Skutterudite Thermoelectric Generator For Automotive Waste Heat Recovery

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General Motors Global Research & Development

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Outline

- Acknowledgements
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- TE Generator Development
  - TEG #1 (preliminary TEG assembly and testing)
  - TEG #2 (Bi-Te modules)
- TE Generator Development: TEG #3
- Future Work
- Summary

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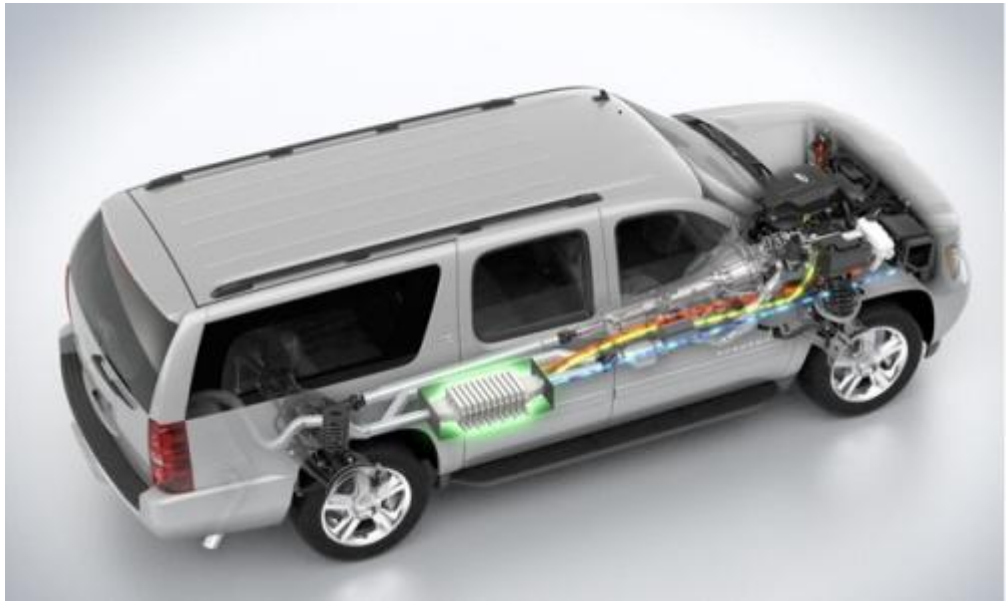
Introduction

- Reduce petroleum usage for transportation by increasing fuel efficiency via waste heat recovery using advanced TE technology.
- Chevrolet Suburban demonstration vehicle:
  - Large amount of heat, high T
  - Adequate cooling capacity of engine coolant system
  - Large space for TEG
  - Simple vehicle modification needed for TEG installation
  - Weight impact small because of large vehicle weight



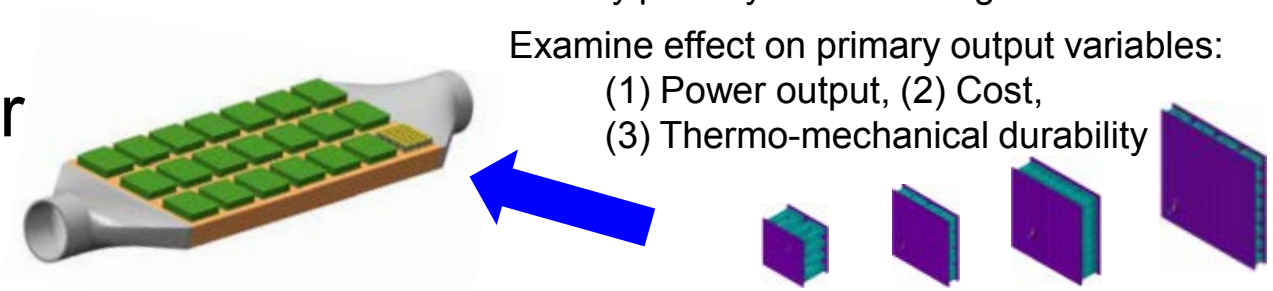
- Optimize TEG design for available space and cost of TE materials
- Construct prototype TEG for advanced TE technology R&D and to demonstrate viability of TEGs for automotive applications

Introduction

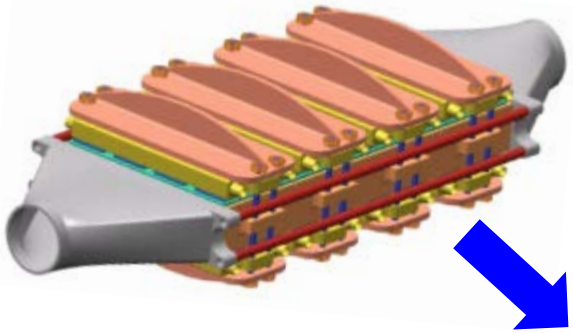
TE Module Design:

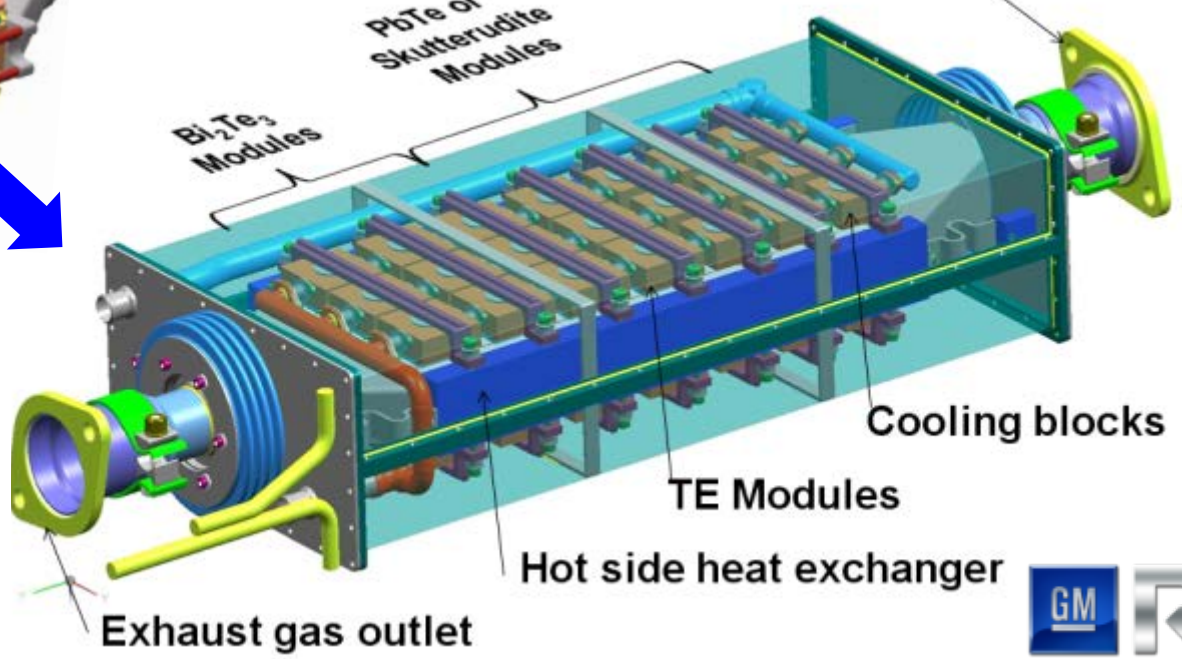
Identify primary module design variables

