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Adaptable Nanotechnology for Cleaner, Energy-Efficient Products

Nanostructured High Temperature Bulk Thermoelectric Energy Conversion for Efficient Waste Heat Recovery

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GMZ Energy

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ACE082

Project Overview

Timeline

- Start: October 2011
- End: September 2015
- Percent complete - ~62%

Barriers

- Barriers addressed
  - Scale-up to practical device size
  - TE device/system packaging
  - Component/system durability

Budget

- Total Funding: $ 12.71M
  - DOE Share: $ 8.67M
  - Contractor Share: $ 3.39M
- Expenditure of Gov't funds
  - FY 13: $ 3.47 M (10/12-9/13)
  - FY 14: $ 1.58 M (10/13-3/14)

Partners

- Interactions/Collaborations
  - Robert Bosch, LLC
  - Oak Ridge National Laboratory
  - University of Houston
  - Boise State University
  - Honda Automotive
  - Eberspaecher North America
  - AVL North America
- Project Lead - GMZ Energy

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Relevance – Overall Objectives

- To demonstrate a robust, thermally cyclable thermoelectric exhaust waste heat recovery system that will provide at least a 5% fuel efficiency improvement for a light-duty vehicle platform
- To develop a 1 kW TEG for a Bradley Fighting Vehicle (TARDEC)

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Relevance – Objectives (3/13 – 3/14)

Materials & Modules

- Develop high-performance low-cost TE materials
- Scale-up the production of TE modules to pilot-scale manufacturing
- Improve the reliability and robustness of the TE devices and modules

Subsystem

- Design a TEG for integration into the Honda Accord vehicle platform
- Develop a final design for the 1 kW BFV TEG
- Fabricate a 200 W TEG prototype for the BFV application

Vehicle System

- Initiate vehicle modeling on Honda Accord test platform
- Develop detailed plan for the integration and testing of the TEG on-board the Honda Accord vehicle

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Project Milestones – 2013/2014

Date	Description	Status
12/12	Bi_2Te_3 Device, 4% efficiency	Completed
12/12	Half-Heusler device, 4% efficiency	Completed
12/12	Heat exchanger and system initial design	Completed
12/12	Initial vehicle model	Completed
12/12	Initial testing plan	Completed
12/12	Initial cost assessment	Completed
6/13	TARDEC design finalized	Completed
5/14	Half-Heusler device, >5% efficiency, <10% degradation after 100 thermal cycles	On Schedule
5/14	Final heat exchanger design for passenger vehicle	On Schedule
5/14	Fabricated thermoelectric and heat exchanger sub-systems for testing	Behind Schedule
5/14	Vehicle Model	Behind Schedule
5/14	Advanced Cost Analysis	On Schedule
5/14	Advanced Testing Plan	On Schedule
5/14	Delivery of 1 kW TARDEC TEG	On Schedule

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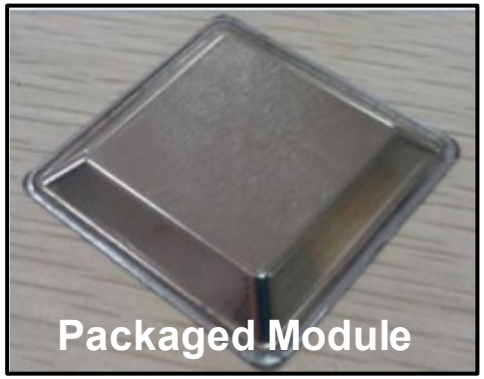
Project Approach

Materials Development

- Improve ZT and reduce cost of half-Heusler material via simulation and experimentation
- Scale-up the production of bulk TE material
- Nano-structured material

