Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power

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General Motors Global Research & Development

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Project ID # ACE081

Overview

Timeline

- Start date – April 2012
- End date – April 2016
- Percent complete – ~2%

Budget

- Total funding: $13,500,000
  - DOE share: $8,000,000
  - Contractor share: $5,500,000
- Expenditure of DOE funds in
  - FY12: $1,000,000
  - FY13: $2,000,000

Barriers

- Improved TE materials and modules
- Optimized temperature profile and ΔTs
- Low cost and durable TEG system design

Partners

- Interactions/collaborations

  Marlow – TE module development & fabrication

  Purdue – Thermal Interfaces, heat exchanger modeling and design

  Dana, Inc. – Heat exchanger design & fabrication

  Eberspaecher – Exhaust system design & fab.

  JPL – Modeling of TEG system, heat exchangers, & modules; TE module testing & durability studies

  Delphi – TEG electronics, packaging, & assembly

  Magnequench – TE materials synthesis

  MSU – Passivation/protection of TE materials

  ORNL – High temperature transport & mechanical property measurements

  BNL – TE material synthesis

- Project lead: GM Global R&D

Relevance – Objectives

- **Improve the US06 fuel economy for light-duty vehicles by 5% using advanced low cost TE technology:**
  - Low cost materials, modules, heat exchangers, power conditioning, and vehicle integration for exhaust gas waste heat recovery
  - Leverage innovative electrical & thermal management strategies to:
    - Reduce electrical accessory load on the alternator via TEG power
    - Electrify engine-driven accessories for increased electrical power usage
    - Use TEG power other ways than just for the present vehicle electrical load (e.g., hybrid vehicle propulsion)
    - Implement fast engine/transmission warm-up
  - Develop low cost, commercially viable manufacturing processes and plans for scaled-up TEG production (100k units/year)
- **This project is specifically focused on reducing petroleum usage for transportation by increasing fuel efficiency via waste heat recovery using advanced TEG technology.**

Relevance – Objectives

TE materials and modules:

- Boost TE material performance for large-scale production to be as good as laboratory results (e.g., ZTs)
- Improve and optimize p-type skutterudites
- Enhance interfaces (thermal, electrical), bonding (mechanical compliance), diffusion barriers, protection (oxidation & sublimation)
- Develop better high throughput synthesis processes

Temperature profile and ΔTs:

- Create innovative heat exchanger design for uniform temperature profile
- Develop good thermal interfaces for high temperature to help optimize actual ΔT

Low cost and durable TEG system design:

- Focus on simple and manufacturable components
- Reduce complexity of TEG system and subsystems
- Low cost and durable TEG system and subsystems accommodate a broad range of operating temperatures

Electrical power conditioning:

- Reduce electrical system complexity
- Avoid electrical impedance mismatch (e.g., staged module arrays or segmented legs)

Low cost vehicle controls & integration:

- Design TEG system to be integral to vehicle systems

Approach – Milestones

Q1 Select demonstration vehicle (e.g., Buick Lacrosse with eAssist)
Q2 Complete vehicle and TEG system analysis
Q3 Select TE materials for first prototype modules
Q4 Establish initial design targets for TEG subsystem
Q4 Establish initial design targets for TEG components
Q5 Deliver TE modules for initial TEG prototype
Q6 Complete preliminary estimate of TEG performance
Q8 Select TE materials for final prototype modules
Q10 Deliver TE modules for final TEG prototype
Q16 Report final TEG performance test results
Q16 Provide demonstration vehicle to DOE
Q16 Complete plan for scale-up of TE module manufacturing
Q16 Identify viable source for TE materials at automotive scale
Q16 Complete detailed production cost analysis for 100k units/year and cost reduction plan

Approach – TEG Team

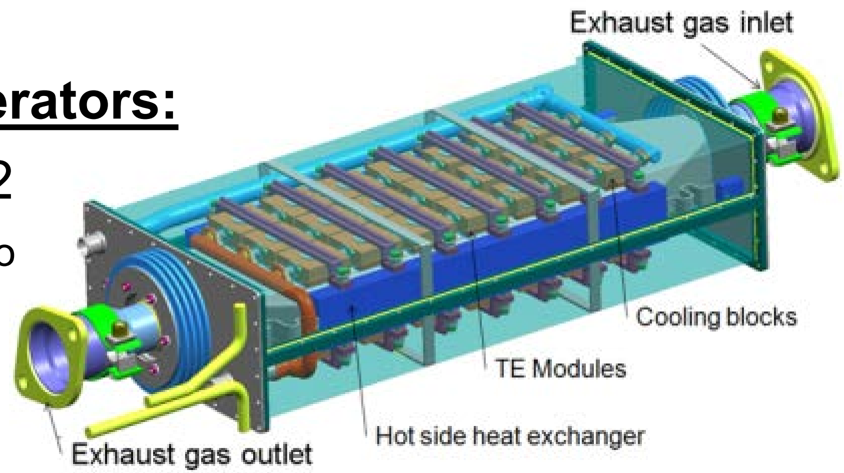
- Project lead: GM Global R&D
  - GM Global R&D: Greg Meisner (PI), Michael Reynolds, Norm Bucknor, James Salvador, Darsh Kumar, Kevin Rober
  - GM Energy Center: Vehicle Energy Analysis & Vehicle Selection
  - GM Powertrain: Vehicle controls & Integration, dynamometer testing