Examine effect on primary output variables:
(1) Power output, (2) Cost,
(3) Thermo-mechanical durability



Heat Exchanger Design:



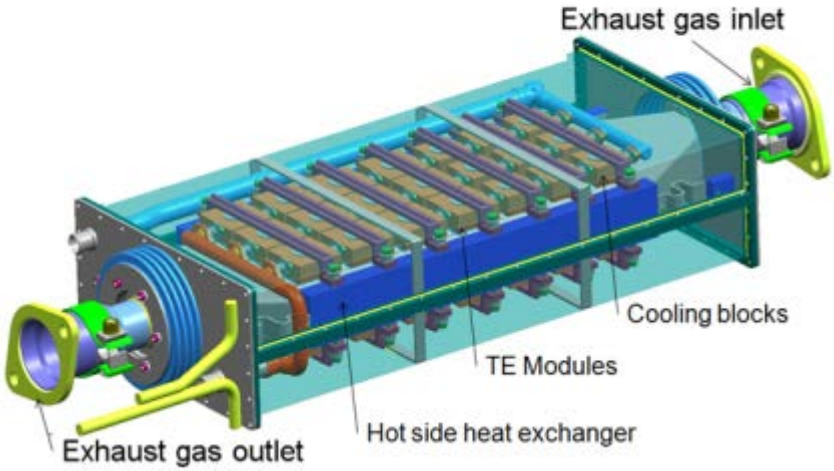


TEG Design:

Program metric: $/Watt

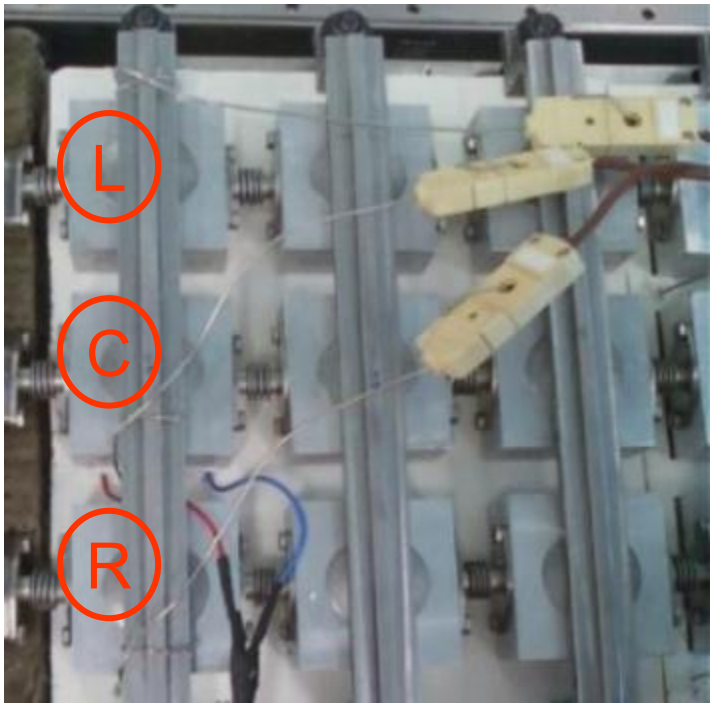
TE Generator Development

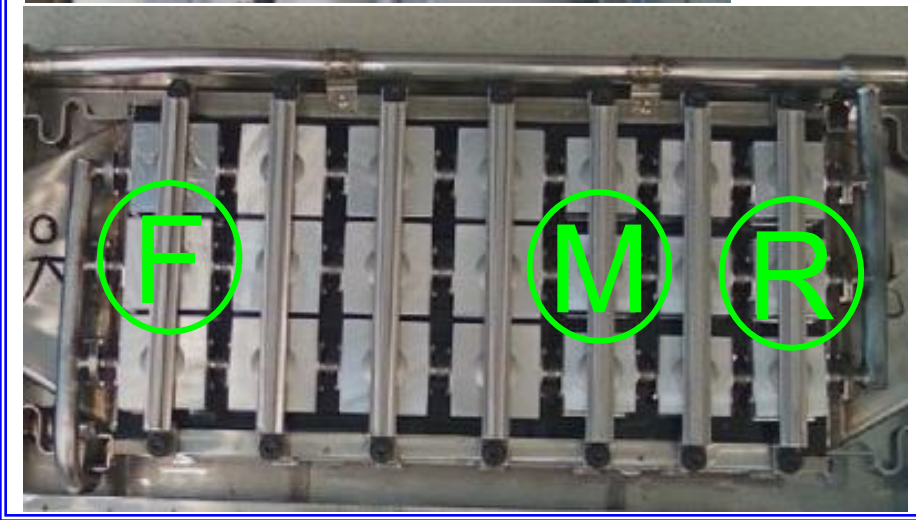
- Developed prototype TEGs #1 and #2
  - Evaluated design and execution for roadblocks to commercialization:
  - Incorporated off-the-shelf Bi-Te TE modules
  - Control systems (bypass) for temperature and back pressure
  - Exhaust system modified for TEG and bypass valve installation
  - Electrical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