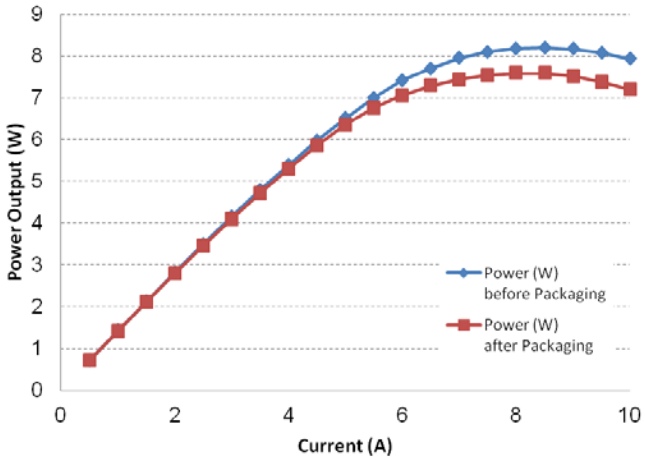


Thermoelectric Module

- Improve device architecture
- Hermetically sealed module

Advantages

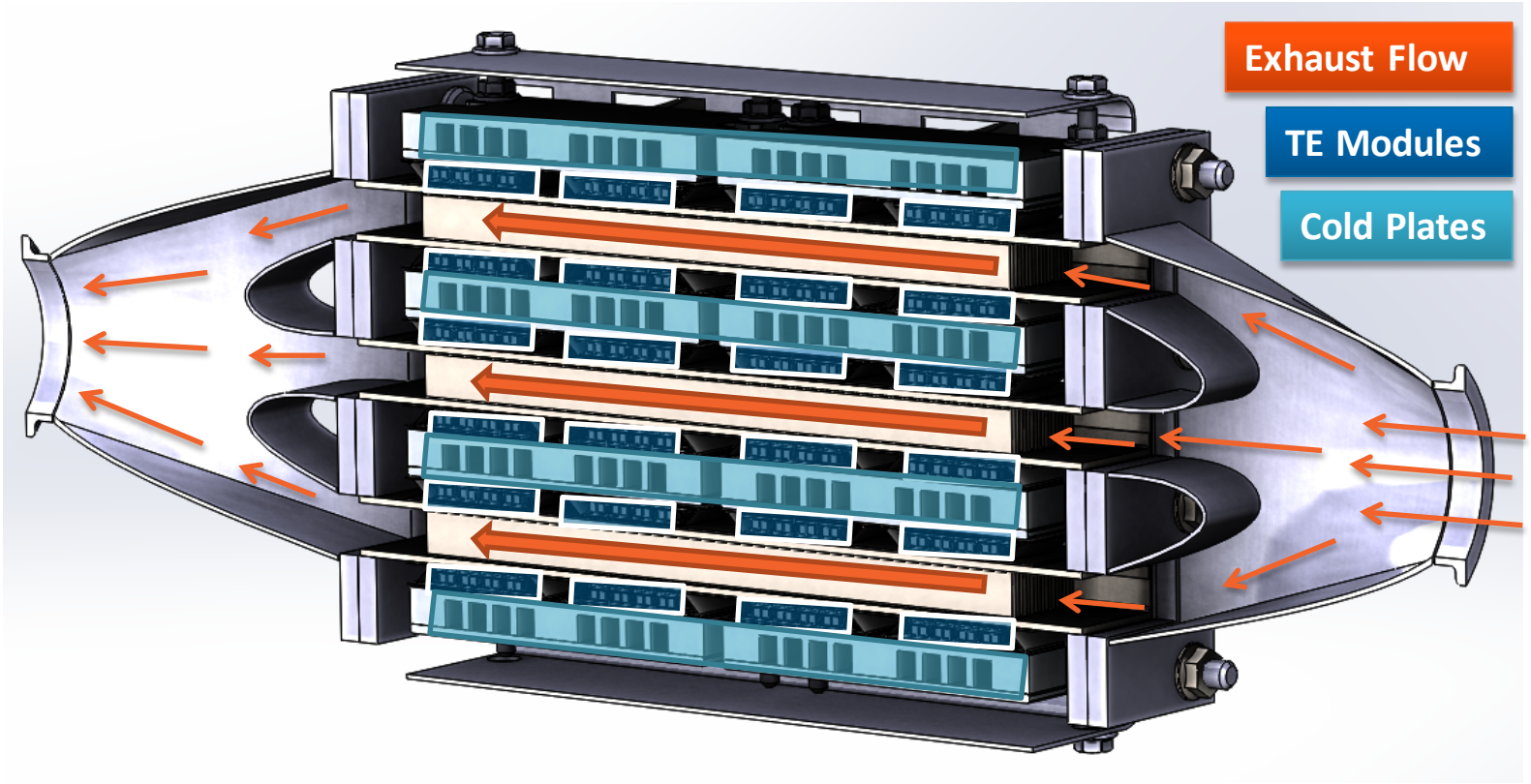
- Small size – 40 x 40 x 5 mm^3
- High power – 7.5 W at ΔT = 500 °C
- No metallization or encapsulation of legs
- Half-Heusler mechanical properties superior to competing materials (e.g. Skutterudites)
- Reliability
  - Devices: >1000 thermal cycles
  - Modules: >700 hours steady state
  - Modules: >150 hours vibration testing



Project Approach

Automotive TEG Design

- TEG optimized to maximize improvement in fuel economy
  - CFD simulations on TEG
- Mechanical design of TEG
- Vehicle modeling to assess the improvement in fuel economy
- Testing of TEG on engine dynamometer
- Installation of TEG in Honda Accord vehicle platform



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Project Approach – Milestones Progress

- **Half-Heusler device, >5% efficiency, <10% degradation after 100 thermal cycles (go/no-go)**
  - Devices tested for over 1000 thermal cycles with <1 % degradation

- **Deliver 1 kW TEG for BFV (TARDEC)**
  - 200 W modular component of 1 kW TEG successfully tested
  - 1 kW TEG under fabrication and on schedule
- **Vehicle Model**
  - Vehicle modeling commenced and initial model developed
- **Final heat exchanger design for passenger vehicle**
  - Heat exchanger design developed and near finalization
- **Fabricated thermoelectric and heat exchanger sub-systems for testing**
  - A single layer of the final TEG design is close to a design freeze
- **Advanced Cost Assessment Analysis**
  - An advanced cost analysis on the materials and module production has been performed
- **Advanced Testing Plan**
  - An advanced testing plan is under development