- Interactions/collaborations:
  - Marlow – TE module development & fabrication
  - Purdue – Thermal Interfaces, heat exchanger modeling and design
  - Dana, Inc. – Heat exchanger design & fabrication
  - Eberspaecher – Exhaust system design & fabrication
  - JPL – Modeling & design (system, heat exchangers, module); module testing & durability
  - Delphi – TEG electronics, packaging, & assembly
  - Magnequench – TE materials synthesis
  - MSU – Passivation/protection of TE materials
  - ORNL – High temperature transport & mechanical property measurements
  - BNL – TE materials synthesis

Technical Accomplishments and Progress

Previous work on thermoelectric generators:

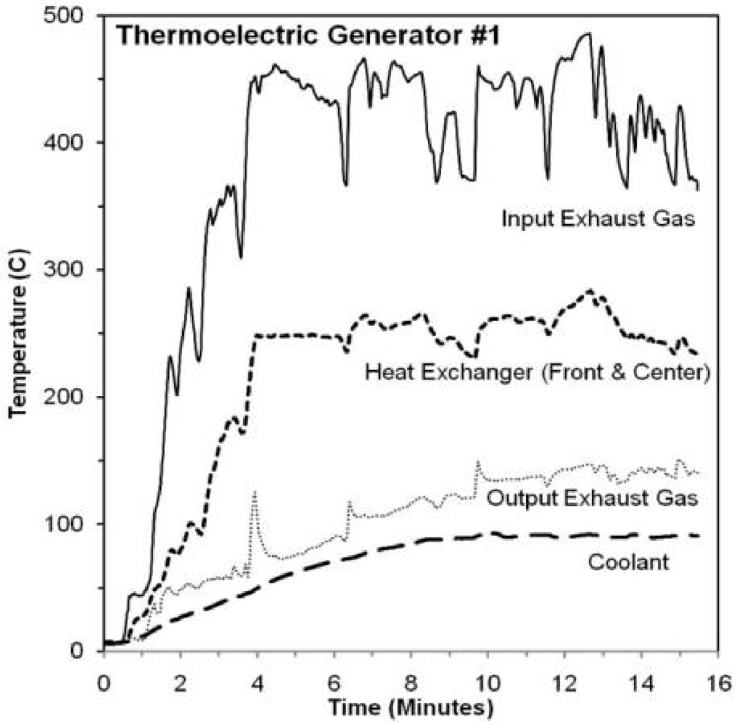
- Developed prototype TEGs #1 and #2
  - Evaluated design and execution for roadblocks to commercialization:
  - Incorporated off-the-shelf Bi-Te TE modules
  - Control systems (bypass) for temperature and back pressure
  - Exhaust system modified for TEG and bypass valve installation
  - Electrical system development and integration
- Tested on demonstration vehicle
  - Install in exhaust system, verify functions of TEG and vehicle controls and integration
  - Evaluate performance of temperature control (bypass valve) and TEG temperature profile
  - Assess output performance of TEG with Bi-Te TE modules (TEG #1 and #2)

