Development of Thermoelectric Technology for Automotive Waste Heat Recovery

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This presentation does not contain any proprietary or confidential information

Outline

- Purpose of Work
- Barriers
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- Accomplishments
- Publications/Patents
- Plans for Next Fiscal Year
- Summary

Purpose of Work

- Finalize material selections for the exhaust waste heat recovery device
- Complete the initial design for the exhaust waste heat recovery device with estimated performance
- Identify volume capable and cost effective manufacturing processes for thermoelectric modules

Barriers

- Need variety of higher ZT materials
- Need engineering design for modules, subsystems and integration
- Many thermoelectric material advances are recent, and not independently confirmed (several cases)
- Uncertainty in materials, modules, subsystems & vehicle integration cost, and OEM market size

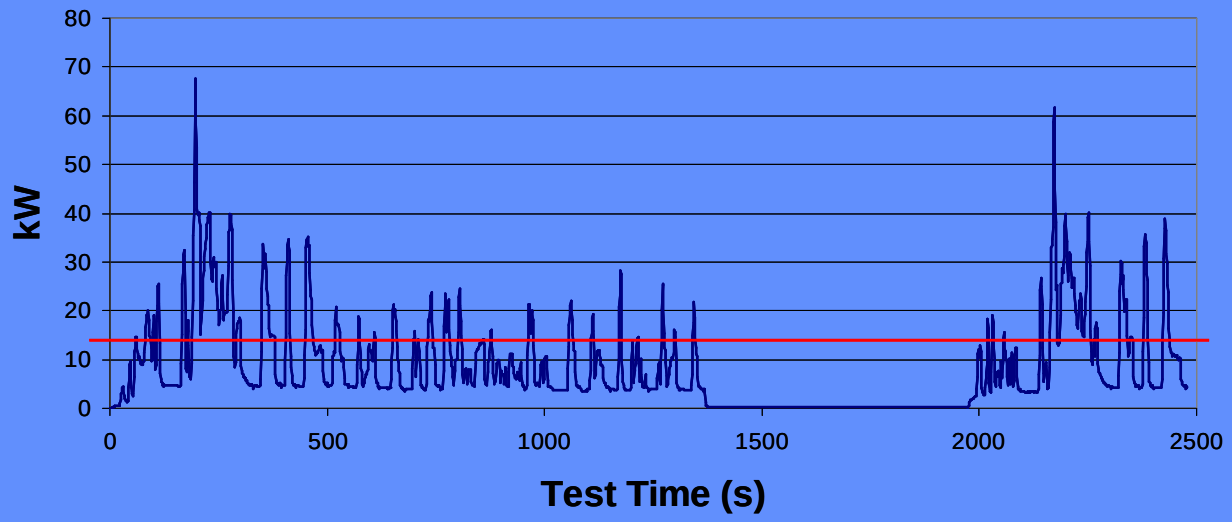
Approaches

- Need variety of higher ZT materials
  - skutterudite nano-composites, nano-grain PbTe, anti-fluorites, etc.
  - Patent application for novel TE materials
- Need engineering design for modules, subsystems and integration
  - Developed novel diffusion bonding and diffusion barrier materials for TE modules
  - Completed exhaust waste heat recovery devices design with estimated performance
  - Patent application on heat exchanger design
  - 2 Patent applications on subsystem vehicle integration design
- Many thermoelectric material advances are recent, and not independently confirmed
  - material properties validation at Oak Ridge (also UM, USF, and GM)
  - high temperature material thermo-mechanical properties characterization at Oak Ridge
  - monitoring the latest developments in the community
- Uncertainty in materials, modules, subsystems & vehicle integration cost, and OEM market size
  - established $/W as a program metric
  - low cost materials: misch-metal filled skutterudites, anti-fluorites
  - Identify a volume capable and cost effective TE module manufacturing process.