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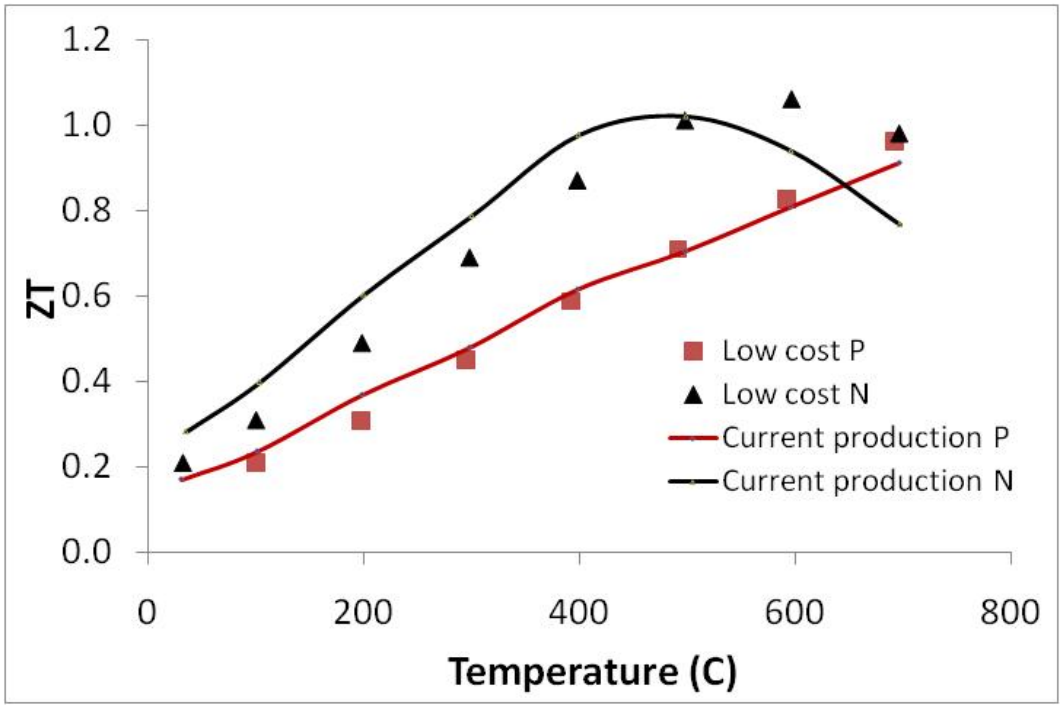
Accomplishment: Half-Heusler Cost Reduction

- Low-cost half-Heusler compositions developed
  - p-type material contains no Hafnium
  - n-type material contains reduced Hafnium content
- Material ZT comparable to previous composition



Composition	Current Production HH	Low Cost HH
Hf content	30% of total mass	8% of total mass
Peak ZT	1.0 (n), 0.9 (p)	1.0 (n), 0.95 (p)
Power density	5.5 W/cm^2	6 W/cm^2
*Cost/kg	$180	$75

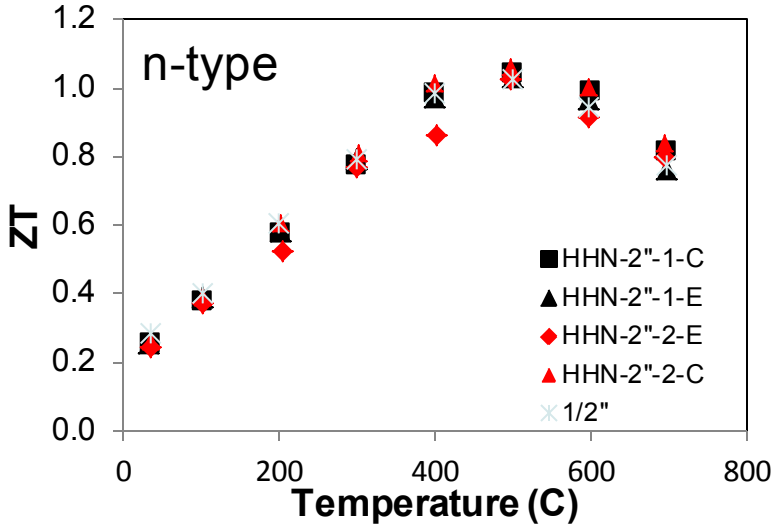
*Cost estimated using US Geological Survey data

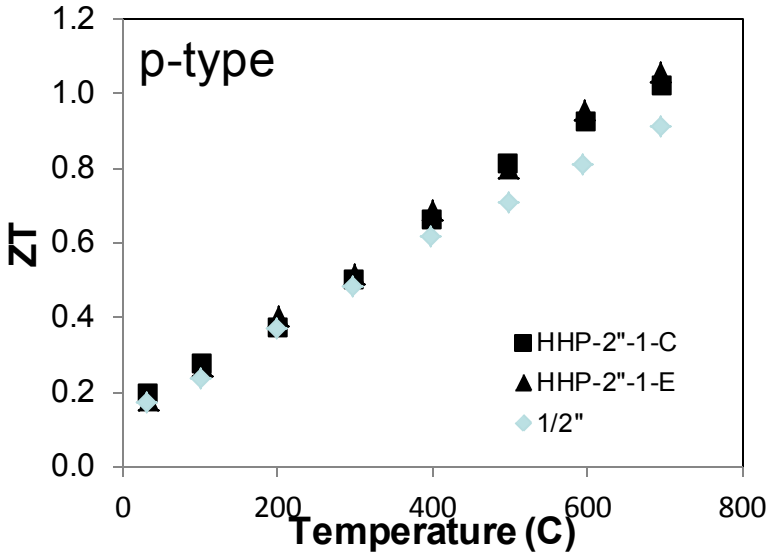
TE material cost reduced by >50 %

Accomplishments: Half-Heuslers Production Scale-up

- Disc diameter for hot pressing stage of materials fabrication process increased
  - Reduce cost
  - Step towards mass production
- TE properties of ½”, 1” and 2” disks are within experimental error
  - p-type peak ZT = 0.9 10%
  - n-type peak ZT = 1.0 10%
- Dicing yield improved from 48% (1/2”) to 68% (2”)
- Power density = 5.3 10% W/cm2

