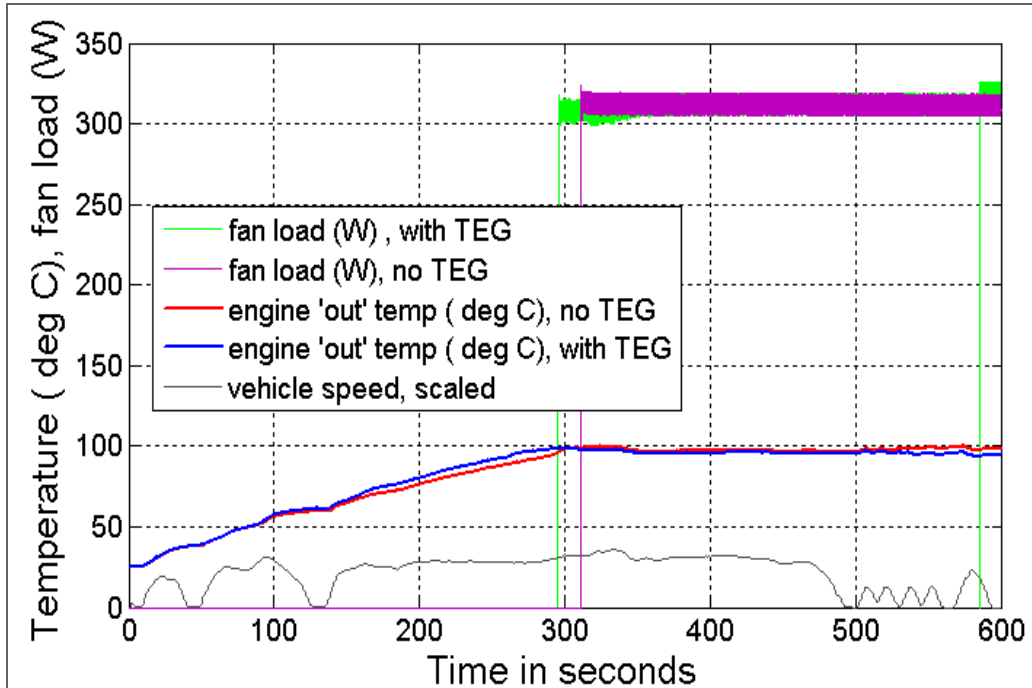
Cold Start Test Shows Higher Efficiency Due to Lower Initial Coolant Temperature



Quicker Engine Warm-up with TEG Results in Additional Fuel Economy Gains.



TEG Heat Injected in the Coolant Loop Does not Cause a Significant Change in Fan Load



| | |
|---|-----------|
| Fan load (baseline test) (kJ) | 90.2 |
| Fan load (with TEG) (kJ) | 94.6 |
| Extra fan load due to TEG (kJ) | 4.2 |
| TEG energy produced (kJ) | 47.2 |
| TEG energy consumed by additional fan load | 9% |