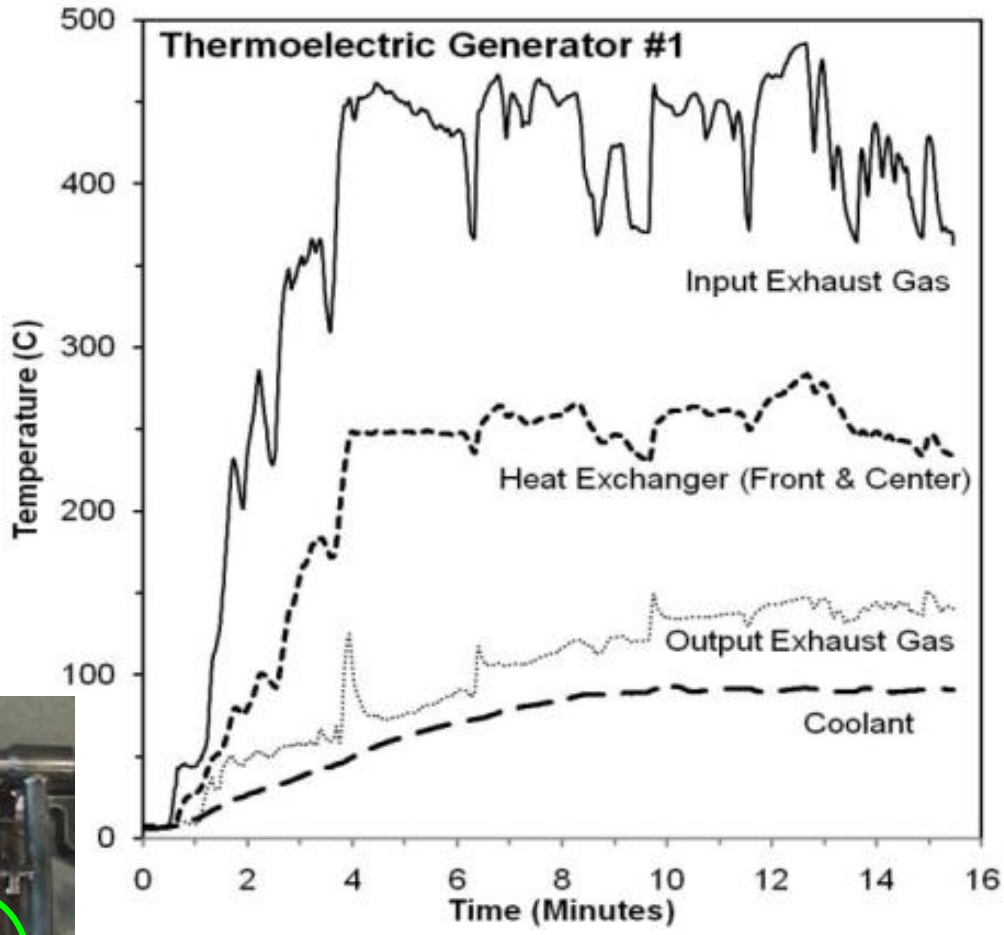


Bypass valve

TE Generator Development



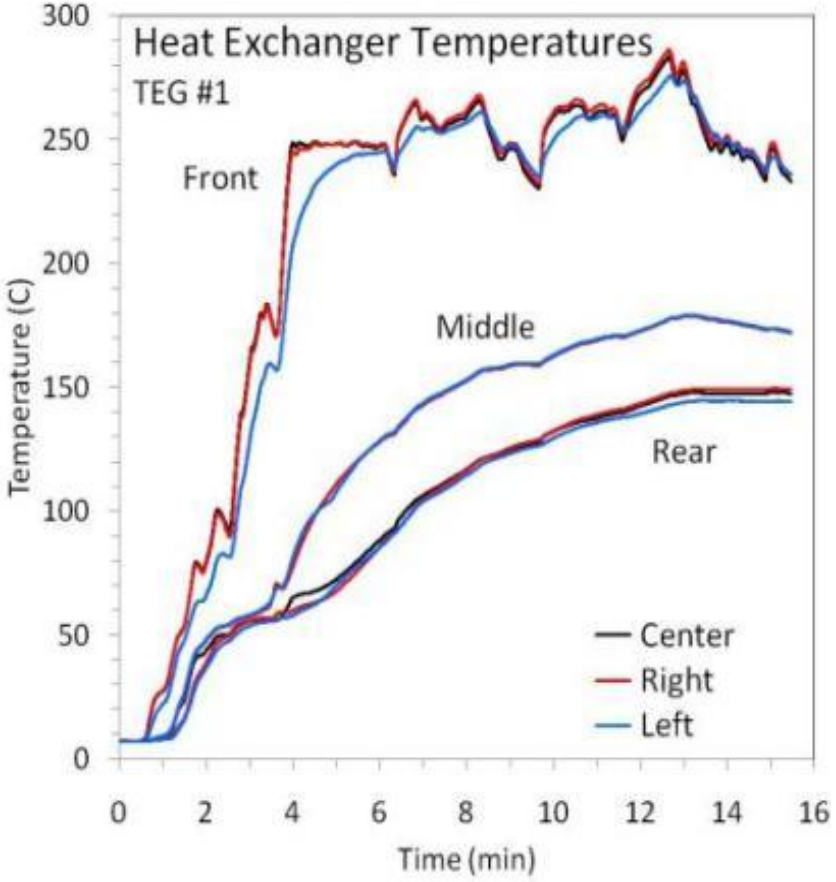




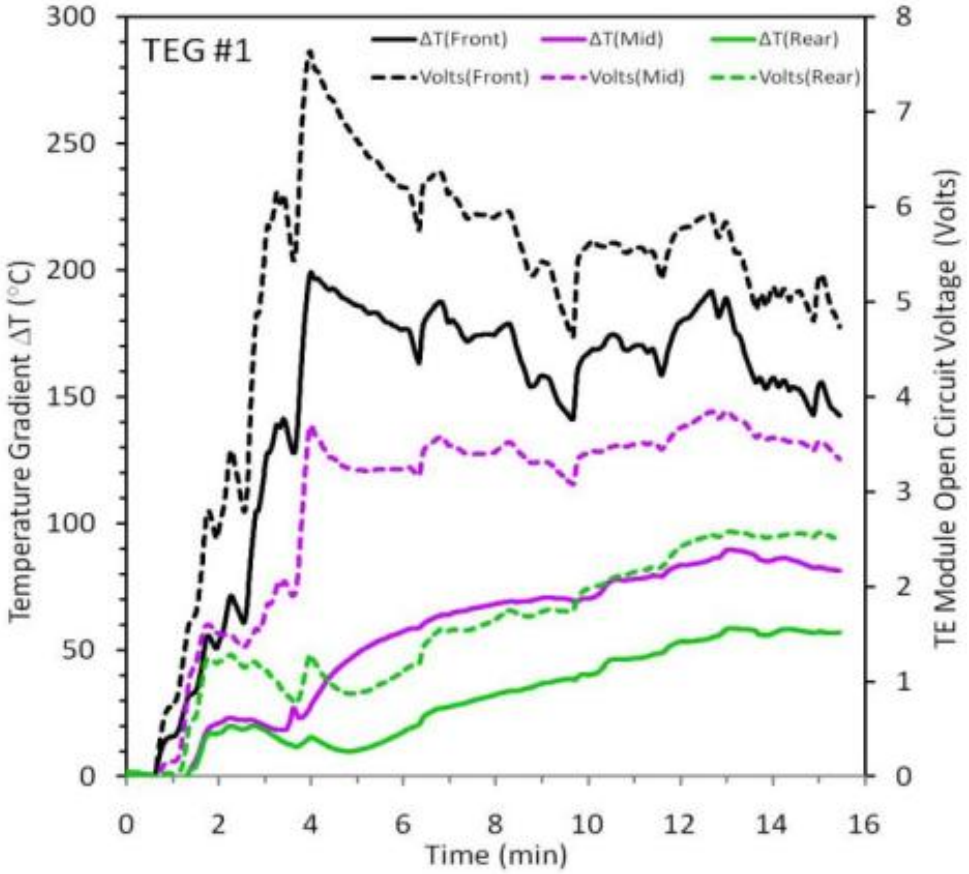
Temperature variation along the TEG parallel to the exhaust gas flow is substantial : 250°C (Front), 178°C (Middle), and 148°C (Rear)