Increased materials scale of production, which ultimately decrease material cost

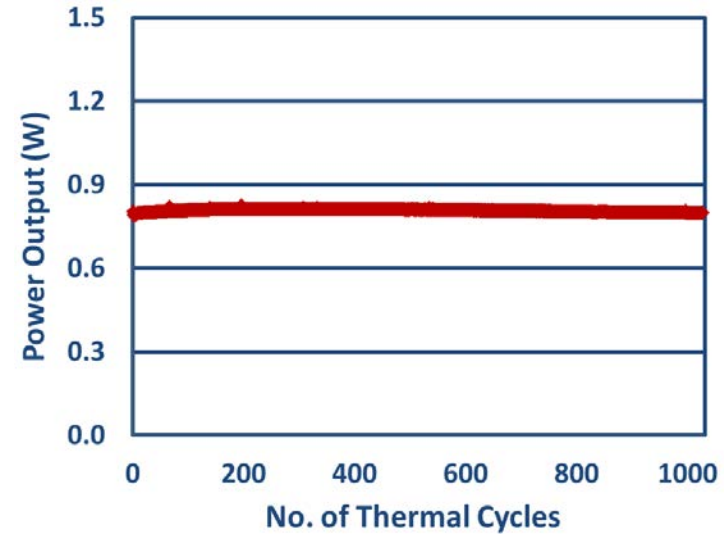


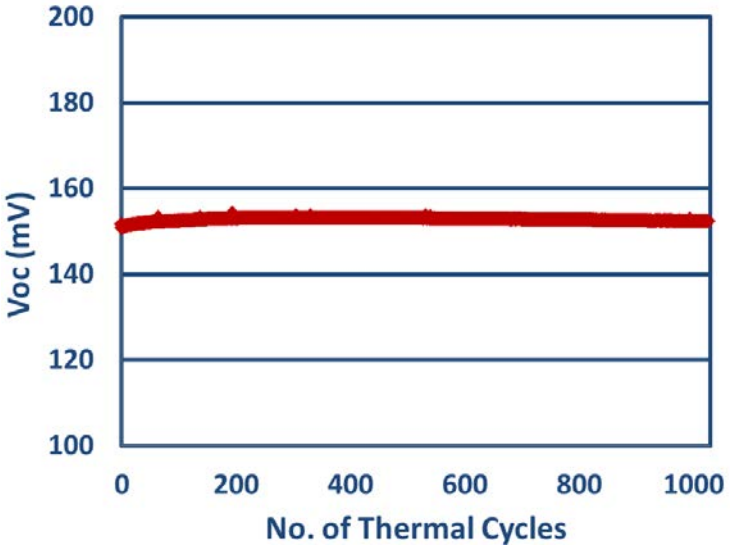


Accomplishments: Device Reliability

- >1000 thermal cycles performed
  - T_{hot}= 600 ºC – 200 ºC
  - T_{cold}= 100 ºC
- Power output change <1 % over 1000 thermal cycles
- V_{oc} change <1% over 1000 thermal cycles
- Resistance change ~1% over 1000 thermal cycles