Fuel energy in a US06 cycle

35.52 MJ

Engine shaft energy in a US06 cycle

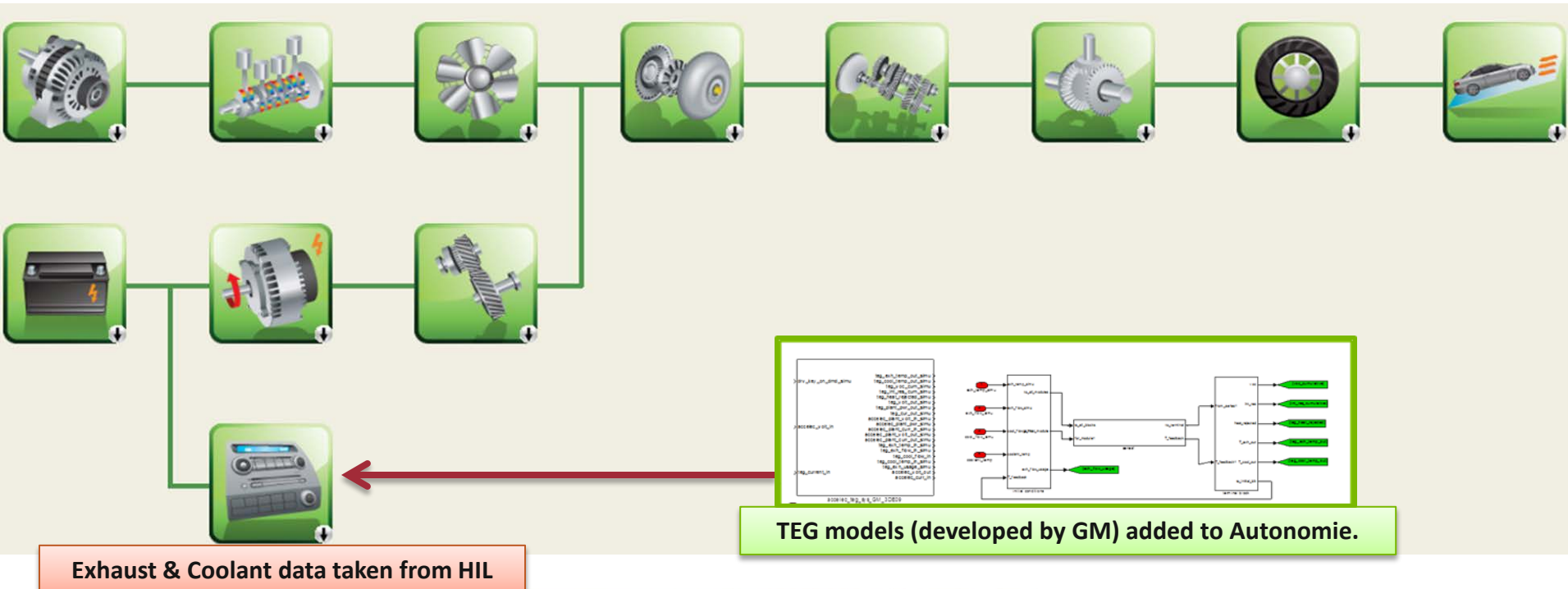
9.5 MJ

Heat injected by TEG increases engine block temperature for a cold start, and therefore does not impact engine 'coolant out' temperature, which is used for Fan ON decision

Decision => Using M&S using inputs from testing will give accurate results

Autonomie Simulation for Evaluating TEGs on Other Cycles & At Higher Temperature Limits

- TEG architecture information based on GM prototype
- TEG model provided by GM
- TEG model added to a conventional baseline vehicle
- Estimate potential electrical benefits through simulation
- Conventional 2wd, 2.2L, 110kW SI engine. (1kW auxiliary electric load)