TE Generator Development

Results for TEG #1:



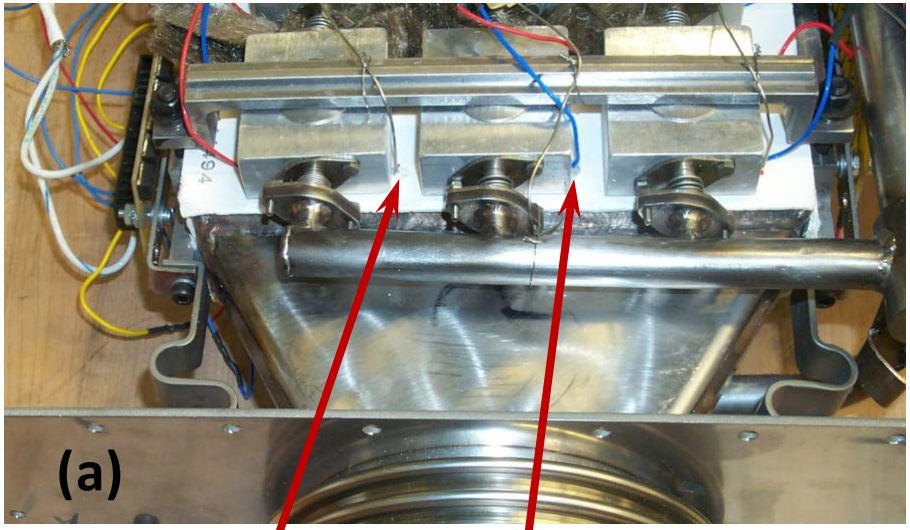
Temperature variation transverse to the exhaust gas flow is small: <3°C.



Open circuit voltages are consistent with 50°C smaller ΔT than measured between the heat exchanger and the coolant.

