Energy Efficient HVAC system for Distributed Cooling/Heating with Thermoelectric Devices

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General Motors - Vehicle Engineering Center

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Project ID # ACE048 Rev 0

Overview

Timeline

- Start date – November 2009
- End date – March 31, 2014
- Percent complete – 80%

Budget

- Total funding: $9,097,593
  - – Government* share: $4,548,796 (DOE obligations thru March 2013: $4,359,946)
  - – Contractor share: $4,548,797
- Expenditure of Gov't funds in
  - – FY12: $ 1,703,847 (10/11-9/12)
  - – FY13: $ 418,540 (10/12-2/13)
  - – Total: $ 3,652,375 (thru 2/13)

* Thank you to the California Energy Commission and the DOE Vehicle Technologies Program for their support and funding of this project

Barriers & Targets

- – Early stage of development for thermoelectric (TE) automotive HVAC devices (reliability concern)
- – TE coefficient of performance > 1.3 to cool and > 2.3 to heat
- – Reduce HVAC energy by > 30%

Partners

- Interactions / collaborations
  - – *University of California – Berkeley:* Thermal Comfort testing & modeling
  - – *Delphi Thermal Systems:* HVAC component development
  - – *Marlow Industries*: Thermoelectric module development
  - – *University of Nevada – Las Vegas*: Thermoelectric materials research
  - – *Oak Ridge National Lab*: Thermoelectric materials research
- Project lead – *GM*

Relevance

Primary DOE goal to use TE HVAC for distributed cooling/heating

- Reduce by at least 30% of the “billions of gallons” the fuel used to maintain occupant comfort through the localized use of TE technology while maintaining occupant comfort and safety.
- Develop TE HVAC components with a coefficient of performance > 1.3 for cooling and > 2.3 for heating, then integrate & test as a reliable system in an eAssist Buick LaCrosse and an extended range electric Chevrolet Volt.
- Develop a Thermal Comfort model and CAE tool to predict the occupant physiological response to localized heating and cooling based on human subject testing – Key to balance and speed the execution of a stratified thermal systems.

Secondary DOE solicitation goal to improve efficiency of TE generators

- Develop new thermoelectric materials for engine waste heat recovery applications (to provide power TE HVAC climate loads)

Approach and Strategy

- **Task 2.1 Applied Research**: Develop Thermal Comfort model of human responses to potential locations for distributed heating & cooling (UCB, GM)
- **Task 2.2 Exploratory Development**: Develop the initial prototype HVAC components and evaluate on bench & demo vehicle (Milestone – Identify initial set of locations for distributed system) (Delphi, Faurecia, Marlow, GM)

- **Task 2.3 Advanced Development**: Develop final prototype HVAC components and evaluate on bench – show efficiency target achievable (Milestone – 1&2. Identify final set of locations for distributed system and Estimate Coefficient of Performance for TE components) (Delphi, Intrepid, GM)
- **Task 2.4 Engineering Development**: Integrate final local and central HVAC components into demo vehicle and optimize system performance (Delphi, Faurecia, GM)
- **Waste Heat Recovery Research**: Develop new thermoelectric generator material systems (concurrent with tasks 2.1 - 2.4) to *produce electrical power* for the TE HVAC climatic loads (UNLV, ORNL, GM)

Progress - Milestones

2012 Through Quarter 1 2013

- Vendor Intrepid Control Systems contracted to integrate control of TE systems (TE components and power controllers) into the vehicle interface – Feb 2012
- Faurecia* thermal seating integrated into eAssist Buick LaCrosse – March 2012
- Completed a significant milestone in the development of the PC-based Computer-Aided Engineering (CAE) tool; HVAC air velocity and temperature distributions for the final standard vehicle types were captured and coded – Jan 2013
- Team finalized the design and test for the Volt coolant TE heat exchanger including a unique coolant valve configuration
- Volt test data showed the new coolant TE heater with COP≈ 1 for extremely low temperature (large ΔT) and achieved COP > 2.3 during initial warm-up – Dec 2012
- Plans have been made to modify the TE devices developed for the Lacrosse and adapt them for application in the Volt demonstration vehicle – Jan 2013
- For the waste heat recovery objectives, the team investigated melt-spun skutterudite materials and modules, and they also evaluated diffusion barriers for skutterudites – August 2012.