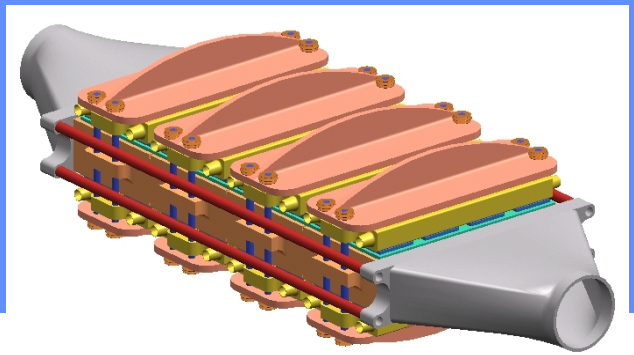
Vehicle Selection – Full Size Truck

- plenty of space for accommodating TE subsystem
- a lot of waste heat: exhaust and radiator
- current muffler: 610 x 310 x235 (mm)
- available envelope: 840 x 360 x 255 (mm)

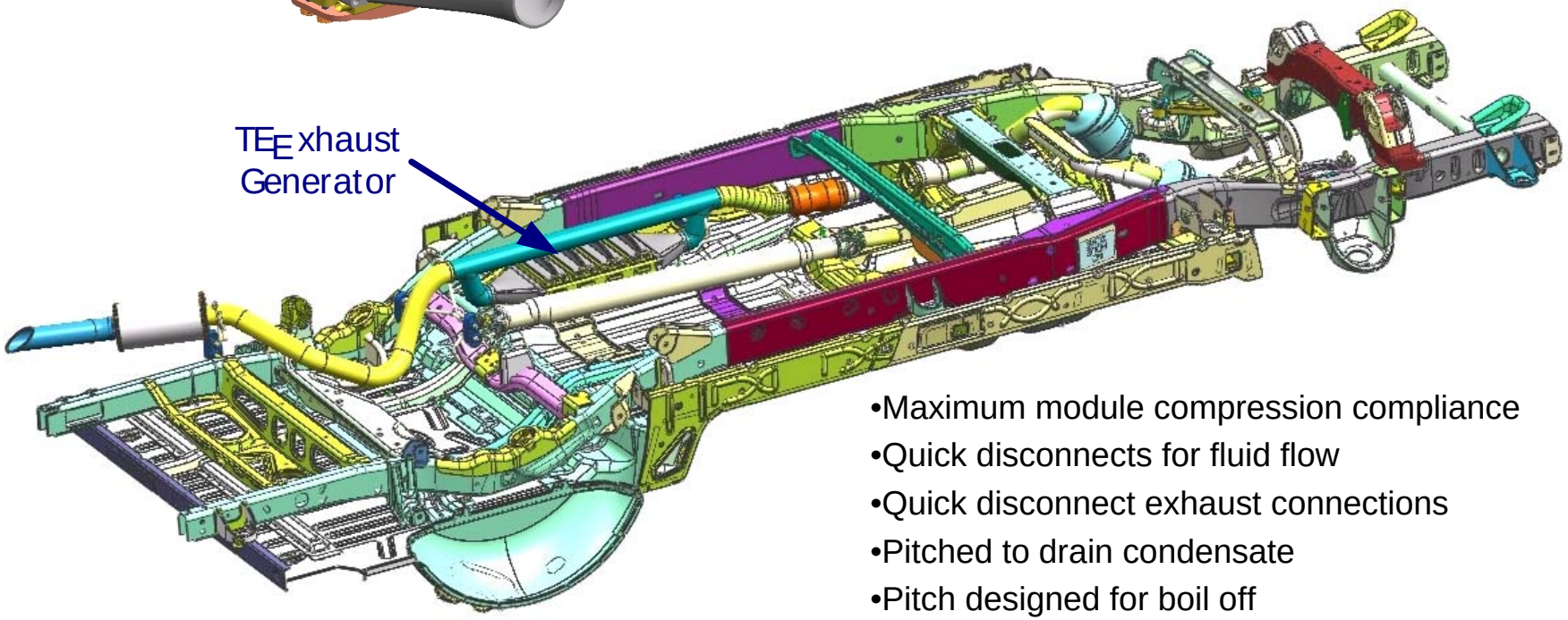
Typical Exhaust Heat -Ci ty Driving Cycle



Subsystem Design - Preliminary

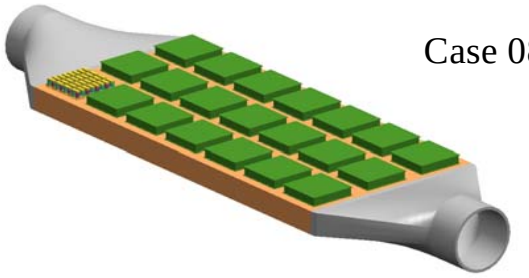


- Located where current muffler is placed; new muffler will be located behind the axle perpendicular to vehicle axis
- Axially compliant for thermal expansion mismatch