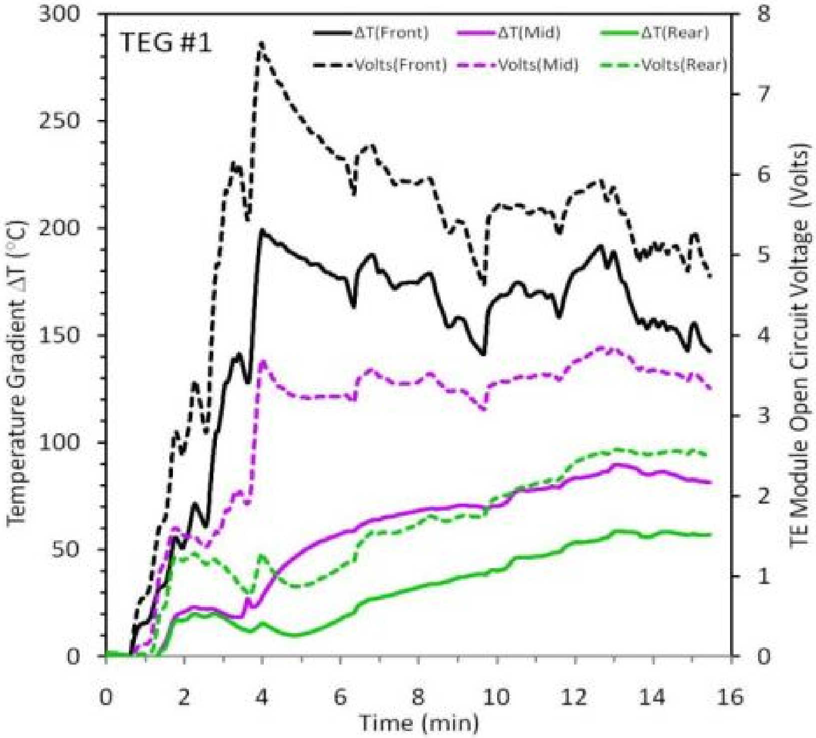


Bypass valve

Technical Accomplishments and Progress (cont.)

Results for TEG #1: Temperature control and heat exchanger temperature profile





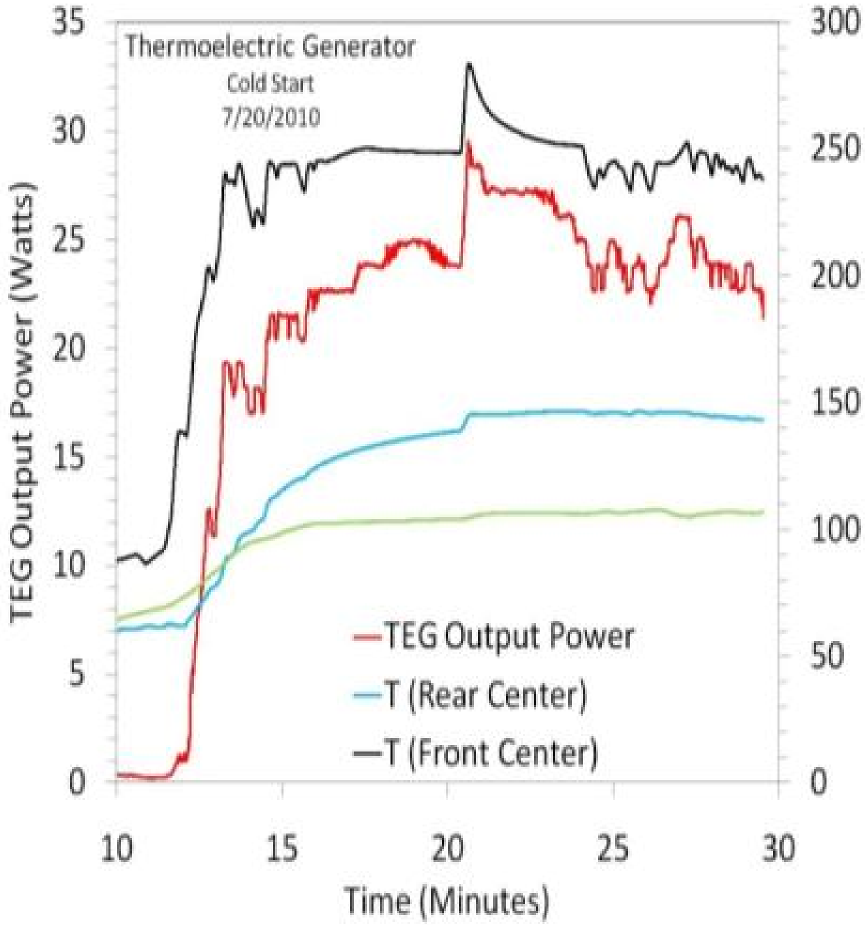
Temperature variation along the TEG parallel to the exhaust gas flow is substantial : 250°C (Front), 178°C (Middle), and 148°C (Rear)