* Faurecia is not involved in TE material development or TE integration in the LaCrosse build

Technical Accomplishments

- eAssist Buick LaCrosse planned for final demonstration. Vehicle and occupants have been modeled for virtual thermal comfort evaluation.

Power Saving under Standard Test Condition (85Fx55%x500watts) with the initial prototype components achieved a **29.5% reduction**. Further vehicle integration enhancements will provide additional savings in the final system.

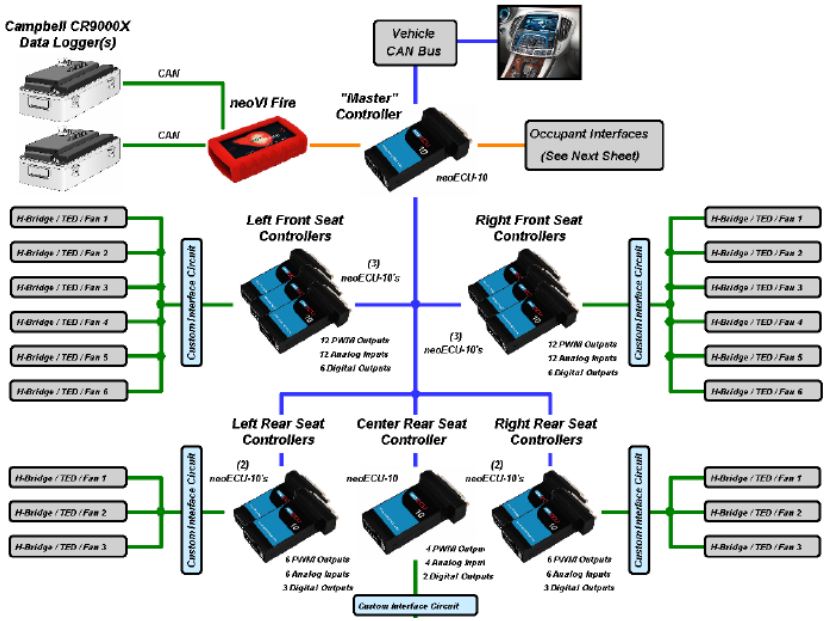
TE devices are well-suited to provide **localized low-flow spot cooling (and heating)** in synergy with a traditional HVAC system, in contrast to a conventional distributed HVAC that picks up too much heat to be effective.

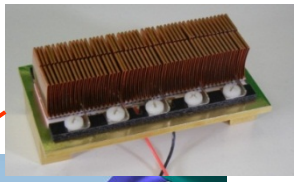
TE COP during the test:

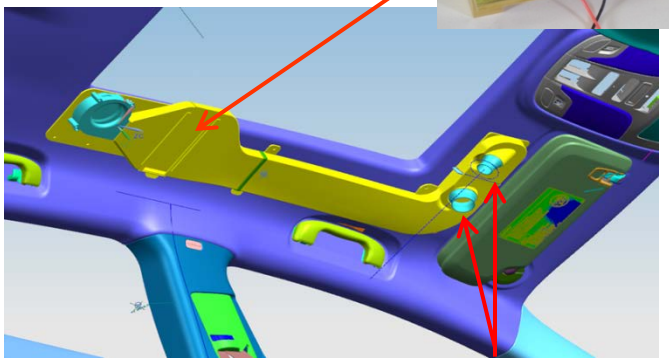
- COP > 1.4 for cooling
- COP > 2.4 for heating

Technical Accomplishments (cont.)