Device subjected to >1000 thermal cycles with <1% performance degradation

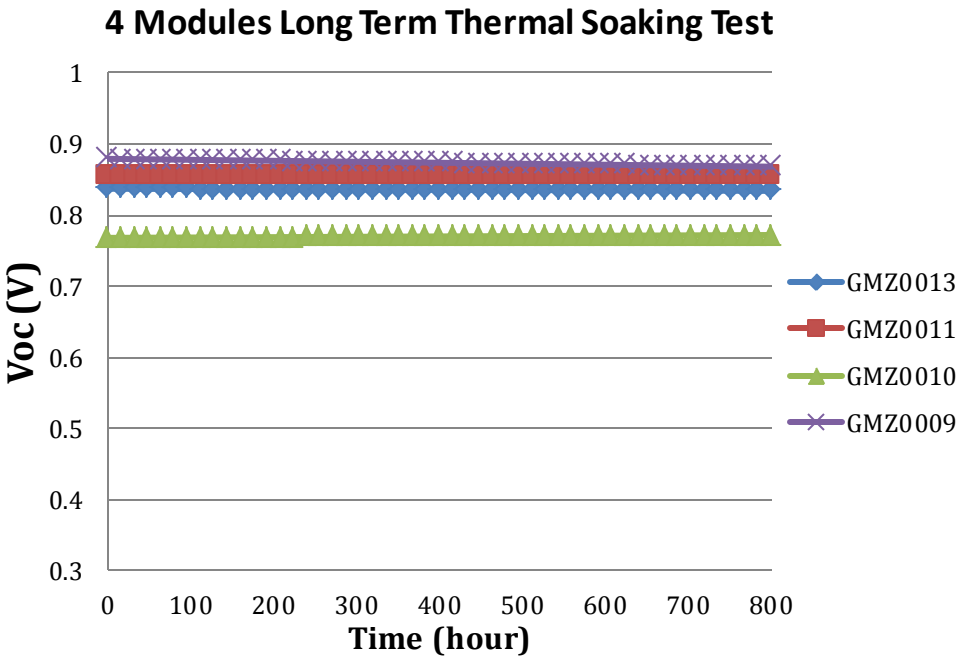


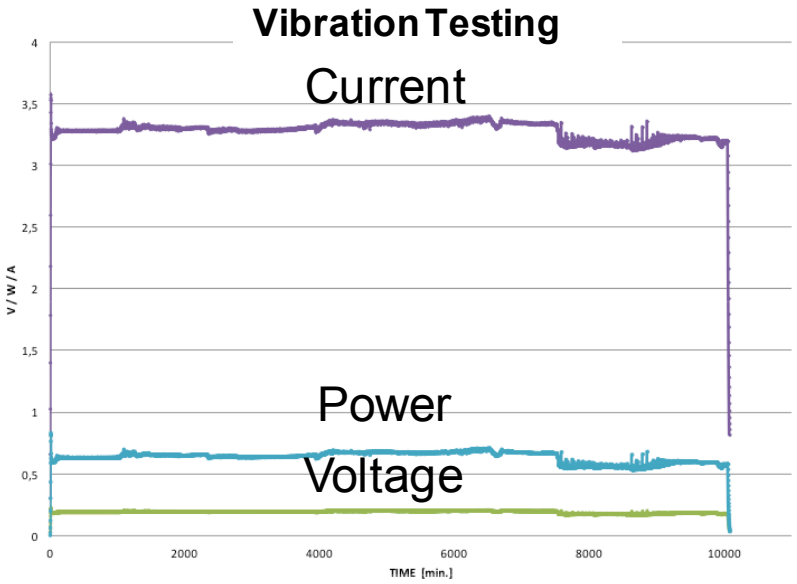


Accomplishments: Module Reliability Testing

- Multiple modules tested under steady-state conditions
  - T_{hot}=600 ºC
  - <2 % degradation in performance
- Modules subjected to vibrational testing at temperature of 300 C for over 150 hours
  - Automotive vibration testing protocol
  - Minimal degradation in performance

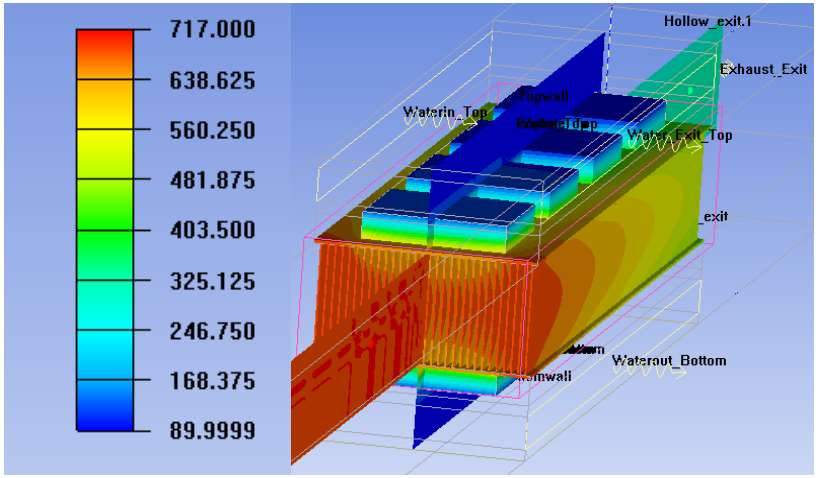
GMZ are fabricating mechanically strong and thermally stable modules