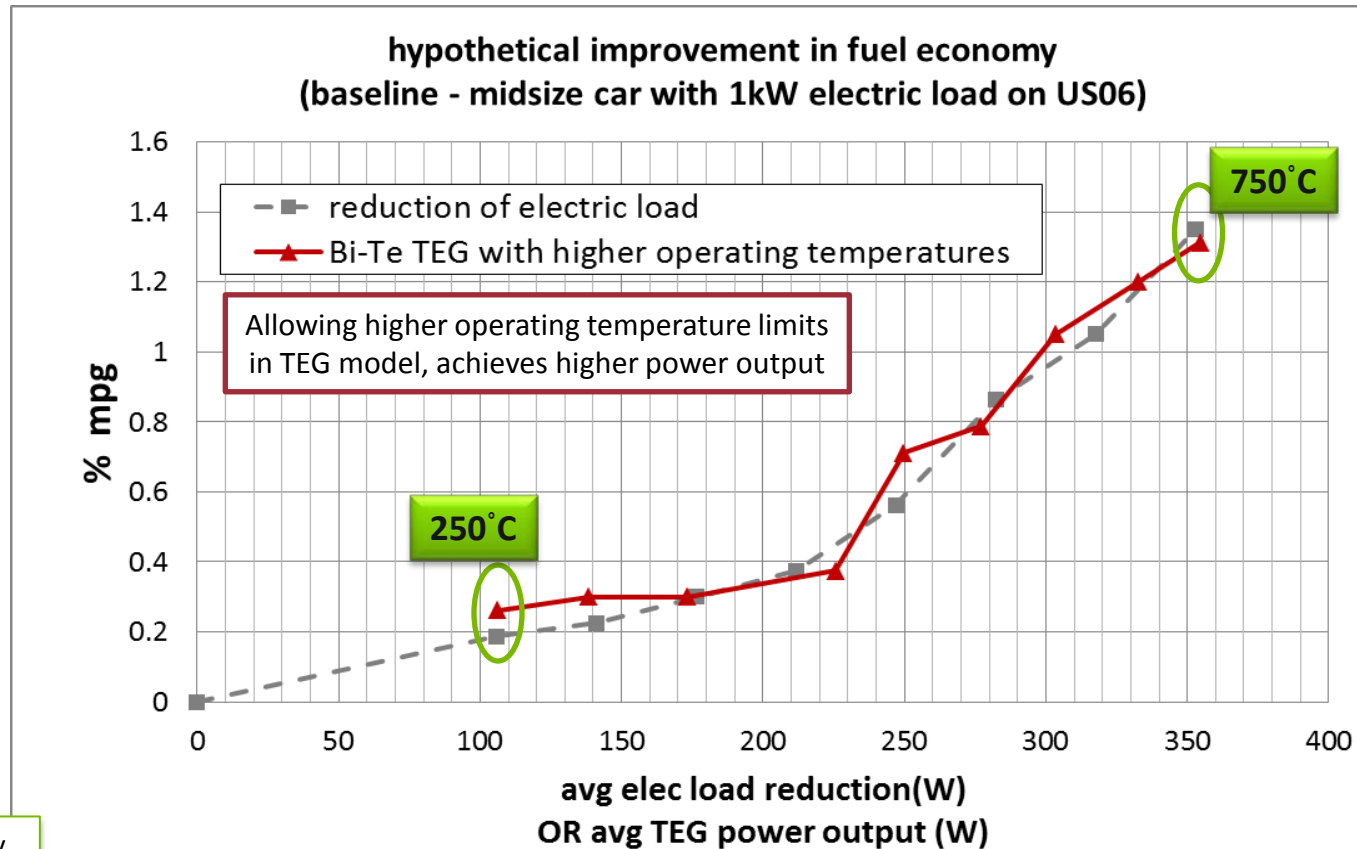
Simulated Benefits of TEG on US06

- having a TEG is similar to having a reduced electric load

- Temperature limit varied from **250°C** to **750°C** to get more power from TEG
- Assume we use the electric power generated by TEG to meet auxiliary loads

Comparing TEG effect to the sensitivity of the vehicle to reduction of electric loads

The effect of power variations while using a detailed TEG model is not negligible, but the general trend can be predicted with simpler models