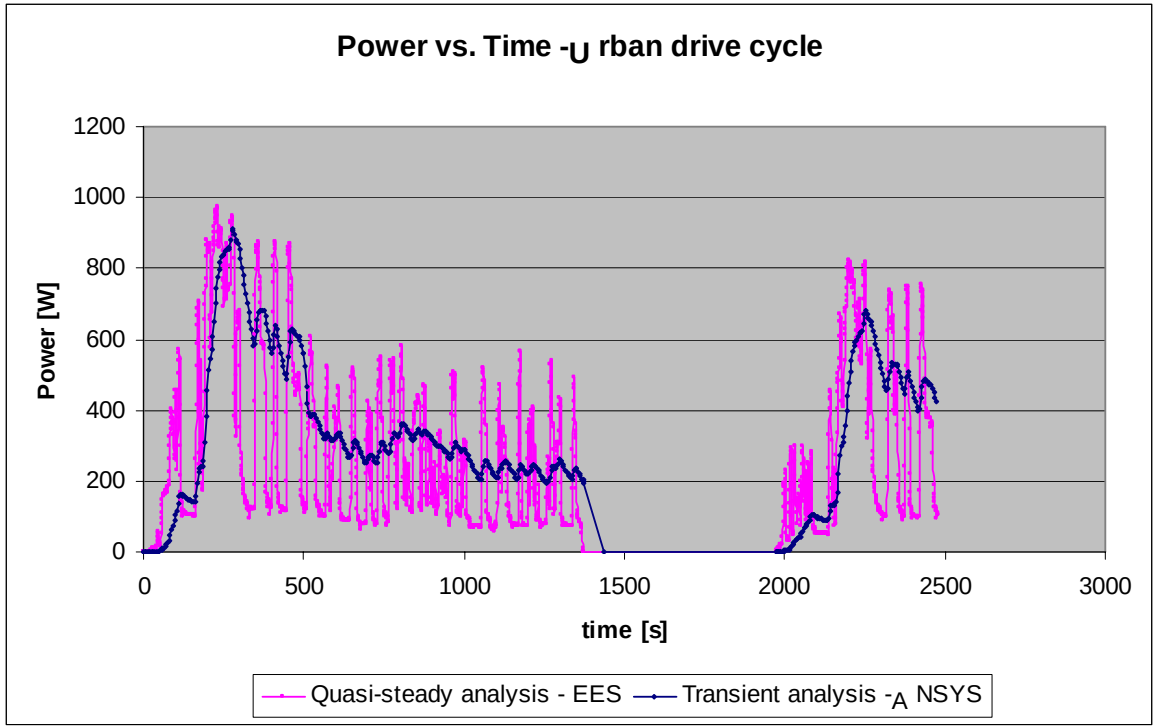


- Maximum module compression compliance
- Quick disconnects for fluid flow
- Quick disconnect exhaust connections
- Pitched to drain condensate
- Pitch designed for boil off
- Sealed electronics