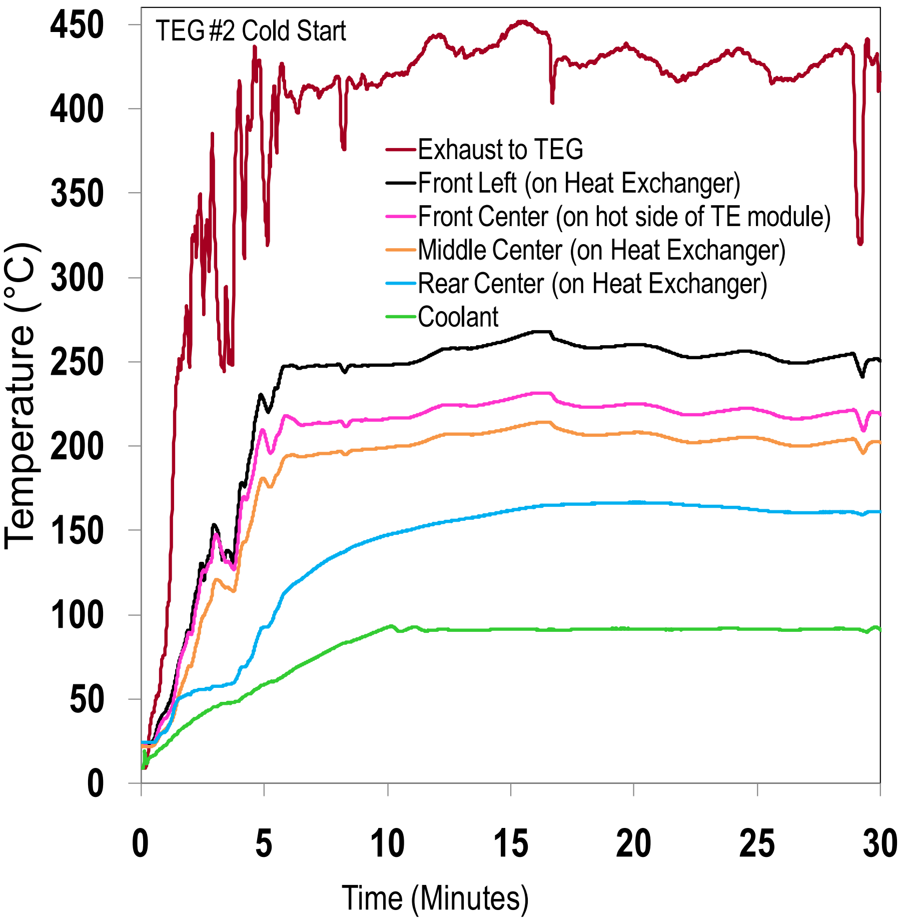
Temperature variation transverse to the exhaust gas flow is small: <3°C.

Open Circuit Voltage measurements are consistent with 50°C smaller ΔTs than measured between the hot side heat exchanger and the coolant.

Technical Accomplishments and Progress (cont.)

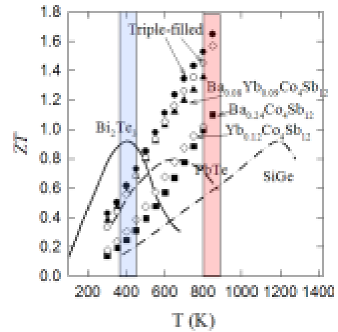
Results for TEG #2: ~25 Watts generated

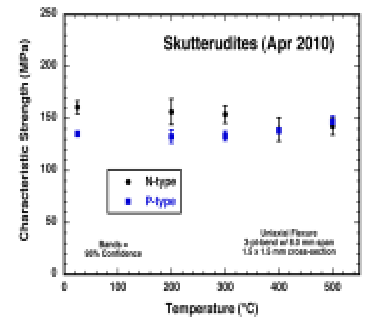




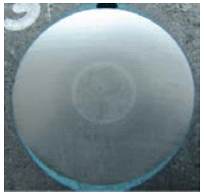
Technical Accomplishments and Progress (cont.)

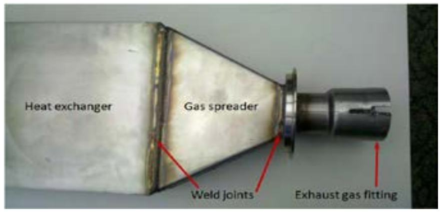
- Improved skutterudite TE materials
  - Increase ZT values (triple filled n-type material)
  - Assess and improve fracture strength and durability
  - Explore new materials for next generation TE modules