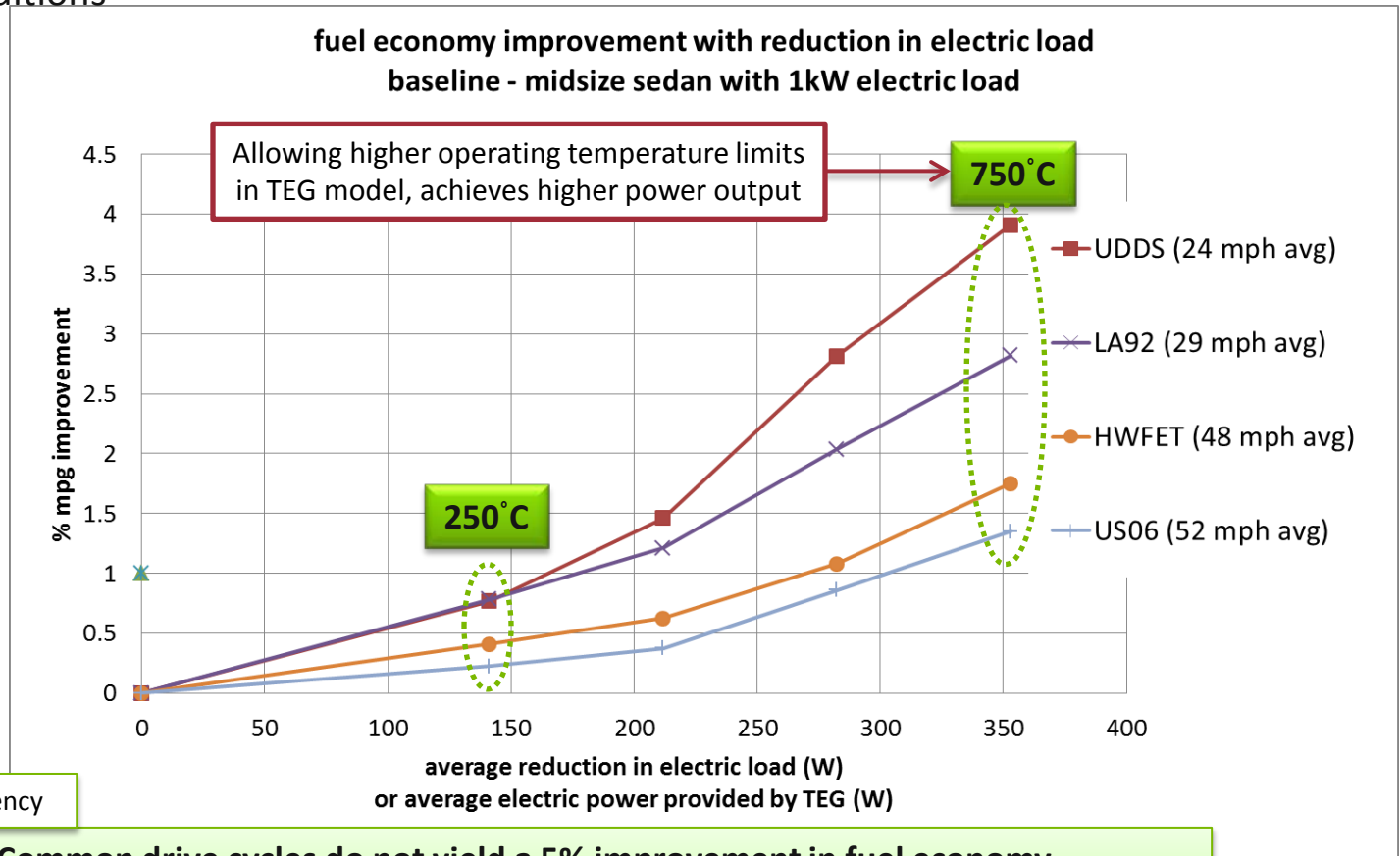


Higher operating temperature limits for TEGs can yield better outputs
The brazing materials may not be robust at high temperatures

Effect of TEG (reduced electric loads) on common test cycles

Assumptions

- We get a steady power output from TEG (same effect as reducing the avg electric load)
- We can utilize all that power to reduce the auxiliary electric load
- Hot start conditions



* Assuming 60% alternator efficiency

Common drive cycles do not yield a 5% improvement in fuel economy
5% improvement may be possible for another vehicle/cycle

What can we expect from TEG?

- defining goals for automotive applications

Common Assumptions and Estimates

- Designed for 500W @ 75mph (120 km/h) steady speed
- 5% improvement in fuel economy

Adverse effect of these assumptions

- 75mph is above speed limits → lower benefits in real world
- Differs from EPA cycles → lower impact on official fuel economy tests
- 5% @ 75mph may not translate to 5% in EPA test cycles for all vehicles
- Only about 200W electric load is present during dynamometer testing* → a higher TEG output may not reflect in the test output as per current procedures

Automotive fuel economy improvement goals & estimates should be more specific

* For most conventional vehicles. Advanced vehicle with several controllers may consume a little more power

Conclusions

- Engine In the Loop testing for a compact car using a Bi-Te TEG device with 50W average power output provided
 - a fuel economy gain between **0.7 % to 1.2 % for cold starts** on US06 cycle
 - a fuel economy gain between **0.3 % to 1.9 % for hot starts** on US06 cycle
 - Lower initial coolant temperature results in higher TEG electrical power output .
 - TEG aids in quicker engine warm-up due to heat rejected to the coolant loop.
 - Need to run more tests to narrow the confidence interval.
- Simulation studies assuming improved materials capable of withstanding higher temperatures, show that a higher power output is possible from such TEG devices
 - In a conventional car with a 2.2L 110kW engine, a reduction of average electric load by 350W can provide a 4 % fuel economy improvement in UDDS cycle
- Future studies
 - Effects of TEGs on hybrids and other advanced vehicles
 - Economic feasibility of TEG
 - Evaluation of new materials, new architectures, better thermal management



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Further Information

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Contacts

Ram Vijayagopal ram@anl.gov

Neeraj Shidore nshidore@anl.gov