Subsystem Performance

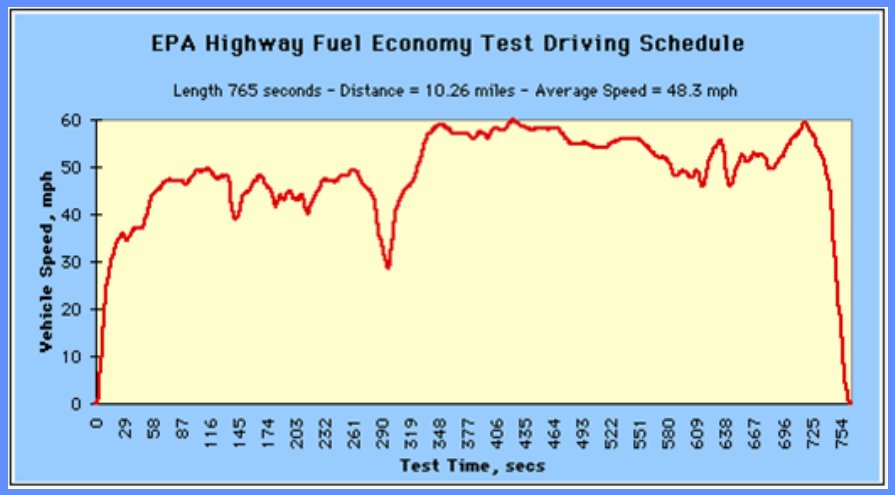


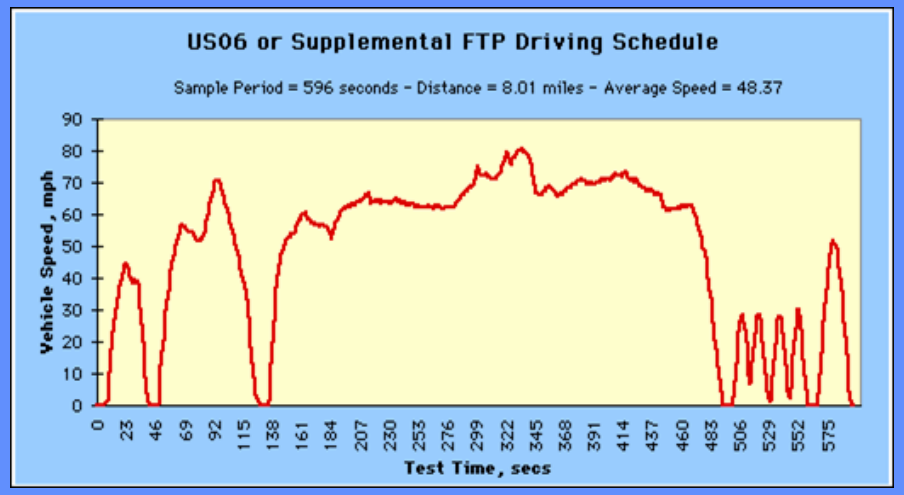
Case 08



- Average output ~ 350 W and max. output ~ 914 W
- 350 W equals the base electrical load of today's generator on FTP, potential composite Urban/Highway fuel economy improvement of ~ 3%
- We expect an additional ~ 1% fuel economy improvement through vehicle integration

Fuel Economy Test Schedules



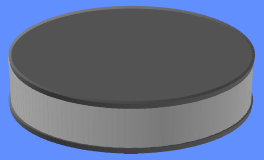


- FTP cycles represent very mild driving pattern (max. speed ~ 60 mph), therefore, does not accurately reflect real world scenario
- The US06 addresses this shortcoming with the FTP test cycles in the representation of aggressive, high speed and/or high acceleration driving behavior, and rapid speed fluctuations
- We expect a TE waste heat generator would generate > 350 W in real world

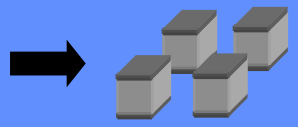
TE Subsystem Experiment Design

- 35 kW exhaust flow: 0-0.1kg/s mass flow rate between room temperature and 650 °C
- Closed-loop temperature / pressure control and computerized data acquisition