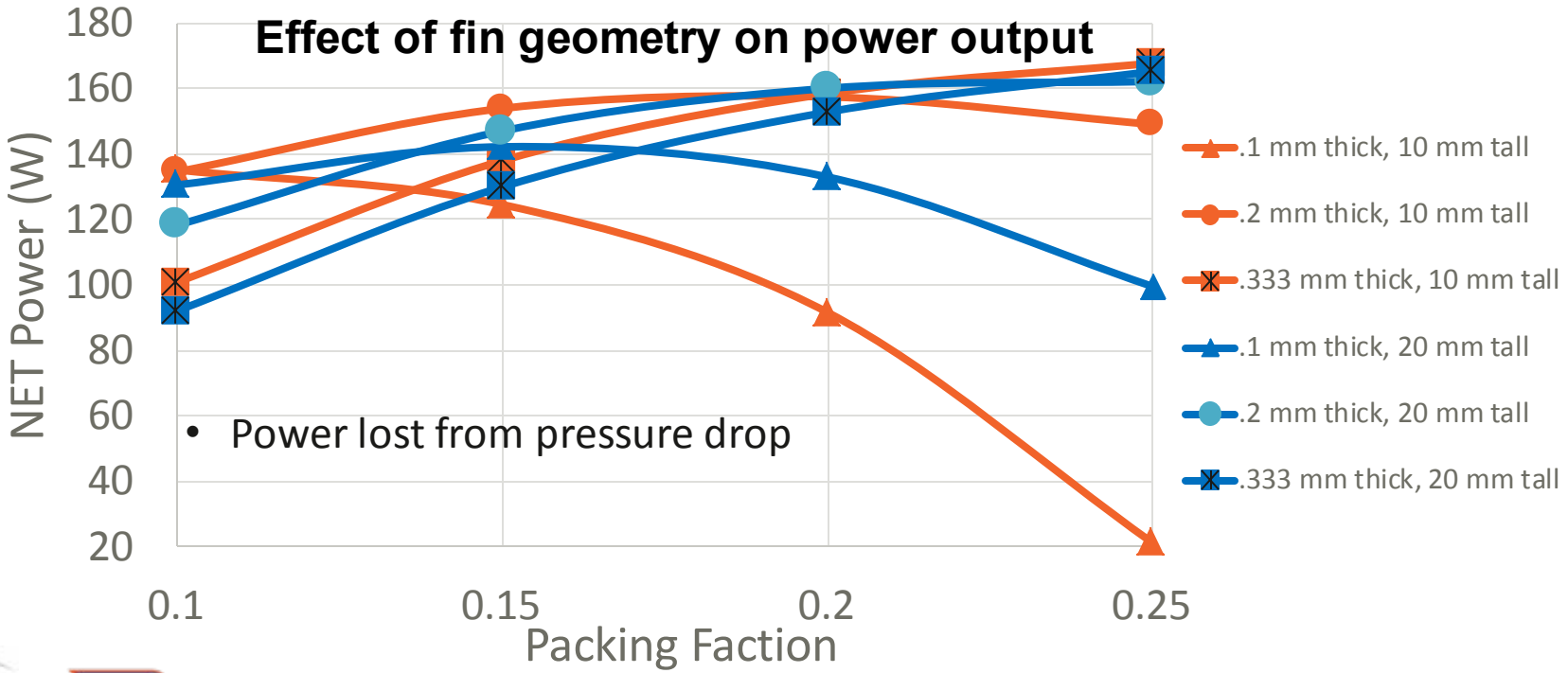




Accomplishment: Automotive TEG Design

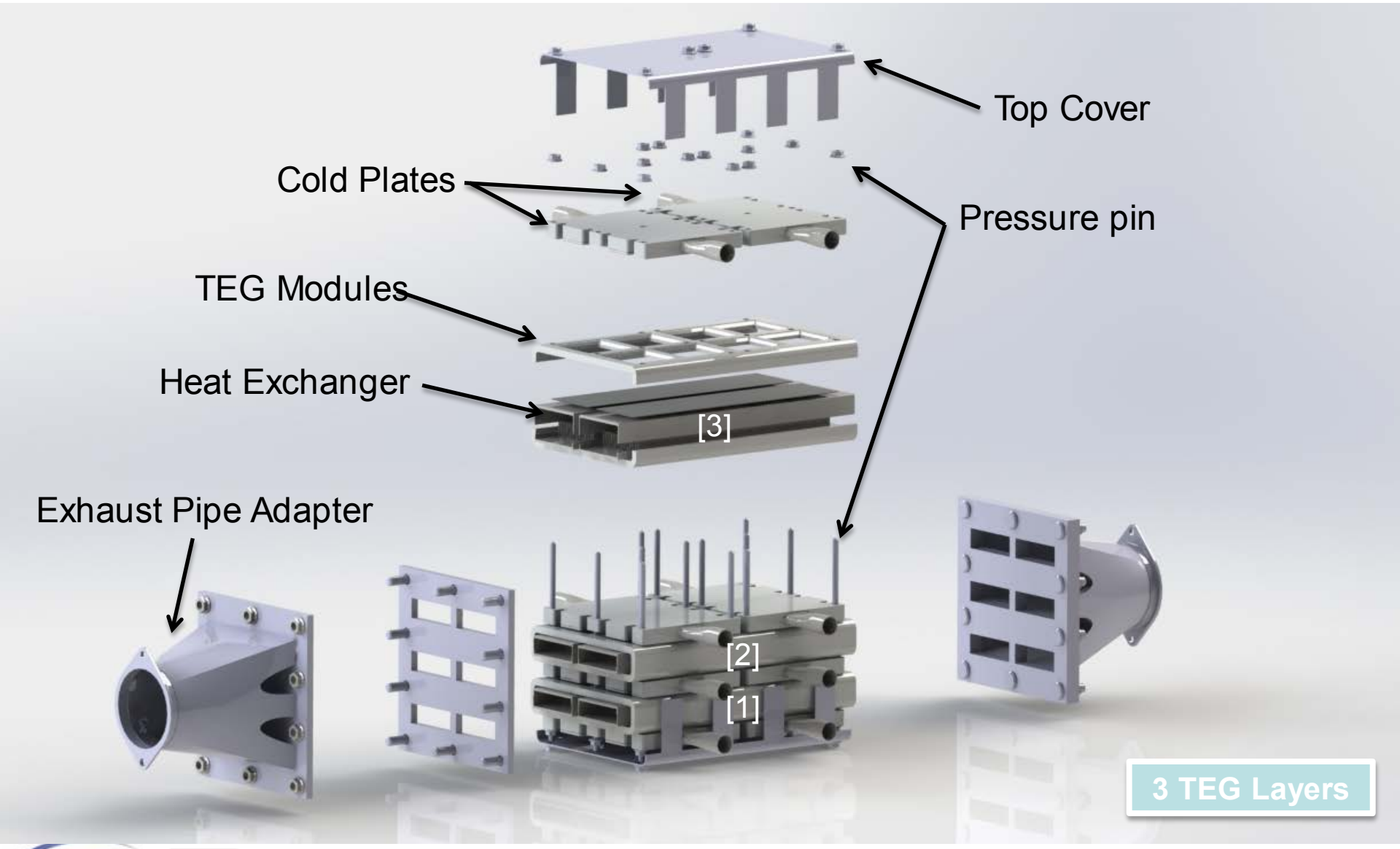
- Parametric CFD analysis performed
- Fin geometry optimized to maximize NET power output
- Single layer TEG under fabrication