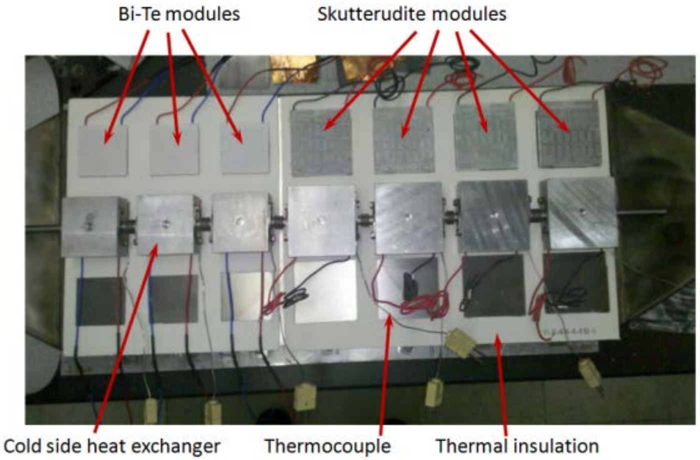


- Developed skutterudite modules



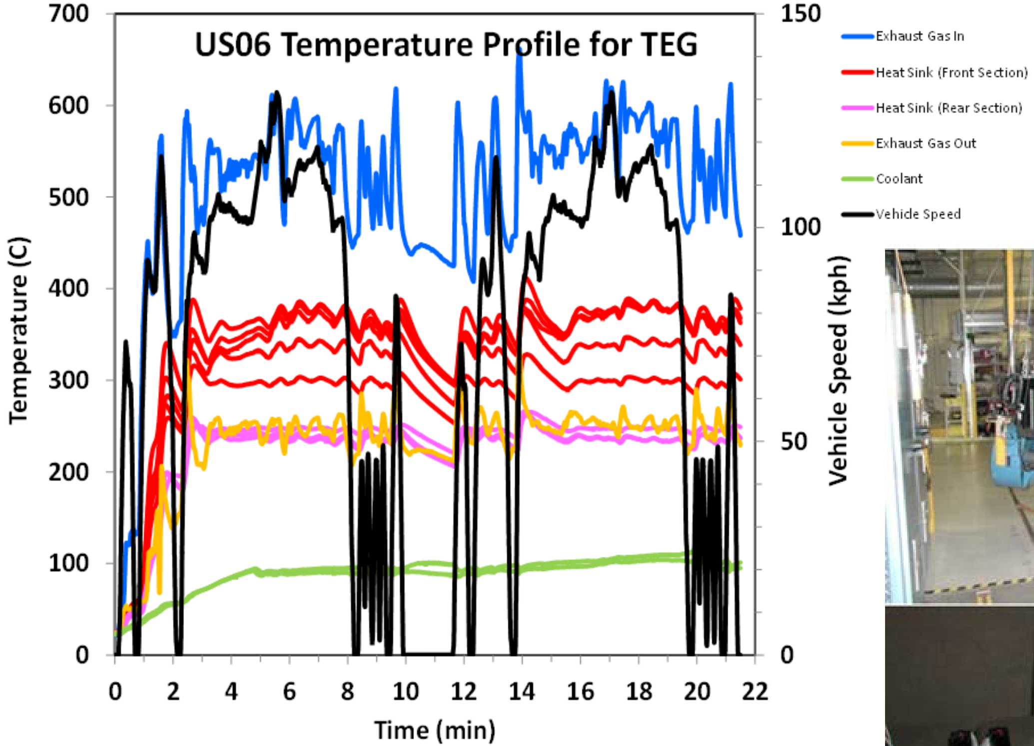


- Refined TEG design for final TEG #3
  - New joining process to heat exchanger: no leakage
  - New heat exchanger material: lower cost, light weight
  - New case design: easier assembly and gas tight seal
  - Wiring configuration for optimum TEG performance

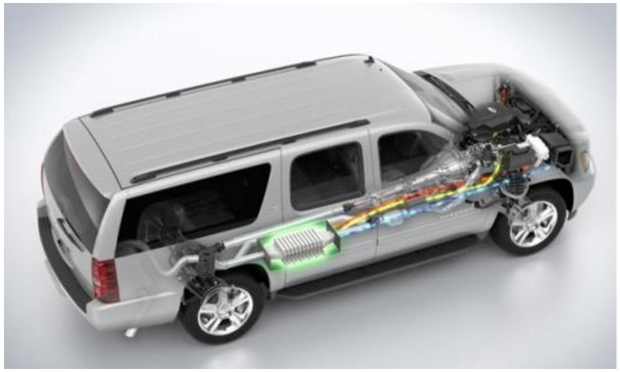


- Assembled TEG #3 with skutterudites
- Test TEG #3 on demonstration vehicle

Technical Accomplishments and Progress (cont.)