Intrepid CS/Delphi Integration of Controls

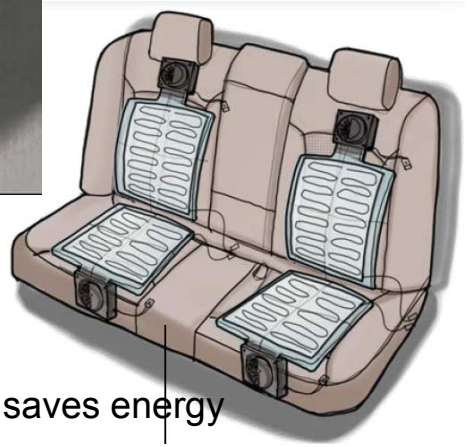






Overhead TE Localized Outlets effective

PC CAE Tool Updated



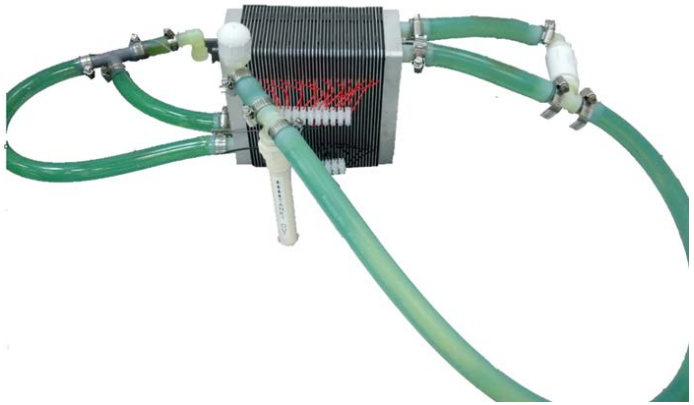
Faurecia thermal seating saves energy

Technical Accomplishments (cont.)

- All four liquid inlets to the Volt TE coolant heater moved to one face
- Heat pump mode is used at vehicle start and when occasional engine operation maintains a ΔT in the system below 30°C
- Steady State EV operation requires a unity coolant routing (no heat pump) due to excessive reverse heat flow in heat pump mode where ΔT > 40°C

Figure 1 Gamma Prototype TEC Plate Exchanger

Coolant valve logic is planned to obtain unity COP. Using parallel flow in both heat exchanger loops to effectively have one heat exchanger loop. Cold side coolant pump is turned off



Due to its high cost and limited 5kW COP advantage (COP ~1 for **EV** steady state < 0 °C ambient use), this design is not commercially viable in present form.

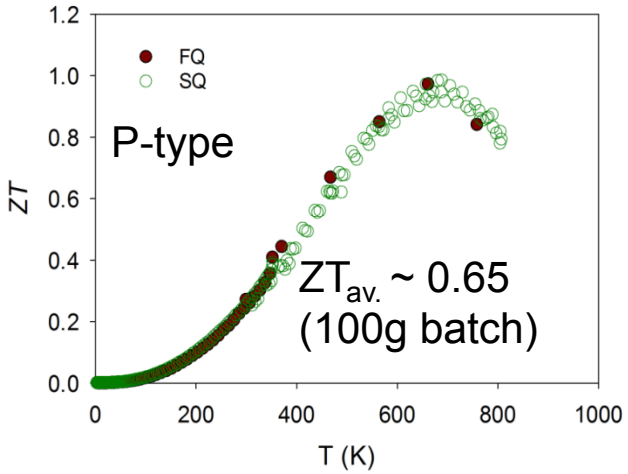
Technical Accomplishment (cont.)

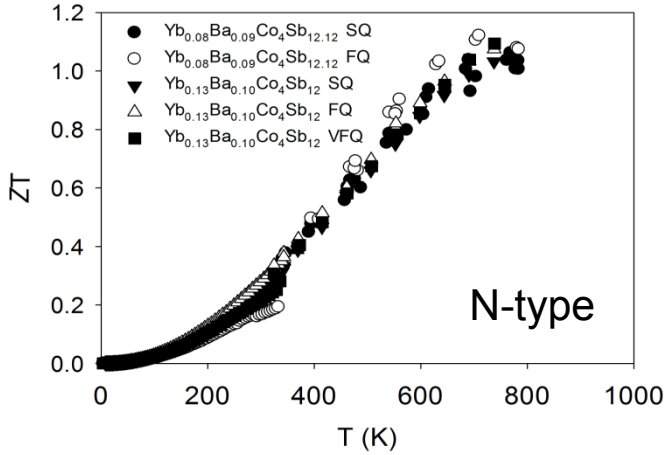
Waste Heat Recovery Material Research:

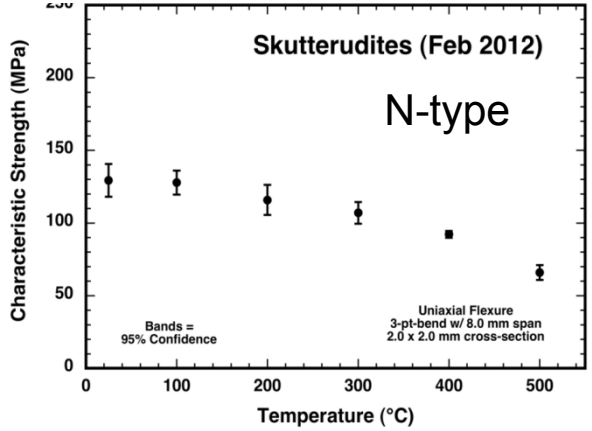
Materials Development efforts

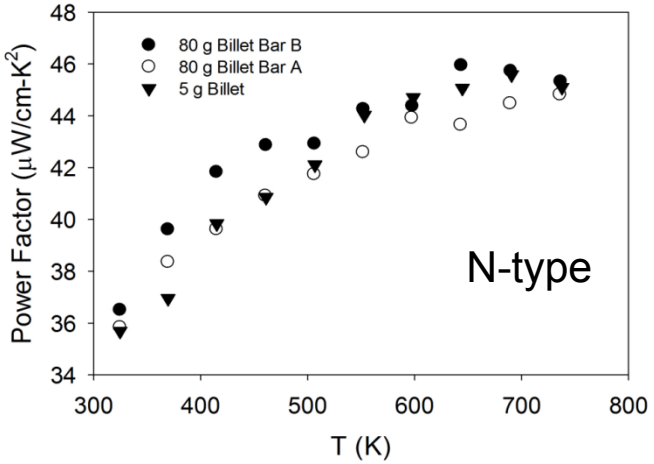
(1) High through-put synthesis method development (Molycorp, Marlow, and GM).

(2) Evaluation of High Temperature Transport and Mechanical Properties of Materials produced by melt spinning combined with spark plasma sinter. (GM, Marlow, ORNL)









Melt spinning combined with spark plasma sintering results in materials with good thermoelectric performance.

The process is scalable with good thermoelectric performance observed in transport bars cut from large billets

Technical Accomplishment (cont.)

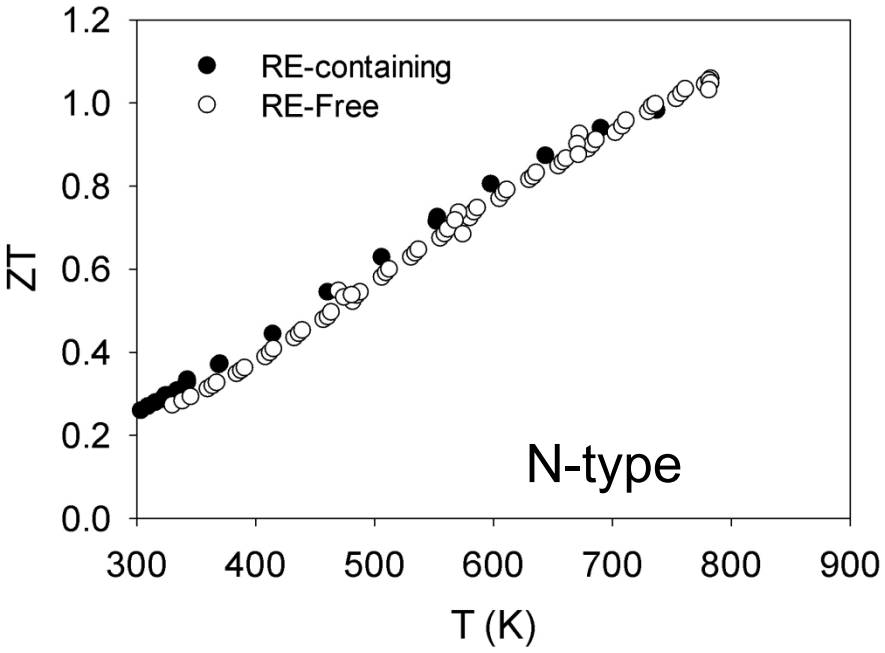
Waste Heat Recovery Material Research:

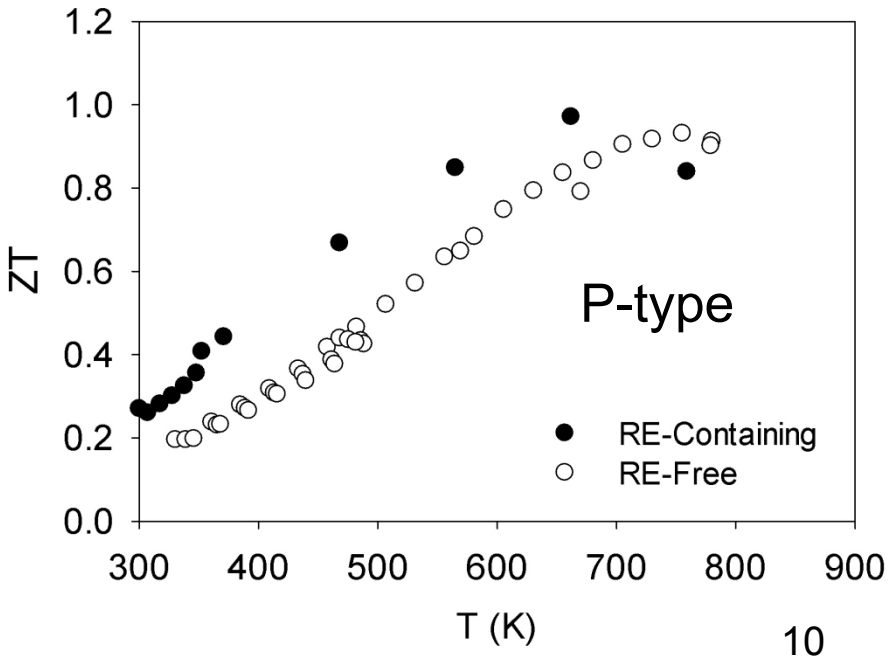
Materials Development efforts

(1) Investigated rare-earth (RE) free formulations of n- and p- type skutterudites. (GM and ORNL)

(2) Have established RE-free n-type materials perform just as well as RE-containing formulations when both are prepared by melt spinning combined with spark plasma sintering.

(3) Comparable performance for p-type RE-free formulations. RE-free materials are also made by melt spinning combined with spark plasma sintering.





Technical Accomplishments

Waste Heat Recovery Material Research

Materials Development efforts at UNLV

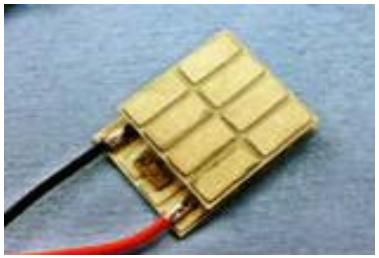
Examined atomistic mechanisms responsible for superior TE material performance; provided crucial guidance for design, processing new high-efficiency TEs for waste heat recovery:

- Developed new computational approach for phonon scattering and for κ_L
- Determined phonon scattering and thermal transport in advanced TE materials
- Examined low κ_L in PbTe: we calculated:
  (a) phonon density of states & vibration modes, (b) anomalous lattice dynamics near the ferroelectric instability, and (c) phonon velocity and anharmonic phonon scattering
- Concluded that low κ_L in PbTe is due to low phonon group velocity and strong LA-TO phonon mode scattering
- Conducted a general search for low κ_L materials based on phonon frequency, group velocity, and anharmonicity; examined κ_L dependence on valence charge, iconicity, and atomic mass of compositional elements in rock salt structure materials
- Investigated order-disorder transition and general ion transport behavior in liquid-like solids, i.e., $Cu_{2-x}Se$ and other related superionic solids:
  Combined first-principles density functional theory and molecular dynamics study, successfully reproduced liquid-like ion diffusion and order-disorder transition of the ion sublattice, and showed that thermodynamic stability and sublattice disorder of liquid-like solids can be altered through doping, lattice distortion, and alloying
- Improved the performance and scalability of our computational techniques