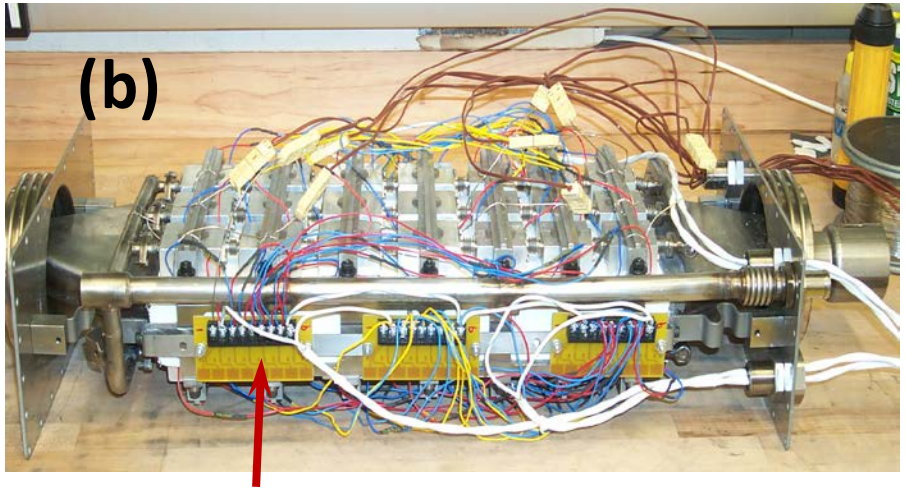
TE Generator Development

TEG #2: 42 Bi-Te modules

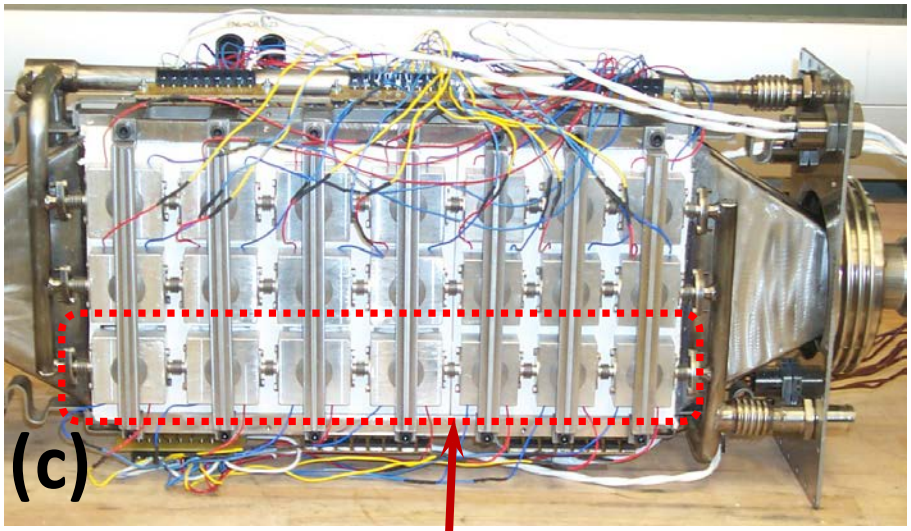


Front Left thermocouple on heat exchanger

Front Center thermocouple on hot side of Bi-Te TE module



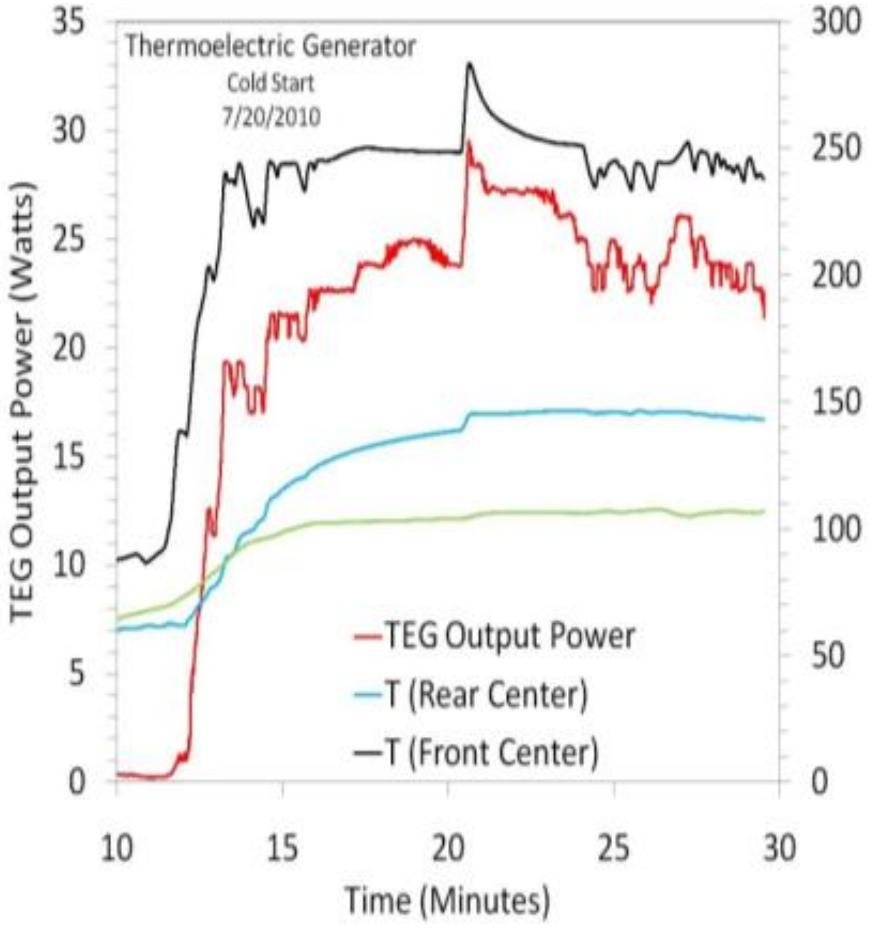
Circuit board for TE module connections

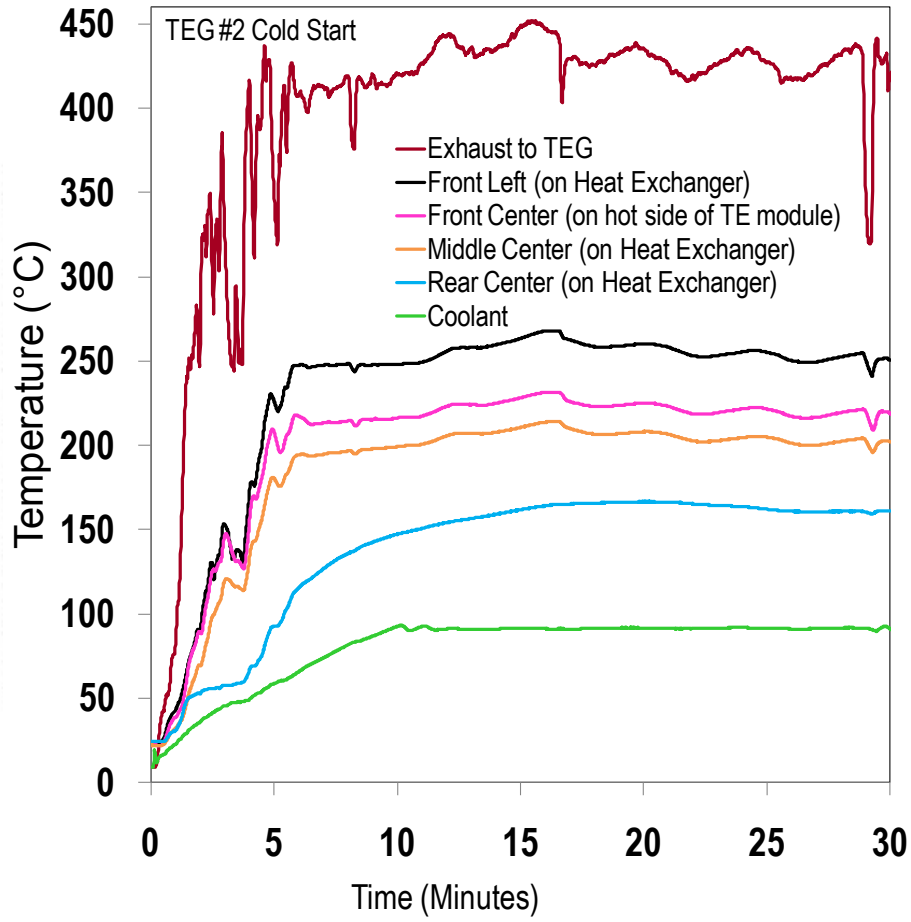


Seven TE module series

TE Generator Development

Results for TEG #2: ~25 Watts

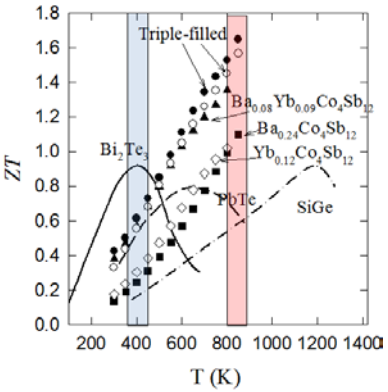


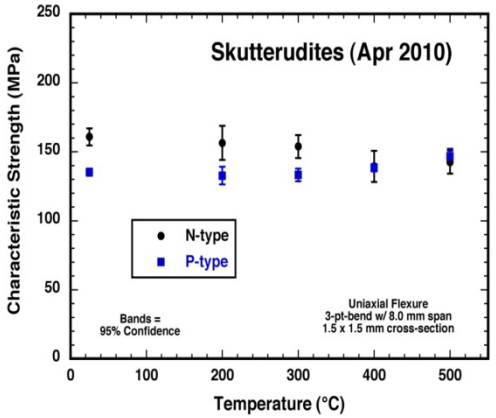


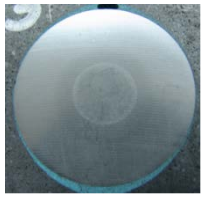
TE Generator Development

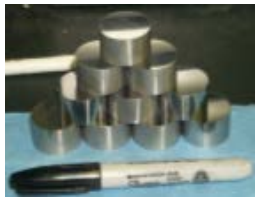
TEG #3:

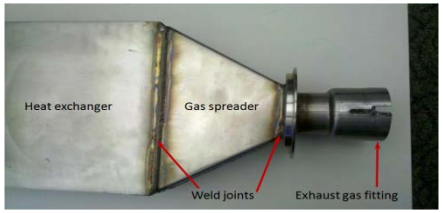
- Improved skutterudite TE materials
  - Increase ZT values (triple filled n-type material)
  - Assess, improve fracture strength and durability
- Developed skutterudite modules



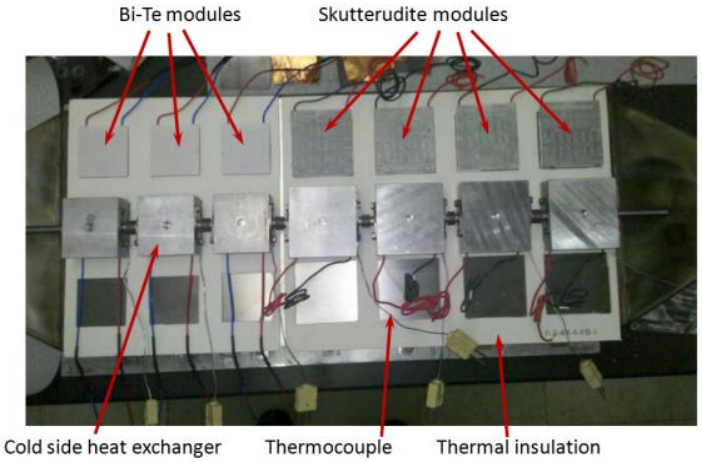






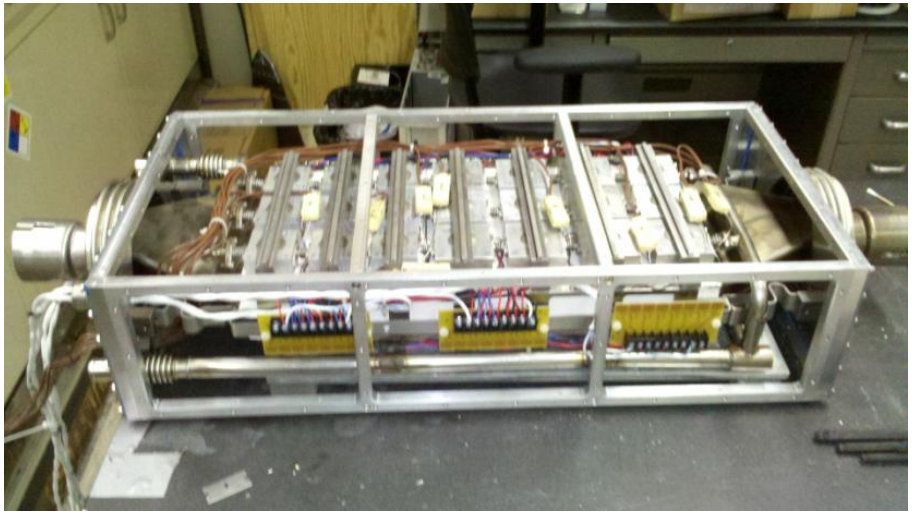


- Refined TEG design for final TEG #3
  - New joining process to heat exchanger: no leakage
  - New heat exchanger material: lower cost, light weight
  - New case design: easier assembly and gas tight seal
  - Wiring configuration for optimum TEG performance
- Assembled TEG #3 with skutterudites
- Test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



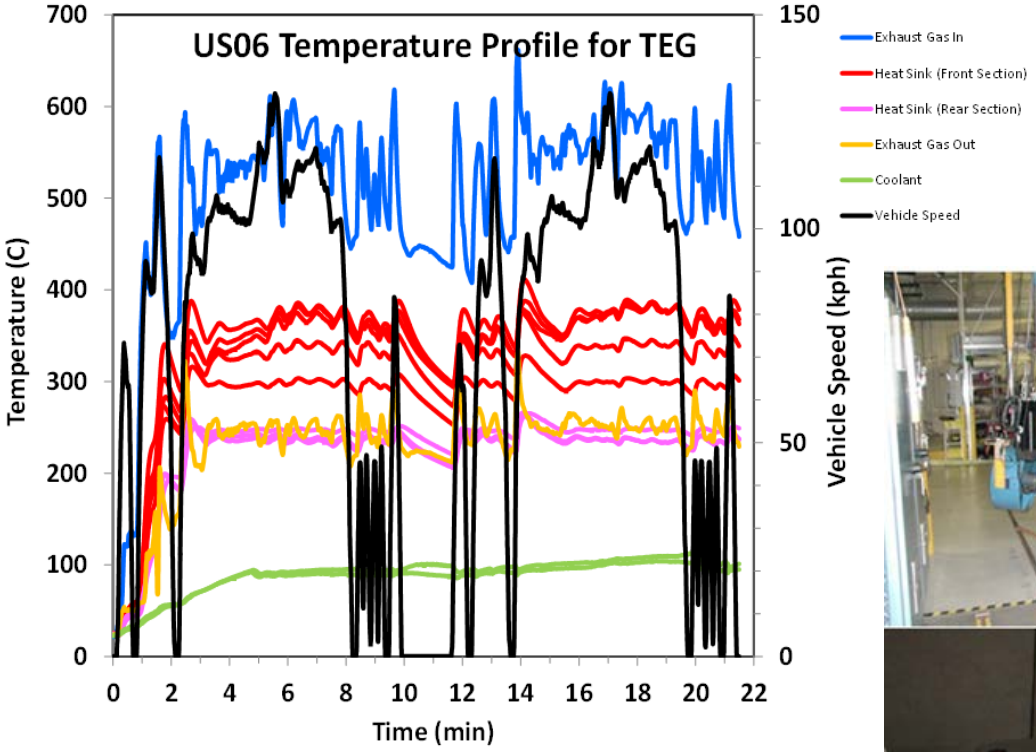
TE Generator Development

TEG #3:



TE Generator Development

TEG #3:

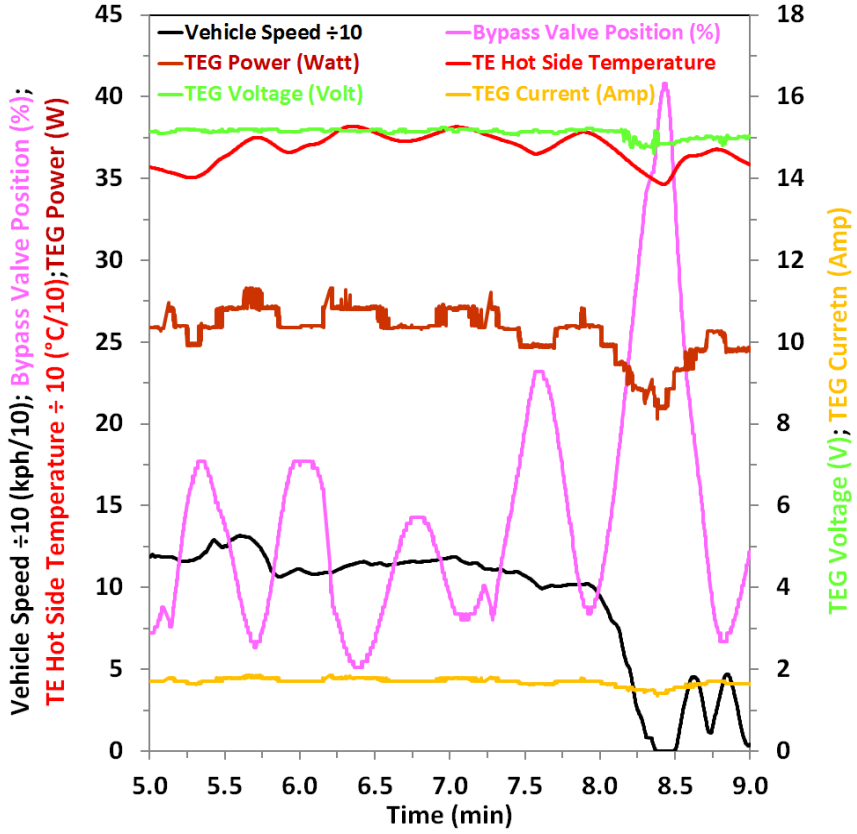


Temperature as a function of time for two sequential US06 drive cycle tests 0 – 10 min and 11.5 - 21.5 min

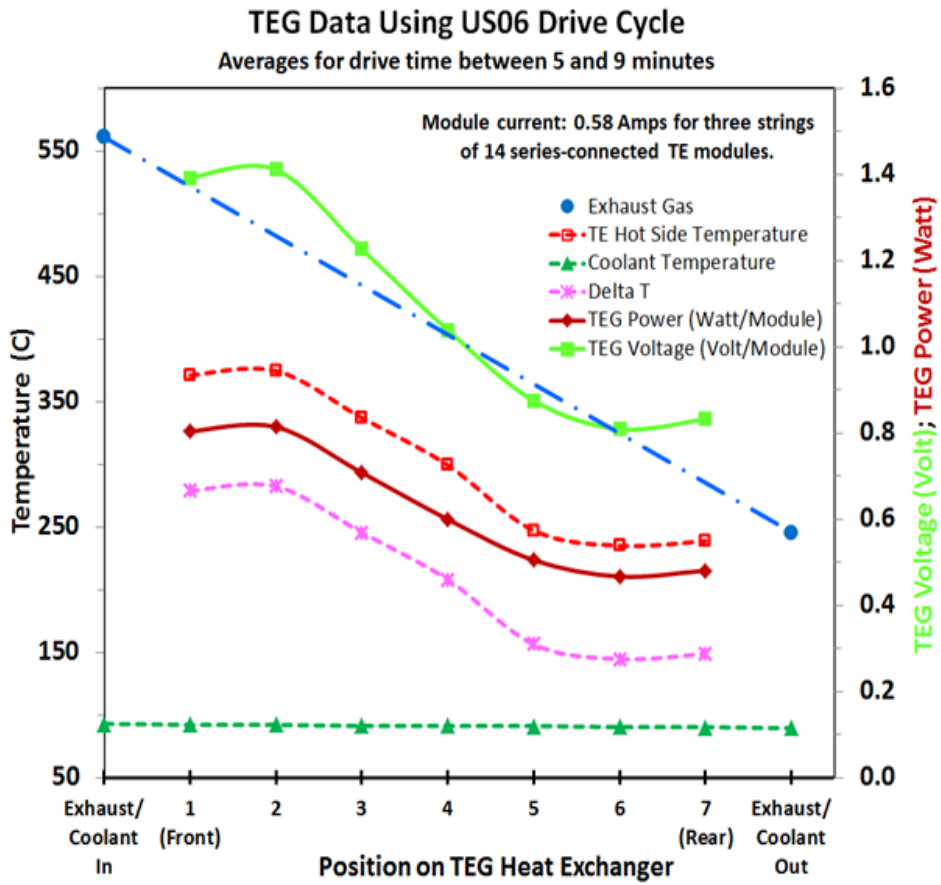
The demonstration vehicle in the dynamometer test facility

TE Generator Development

TEG #3:



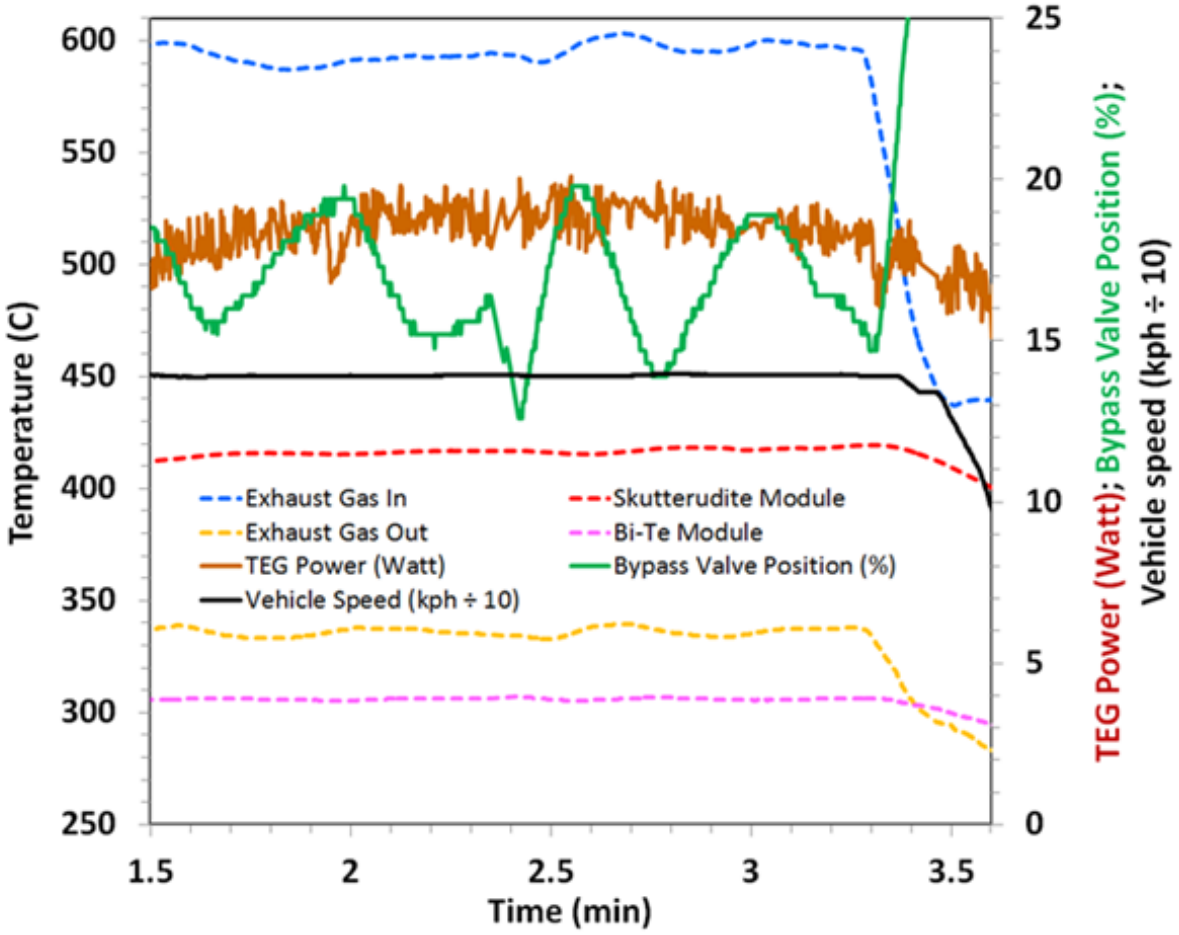
Test data for the 5 – 9 minute portion of the US06 drive cycle test