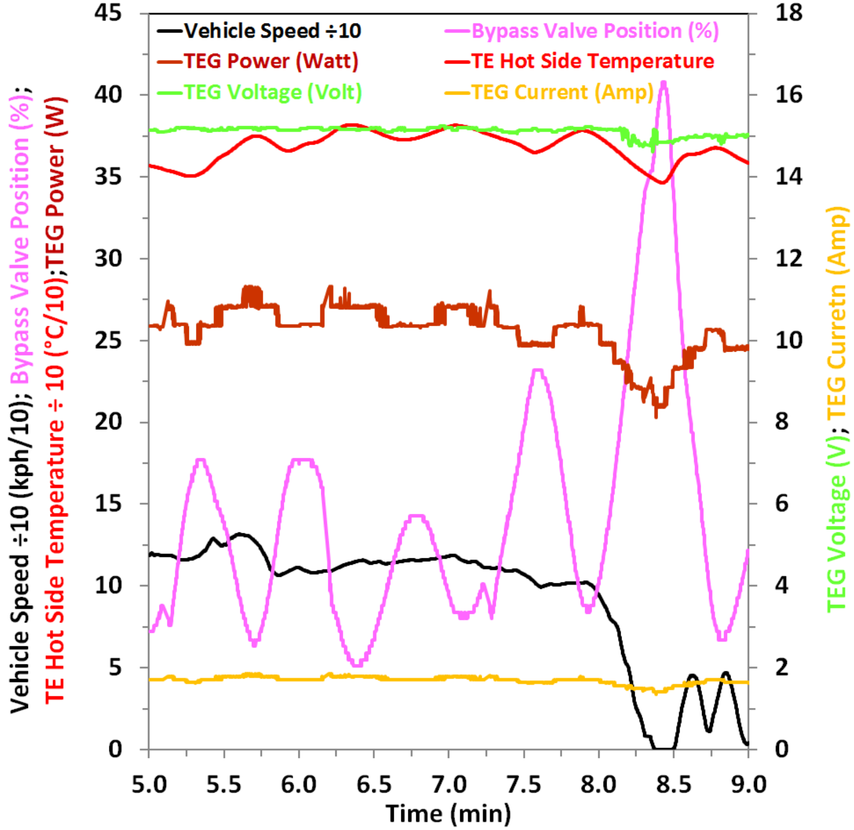


Temperature as a function of time for two sequential US06 drive cycle tests 0 – 10 min and 11.5 - 21.5 min



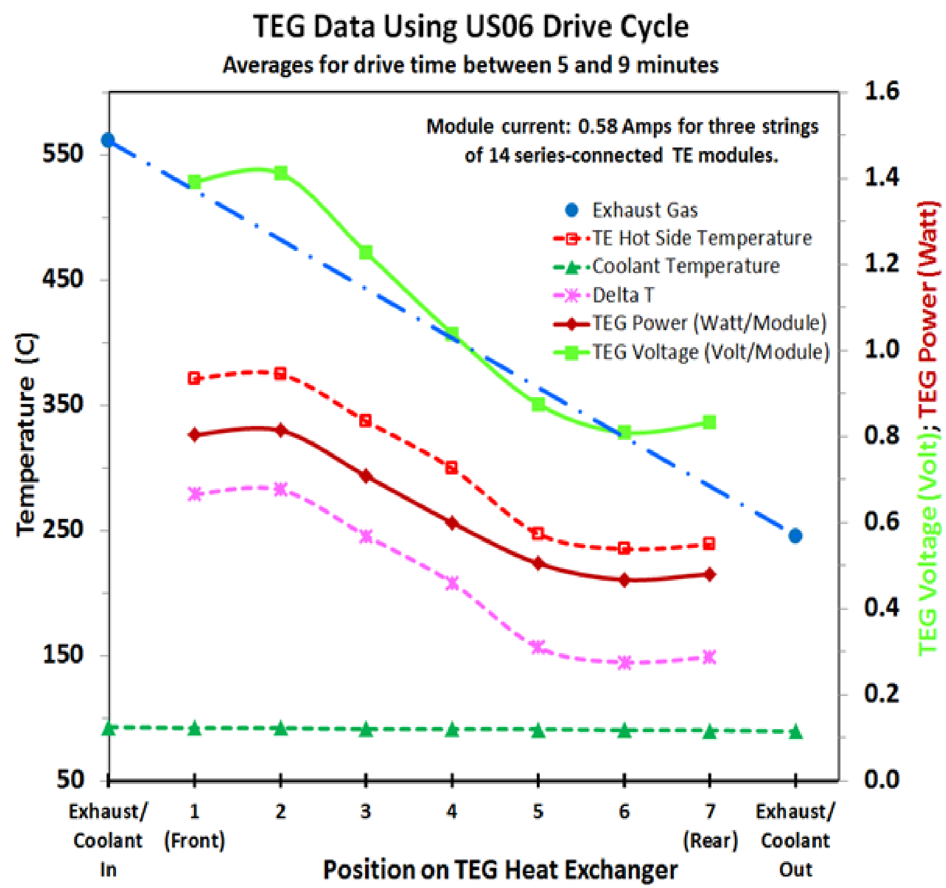
The demonstration vehicle in the dynamometer test facility

Technical Accomplishments and Progress (cont.)