Fin design optimized to maximize NET power output

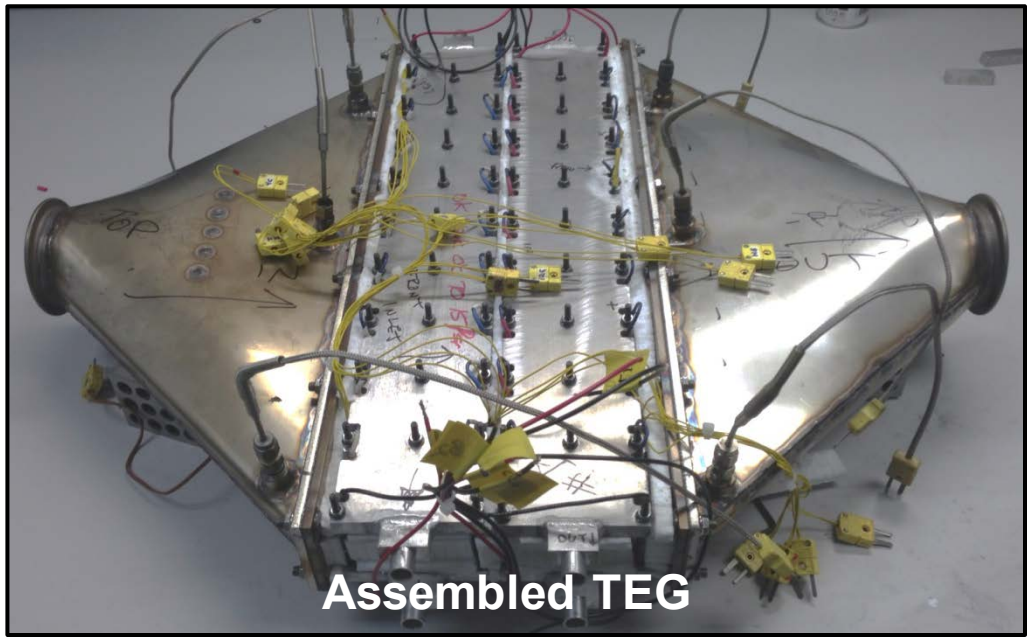
Accomplishment: Automotive TEG Design

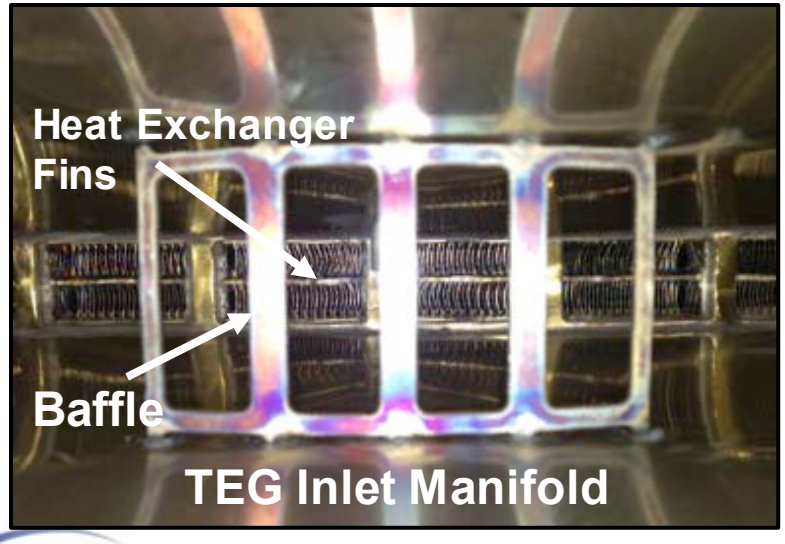


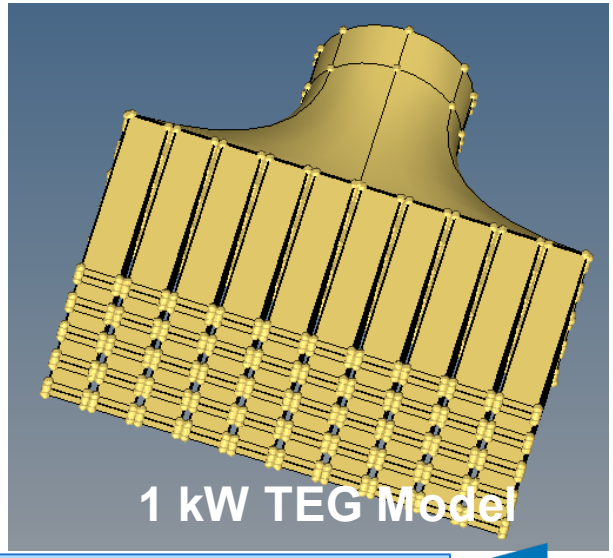
Detailed mechanical TEG design developed

Accomplishment: 200 W TARDEC TEG Tested

Modules (Model TG8-1.0)	80
Gas Inlet Temperature	550 °C
Gas Flow Rate	0.09 kg/s
Water Inlet Temperature	10 °C
Water Flow Rate	0.15 kg/s
TEG Power Output	**270 W**
Average Module Power	**3.4 W**





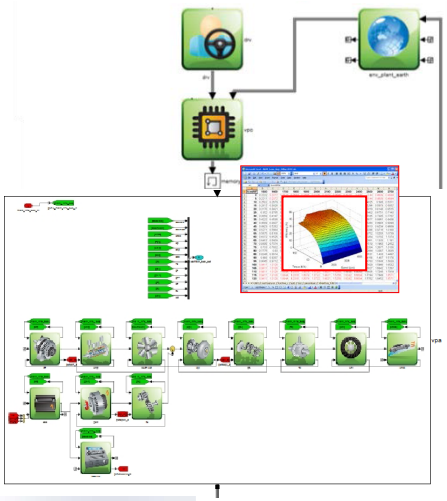


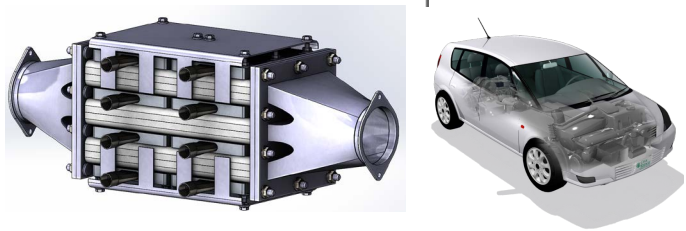
200 W TEG successfully fabricated and tested