TE Module Construction

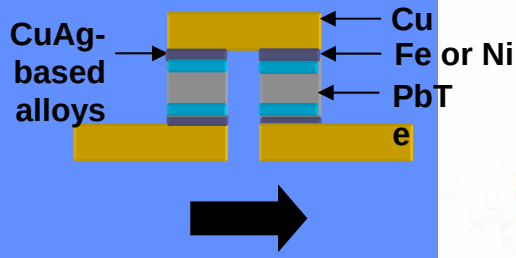


SPS PbTe with Fe or Ni barrier layers

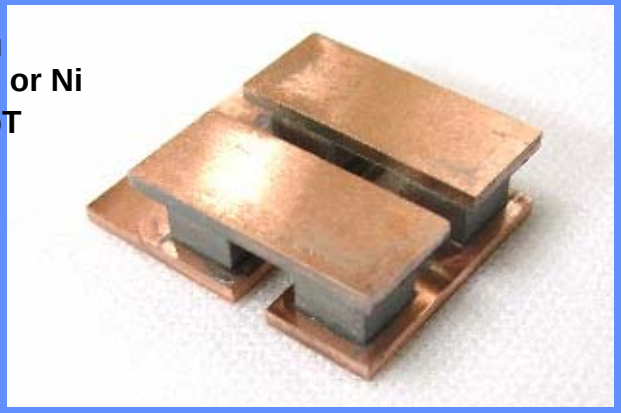


Singulation and surface preparation

Ag bearing Cu electrode

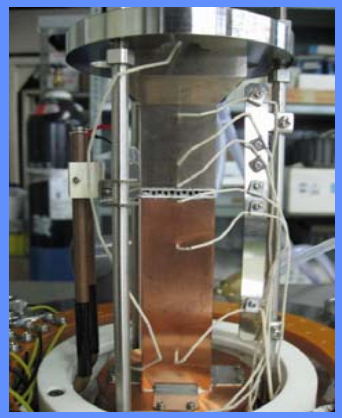


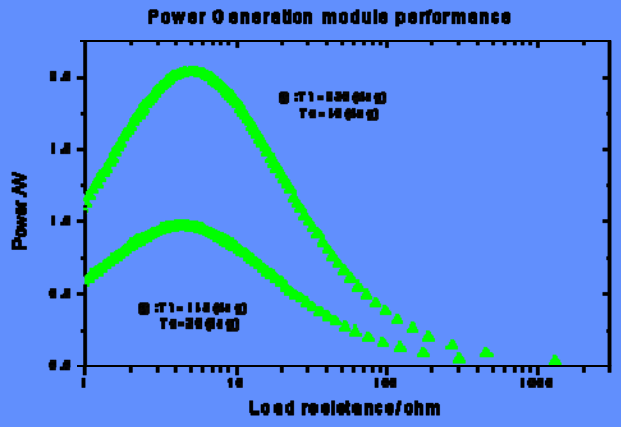
Brazing (in fixture)

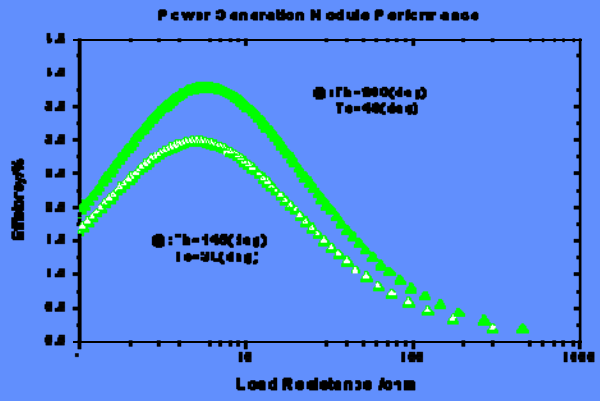


- 2x2 modules for initial process optimization
- Initial header-free design for manufacturability
- Ni diffusion barrier module with 600 °C braze; Fe diffusion barrier modules with 800 °C braze