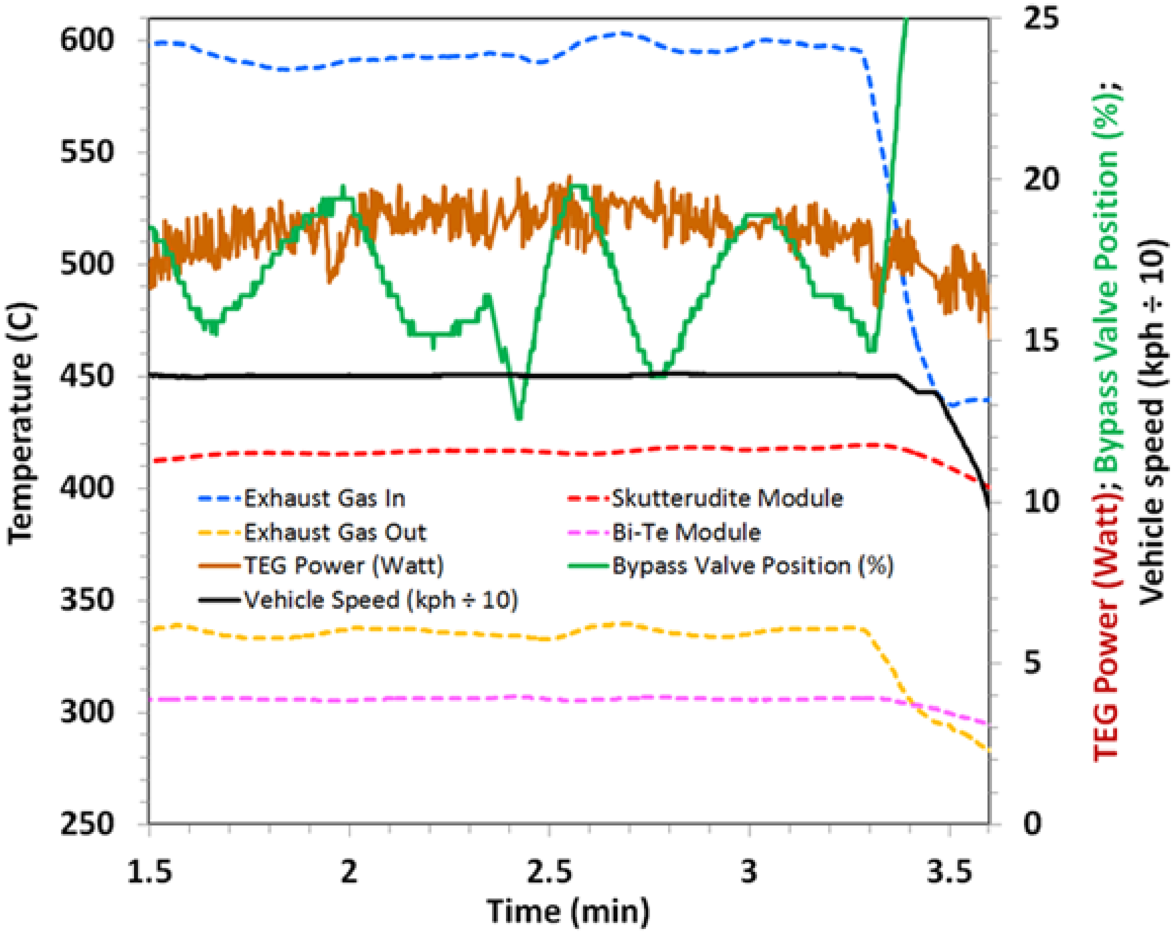
Test data for the 5 – 9 minute portion of the US06 drive cycle test

TEG #3 Results



Technical Accomplishments and Progress (cont.)

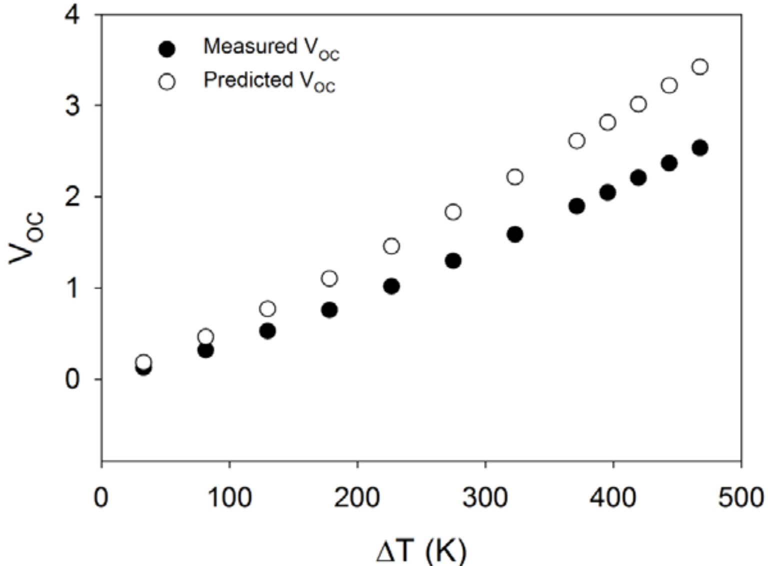
Performance for TEG #3 with increased hot side temperature (T_h = 420 C)
Only 14 of the TE modules = 19 Watts. Full TEG #3 (42 modules) = 57 Watts.