TE Generator Development

TEG #3:

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.

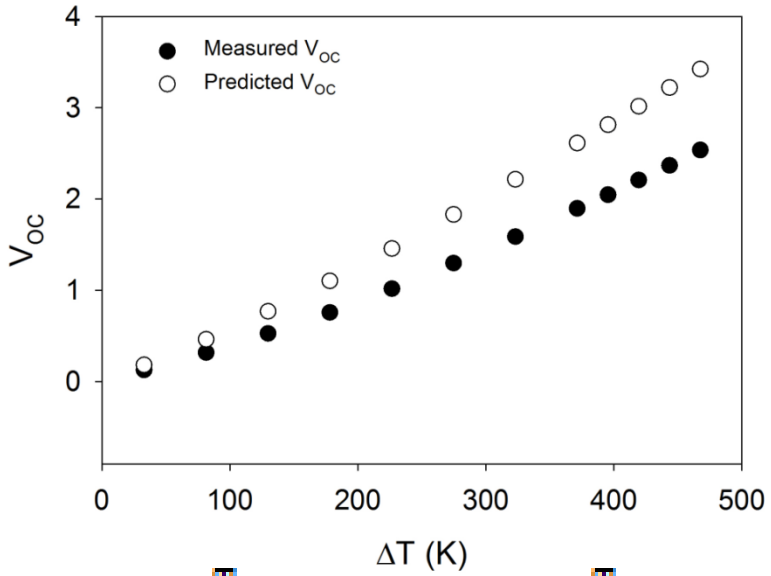


Estimated TEG #3 output with optimum temperature profile: T_c = 100°C
T_h = 600°C (skutterudites)
T_h = 250°C (Bi-Te)

P_{out} ~235 Watts

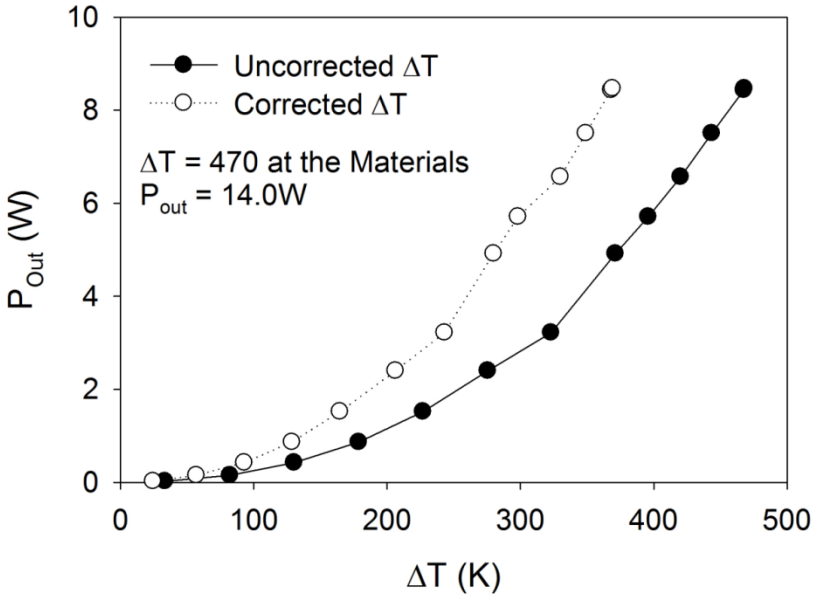
TE Generator Development

Skutterudite TE modules:



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

- 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



J. D König (Fraunhofer Institute)

- 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

Future Work

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 and ΔTs), Power Conditioning, Manufacturability, Production Scale-up
Budget: $13.5M Project $8M DOE Funds	**Project Lead:** General Motors Global R&D With: GM Powertrain, GM Energy Center **Partners:** Marlow, Purdue, Dana, Eberspaecher, JPL, Delphi, Magnequench, MSU, ORNL, BNL

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

  (1) Low cost, (2) Innovative TEG System Design, (3) Leverage innovative electrical & thermal management strategies, (4) Durable TE modules (4) TEG Manufacturability (5) Production Scale-up Plans

- Approach:
  - A team with unique skills and diverse areas of expertise
  - Include industrial partners who will be well-positioned for commercialization
  - Build on results from the previous TEG project

Future Work

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

Low cost vehicle controls & integration:

Design TEG system to be integral to vehicle systems

Summary

- TEG designed; prototypes fabricated & assembled; demo vehicle modified to include bypass system and vehicle controls & integration
- Prototype TEG #1 and TEG #2 (Bi-Te modules) tested on demo vehicle
- Improved & optimized new TE materials; synthesized large quantity of skutterudites for TE module fabrication and assembly into TEG #3
- TEG #3 performance assessed: optimized power output (57 Watts) extrapolated to over 235 Watts for optimized heat exchanger design and uniform temperature profile; or 425 Watts for further optimized ZTs, heat transfer coefficients, and thermal & electrical interfaces.
- Future work: US DOE awarded GM Global R&D $8M, 4-year contract for development of cost-effective TEG technology for automotive applications to increase fuel economy by 5% using the US06 drive cycle.