TE Module Test

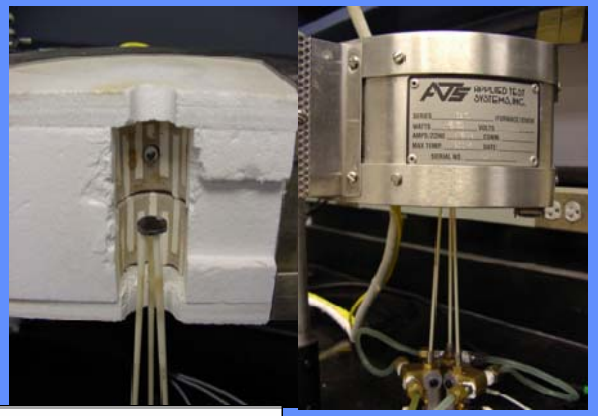


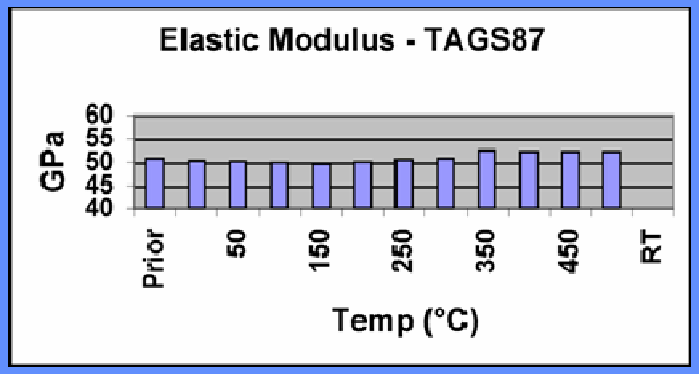


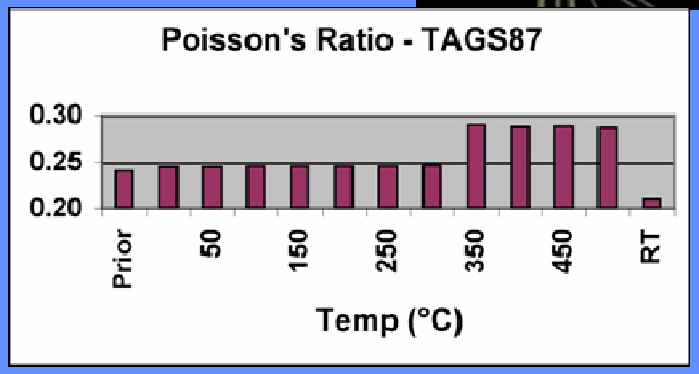


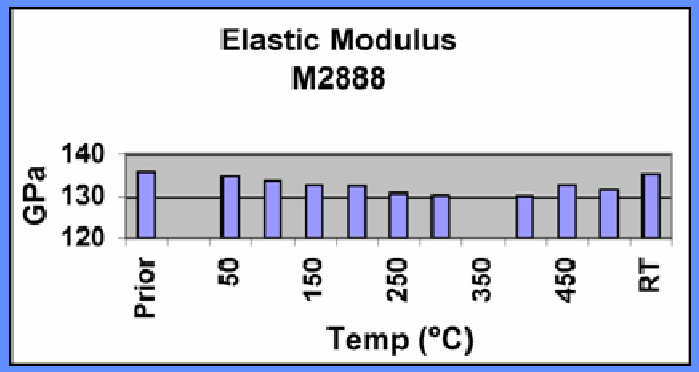
High Temperature Mechanical Properties Characterization

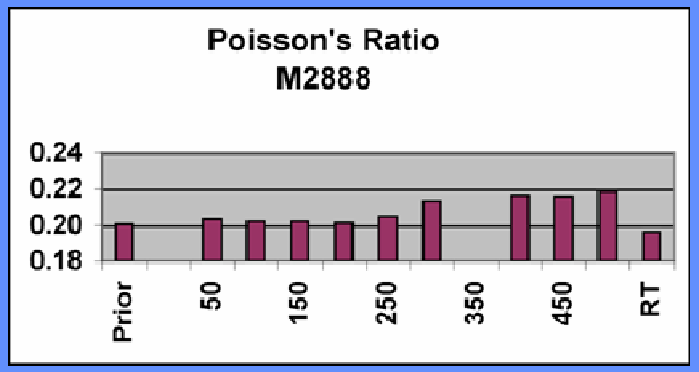
resonance ultrasound spectroscopy











Accomplishments

Materials Research

- Finalized material selections for exhaust waste heat recovery devices
- Established high temperature thermo-mechanical property data for materials of interest

Module & System Development

- Finalized design for exhaust waste heat recovery devices with estimated performance
- Identified volume capable and cost effective manufacturing processes for TE modules, the program team has invented a novel process for diffusion bonding, and novel materials as diffusion barriers for the TE modules
- Initiated TE module construction and preliminary measurement of module performance
- Completed subsystem testing facility
- Designed vehicle integration algorithms for TE waste heat subsystem

Publications, Presentations, and Patents

- 37 presentations & publications
- 4 patent applications on materials, heat exchanger, and vehicle integration