Accomplishments: Vehicle Modeling

- ORNL is Applying Vehicle Systems Modeling Expertise to Determine Effect of TEG on Fuel Economy
- AUTONOMIE vehicle systems modeling platform provides a modular environment to investigate effect of TEG size for a given vehicle/engine pairing
  - 1D transient model of TEG is being adapted for use in AUTONOMIE (developed by Bosch in earlier phase of project)
  - Electric power generation and backpressure of TEG will feedback to alternator duty cycle and engine load
  - Guidance on alternator duty cycle being supplied by Honda
- Once complete, model will allow for parametric investigations of TEG/vehicle configuration
  - TEG size (# of modules) and heat exchanger arrangement
  - Quantify additional potential benefit of electrified accessories (water pump, oil pump)
  - Effect of moving to higher efficiency vehicle configurations
    - Down-speeded transmission
    - Downsized engine
  - Effect of using higher efficiency combustion strategies
    - Dilute combustion with EGR (decreased exhaust temperature)
- Baseline vehicle model on-track for completion in FY14

AUTONOMIE Simulink®/ Stateflow®





Modeled Fuel Economy TEG Performance

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OAK RIDGE National Laboratory

Responses to Previous Year Reviewers' Comments

- **Automotive partner**
  - "The reviewer noted that without a committed automotive partner, the approach must be very general. "
  - "The reviewer also noted that Honda is apparently also involved, but its contribution was not especially clear."

  Response: Honda are a committed supporter of this project. Their role includes providing technical data relating to the vehicle (e.g., exhaust conditions, control algorithms, and technical guidance on integration)

- **Scale-up to mass production**
  - "The element of scale-up and mass production is not as strong."
  - "It is important that the team recognized both the material challenges and engineering challenges of building TEGs for mass production, and that the Half- Heusler (HH) material has shown great potential."

  Response: Over the last year module production has been scaled-up to a pilot production level. Exploration of partners in increase to mass production is ongoing

- **Materials Performance**
  - "This project is focusing on Half-Heusler (HH) materials in designing its TEG system. These TE materials were shown to have ZT values of approximately 1.0 and less at relevant temperatures by the GMZ Energy group, and this does not represent high material performance as claimed by the GMZ Energy team. "
  - "The reviewer added that the team's presentation of the thermal cycling information was incomplete and did not give a strong sense on how the team's TE materials and modules will perform in the actual automotive waste energy recovery environments anticipated. In this automotive application, the devices could easily see nearly 1,000 cycles per year, and the 50 thermal cycles shown so far by this team is unimpressive. "

  Response: It is acknowledged that the ZT of HH are lower than some other TE materials such as SKU. However, the mechanical strength and the reliability of HH compensates for this deficit. This is demonstrated by testing of our TE devices over 1000 thermal cycles, and by the steady state thermal and vibrational testing of our modules

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Collaborations

- **GMZ** (Prime, Industry) – TE (materials, devices, integration and testing), heat exchangers, module integration and subsystem testing, prototype fabrication, automotive systems (electrical, vehicle models and testing)
- **Robert Bosch** (Sub, Industry) –TE materials (ZT improvement, simulations)
- **University of Houston** (Sub, University) – TE materials (ZT improvement, cost-reduction, thermal-mechanical testing)
- **Oak Ridge National Lab** (Sub, Federal Laboratory) – dynamometer testing and vehicle model
- **Boise State University** (Sub, University) – Heat exchanger and sub-system design
- **Honda** (Industry) –Provide technical data and input on vehicle operation, technical guidance on TEG integration and a commercial perspective on system cost and production volume

- **Eberspaecher** (Vendor, Industry) – Heat exchanger design and fabrication
- **AVL** (Vendor, Industry) – Vehicle integration

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Future Work

Materials

- Continue to develop material compositions to improve TE performance
- Further upscale the production of TE materials

Device and Modules

- Continue to improve the device and module architecture

Subsystem

- Finalize HEX design
  - Fabricate initial scaled-down version of TEG, which will influence final design
- Fabricate and test the 1 kW TEG for BFV (TARDEC)
- Refine cost analysis

Vehicle System

- Refine vehicle model with input from Honda
- Finalize vehicle testing plan
- Prepare vehicle for integration
- Test TEG on engine dynamometer and Honda Accord vehicle platform

Project Summary – Technical Accomplishments

Materials

- Developed new half-Heusler compositions that greatly reduce materials cost
- Half-Heusler materials production increased to pilot-scale production

Device and Module

- Measured <1% degradation in output power over 1000 thermal cycles for half-Heusler device
- Thermal stability and robustness of modules demonstrate through steady-state thermal, and vibrational testing

TEG Subsystem

- Developed a TEG design for a Honda Accord vehicle platform
- Fabricated a 1/5th scale TEG for TARDEC that demonstrated an actual power output of 270 W

Vehicle System

- Initiated vehicle modeling to determine effect of TEG on fuel economy