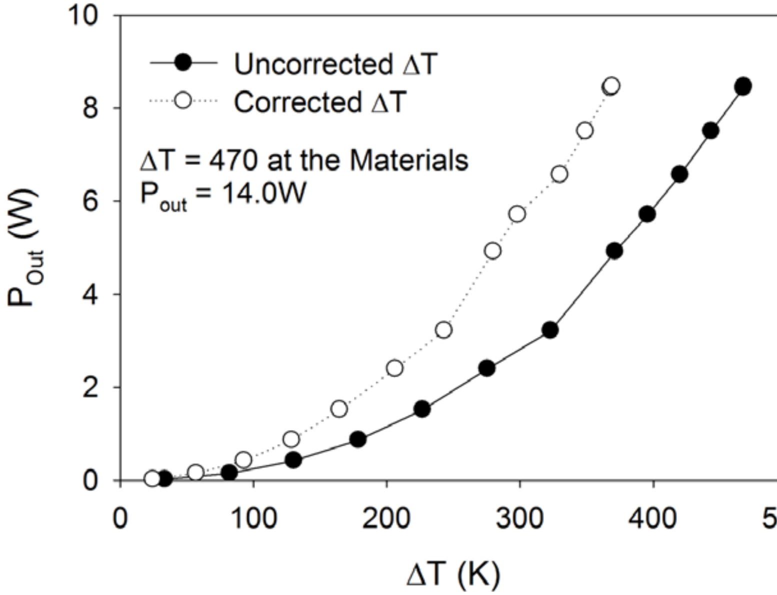


Estimated TEG #3 output with optimum temperature profile: T_c = 100°C
T_h = 600°C (skutterudites)
T_h = 250°C (Bi-Te)

TEG #3 P_{out} ~235 Watts

Technical Accomplishments and Progress (cont.)





$$V_{OC} = n\int_{T_c}^{T_h} S(T)_p dT - n\int_{T_c}^{T_h} S(T)_n dT$$

- Calculated V_{oc} based on intrinsic TE leg properties is larger than measured V_{oc}
- Poor thermal interfaces degrade ΔT
- Implies a 70°C decrease in ΔT compared to measured hot side heat sink temperatures

- By correcting ΔT for measured output power yields a projected 14 Watts per skutterudite module at ΔT = 470°C
- Further improved power output can be achieved with improved average ZT values for the TE legs

Improved ZTs, thermal interfaces: TEG #3 output would be ~ 425 Watts

Collaboration and Coordination with Other Institutions

Partners:

- Marlow (Industry) – TE module development & fabrication
- Purdue University (Academic) – Thermal Interfaces, heat exchanger modeling & design
- Dana, Inc. (Industry) – Heat exchanger design & fabrication
- Eberspaecher (Industry) – Exhaust system design & fabrication
- Jet Propulsion Laboratory (Federal) – Modeling & design (system, heat exchangers, module); module testing & durability
- Delphi (Industry) – TEG electronics, packaging, & assembly
- Magnequench (Industry) – TE materials synthesis
- Michigan State University (Academic) – Passivation/protection of TE materials
- Oak Ridge National Lab (Federal) – High temperature transport & mechanical property measurements
- Brookhaven National Lab (Federal) – TE materials synthesis

Proposed Future Work

Q1 Select demonstration vehicle

Q2 Complete vehicle and TEG system analysis (Gap Analysis)

Q3 Select TE materials for first prototype modules

Q4 Establish initial design targets for TEG subsystem

Q4 Establish initial design targets for TEG components

Summary

Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power

- Overview:

Timeline: 4 years	**Barriers:** Cost, Materials (Performance & Durability), Interfaces, T (profile , ΔTs), Power Conditioning, Manufacturability, Production Scale-up Plans
Budget: $13.5M Project $8M DOE Funds	**Project Lead:** General Motors R&D With: GM Powertrain, GM Energy Center **Partners:** Marlow, Purdue, Dana, Eberspaecher, JPL, Delphi, Magnequench, MSU, ORNL, BNL

- Relevance:

  Objectives: Improve the US06 fuel economy for light-duty vehicles by 5% using advanced low cost TE technology

  (1) Low cost, (2) Innovative TEG Design, (3) TE Module Durability, (4) Manufacturability, and (5) Plan for Production Scale-up

- Approach:
  - Assemble the best team: unique skills and expertise
  - Include industrial partners who will be well-positioned for commercialization
  - Build on results from previous TEG project

Summary (cont.)

Cost-Competitive Advanced Thermoelectric Generators for Direct Conversion of Vehicle Waste Heat into Useful Electrical Power

- Technical Accomplishments and Progress:
  - Previous results for prototype TEGs with skutterudite TE modules
  - Identified areas for improvement
  - Established new Project Plan, Milestones, Deliverables
- Collaboration with Other Institutions:
  - Broad-based team with considerable expertise in TE technology
  - Significant involvement of industry, universities, national labs
- Proposed Future Work:
  - Select the demonstration vehicle
  - Complete analysis of vehicle & TEG
  - Select TE materials
  - Set design & performance targets for TEG components & subsystems