1. J. Yang, W. Zhang, S. Q. Bai, Z. Mei, and L. D. Chen, "Dual-frequency resonant phonon scattering in $Ba_xR_yCo_4Sb_{12}$ (R=La, Ce, and Sr)", Appl. Phys. Lett. **90**, 192111, 2007.
2. J. Yang, G. P. Meisner, C. J. Rawn, H. Wang, B. C. Chakoumakos, J. Martin, G. S. Nolas, B. L. Pedersen, and J. K. Stalick, "Low temperature transport and structural properties of misch-metal-filled skutterudites", Journal of Applied Physics **102**, 083702 (2007).
3. J. Yang, invited, Department of Mechanical Engineering, University of Colorado at Boulder, Boulder, CO, March 2007: "Materials for High-efficiency Automobiles".
4. J. Yang, invited, United States Council for Automotive Research, Southfield, MI, May 2007: "Thermoelectric Technology for Automotive Waste Heat Recovery".
5. J. Yang, invited, GM Global Electrical Council Meeting, Warren, MI, June 2007: "Cost of Automotive Electric Power and Thermoelectric Waste Heat Recovery Program".
6. J. Yang, 26th International Conference on Thermoelectrics, Jeju, Korea, June, 2007: "Dual-frequency resonant phonon scattering in $Ba_xR_yCo_4Sb_{12}$ (R=La, Ce, and Sr)".
7. J. Yang, invited, Electronic Structure and Functionality of Thermoelectric Materials Workshop, Reykjavik, Iceland, July 2007: "Thermoelectric Waste Heat Recovery Based Efficient Automobiles".
8. J. Yang, invited, Electronic Structure and Functionality of Thermoelectric Materials Workshop, Reykjavik, Iceland, July 2007: "Properties of Novel Skutterudites".
9. J. Yang, 2007 Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Detroit, MI, August 2007: "Developing Thermoelectric Technology for Automotive Waste Heat Recovery".
10. J. Yang, invited, Ceramics Division, National Institute of Standards and Technology, Gaithersburg, MD, October 2007: "Novel Materials for Thermoelectric Waste Heat Recovery Based Efficient Automobiles".
11. G. P. Meisner "Developing Thermoelectric Technology for Automotive Waste Heat Recovery", Direct Energy Conversion Review and Workshop, Vail, CO, August 20-23, 2007.
12. De Bock, P. and Novak, V., "An Efficiency Entitlement Study for Thermoelectric Generators," Proceedings of 2nd Energy Nanotechnology International Conference, ENIC2007-45040, Santa Clara, CA, September 5-7, 2007.
13. Anderson, T.A., De Bock, P., Jiang, J. and Nagarkar, K., "Development of a Thermoelectric Automotive Waste Heat Recovery Generator," Direct Energy Conversion Review and Workshop, Vail, CO, August 20-23, 2007.
14. Shi X., Zhou Z., Zhang W., Chen L. D., Yang J., and Uher C., "Solid Solubility of Ir and Rh at the Co Site of Skutterudites", *J. Appl., Phys.*, 101, 123525 (2007).
15. Shi X., Zhang W., Chen L. D., Yang J., and Uher C., "Theoretical Study of the Filling Fraction Limits for Impurities in $CoSb_3$", *Phys. Rev. B*, 75, 235208 (2007).
16. Shi X., Chen L. D., Bai S. Q., Huang X. Y., Zhao X. Y., Yao Q., and Uher C., "Influence of Fullerene Dispersion on High Temperature Thermoelectric Properties of $Ba_xCo_4Sb_{12}$-based Composites", *J. Appl. Phys.* (in press)
17. Shi X., Zhang W., Chen L. D., Yang J., and Uher C., "Ab Initio Study on the Filling Fraction Limits for Impurities in $CoSb_3$: II. Thermodynamic Analysis" (submitted to *Acta Mater.*).
18. Shi X., Kong H., Yang J., Salvador J. R., Wang H., and Uher C., "Low Thermal Conductivity and High Thermoelectric Figure of Merit in *n*-type $Ba_xYb_yCo_4Sb_{12}$ Double-Filled Skutterudites" (to be submitted to *Appl. Phys. Lett.*).
19. Uher C., Shi X., and Kong H., "Filled $Ir_xCo_{1-x}Sb_3$-based Skutterudite Solid Solutions", *Proceedings of the 26th International Conference on Thermoelectrics* (2007) (in press).
20. J H. Wang, W.D. Porter, Jihui Yang and G. Meisner, "High Temperature Thermoelectric Properties of Misch-metal-filled Skutterudites", submitted to Applied Physics Letter, September 2007.
21. H. Wang, "Thermal Conductivity and Figure of Merit of Bulk Thermoelectric Materials", Invited Talk at MS&T06: MS & T 2006 Cincinnati OH, Oct. 16-19, 2006.
22. H. Wang, J. Yang, W.D. Porter, and G.P. Meisner, "Thermoelectric Properties of Misch-metal-filled Skutterudites from 300K to 800K", International Conference of Thermoelectrics (ICT2007) Jeju Island, South Korea, June4-7 2007.
23. H. Wang, "Thermoelectrics Power Generation: A Review of DOE Waste Heat Recovery Program at ORNL", invited talk at Material Science and Engineering Department, Seoul National University, Seoul, South Korea, June 11m 2007.
24. H. Wang, J. Yang and G.S. Nolas, "Low Thermal Conductivity Bulk Thermoelectrics", Thermal Conductivity 29, June 25-27, Birmingham AL 2007.
25. Timothy P. Hogan, H. Wang, Chun-I Wu, Joseph Sootsman, Duck-Young Chung, Mercouri G. Kanatzidis, Edward Timm, Harold Schock, "Transport Properties of Bulk Nanostructured Thermoelectric Materials", invited talk, Thermal Conductivity 29, June 25-27, Birmingham AL 2007.
26. Jane Y. Howe, H. Wang, and Jihui Yang, " Structure of the Polycrystalline Thermoelectric Bulk Material AgPbmSbTe2+m", Microscopy and Microanalysis 2007 in Ft. Lauderdale, Florida, USA, August 5-9, pp. 852-853, 2007.
27. G.S. Nolas, D. Wang and M. Beekman, 'Transport properties of polycrystalline Mg2Si1-ySby', Phys. Rev. B (in press).
28. J. Martin, G.S. Nolas, H. Wang and J. Yang, 'Thermoelectric properties of silicon-germanium type I clathrates', J. Appl. Phys. (in press).
29. G.S. Nolas, D. Wang and X. Lin, 'Synthesis and low temperature transport properties of Mg2Ge1-ySby', Physica Status Solidi (Rapid Research Letter) 1, 223 (2007).
30. J. Martin, G.S. Nolas, W. Zhang and L. Chen 'PbTe nanocomposites synthesized from PbTe nanocrystals', Appl. Phys. Lett. 90, 222112 (2007).
31. D. Wang and G.S. Nolas, "Thermoelectric Properties of mix-crystals of Mg2E (E=Si, Ge)-Mg3Sb2", Proc. Adv. Elec. Ceramics 28(8), 185 (2007).
32. J. Martin, D. Wang and G.S. Nolas, "Synthesis and characterization of nanocrystalline chalcogenides" Proc. Adv. Elec. Ceramics 28(8), 221 (2007).
33. G.S. Nolas, given an Invited presentation to The International Conference on New Quantum Phenomena in Skutterudite and Related Systems (Skutterudite2007), Kobe, Japan, Sept 26 – 30, 2007 (due to scheduling conflicts, I was not able to attend this conference).
34. G.S. Nolas, 'Fundamental study of inorganic clathrates', Invited, Max Planck Institute for Chemical Physics of Solids, Dresden, Germany, August 7, 2007.
35. G.S. Nolas, 'Novel Materials for Energy Technology", Invited, University of Kentucky Physics Seminar, Lexington, KT, March 21, 2007.
36. G.S. Nolas, 'Overview and new directions in bulk materials research for thermoelectric power generation applications', Invited, Presented at the 31st International Cocoa Beach Conference & Exposition on Advanced Ceramics and Composites, Daytona, FL, January 21, 2007.
37. J. Martin, W. Zhang, L. Chen and G.S. Nolas, "Synthesis and Characterization of Nanocomposite Chalcogenides", presented at the American Physical Society, Denver, CO, March 7, 2007.

Activities for Next Fiscal Year

- Initial production ready TE modules for lab and application-based testing
- Finalize TE waste heat recovery subsystem design
- Subsystem prototype construction
- Search for higher ZT materials
- Optimize mechanical properties of materials selected

Summary

- Exhaust waste heat recovery system can generate an average of ~ 350 W for the FTP cycles, which corresponds to ~ 3% fuel economy improvement
- We expect the output would be higher in real world scenario
- Advanced vehicle integration could result in additional fuel economy improvement
- Strategy for achieving 10% fuel economy improvement includes discovery of materials with higher ZT values, optimized module design, and advanced vehicle integration methods.