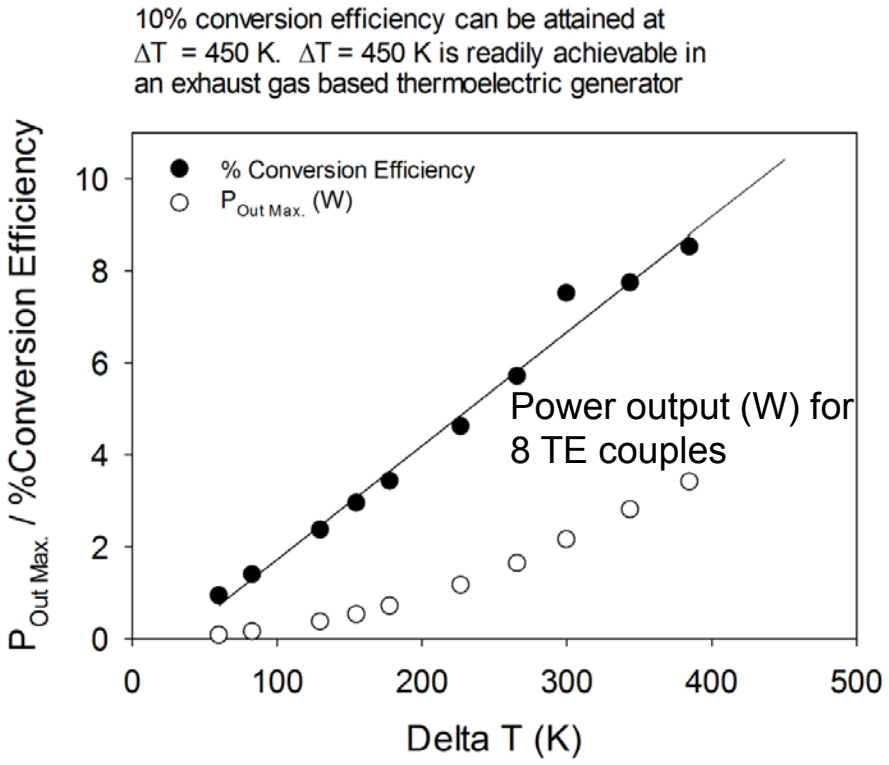
Technical Accomplishment (cont.)

Module Development and Evaluation Efforts (Marlow and GM)

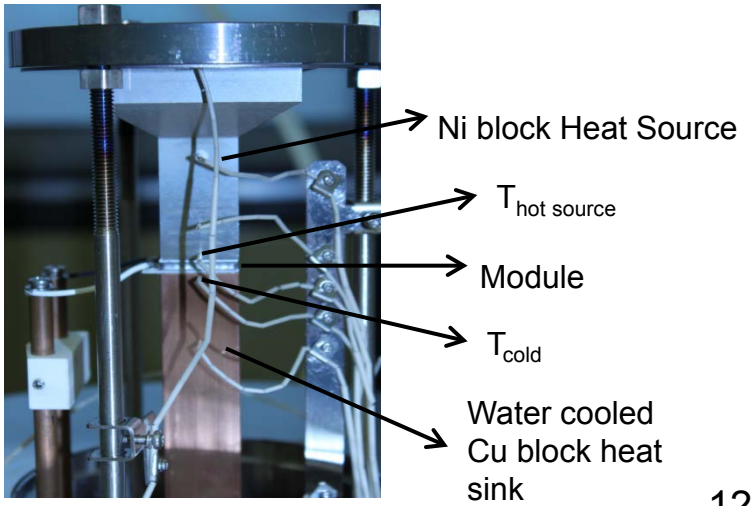
(1) Modules produced by Marlow and evaluated by GM. 8% Conversion Efficiency found for ΔT of 400 K. Materials for modules produced by melt spinning.



Skutterudite TE Module (Marlow)



GM's Module test stand



Collaboration and Coordination

GM GVE GLOBAL VEHICLE ENGINEERING

Vehicle Integration
System Controls
T

DELPHI

TE Component Design
Climatic Wind Tunnel Testing
Vehicle Instrumentation

faurecia

Modify Passenger Seating to
Optimize Thermal Comfort

GM R&D

CAE Modeling
Project Management
TE Material Research

marlow industries, inc.
Thermoelectric Innovation Through Research

TE Module
Development

INTREPID CONTROL SYSTEMS, INC.
Global provider of innovative vehicle network and embedded tools since 1994.

Vendor for Prototype TE device
control system

Berkeley
UNIVERSITY OF CALIFORNIA

Human Subject Testing
Comfort Model Enhancement

OAK RIDGE
National Laboratory

TE Material
Measurement

UNLV

TE Material Research
Computational Research Methods

Proposed Future Work

- **Complete Phase 3 and 4 activities by December 2013**
  - Commercialize design of new components – enhance imperative tradeoff and consider configuration in mainstream, hybrid and EV applications
  - Test and evaluate final components and integration
  - Component Qualification Report
- **Develop localized strategy for Chevrolet Volt**
  - Complete vehicle build/test with TED 5 kW coolant heater (defrosting, defogging. cabin heating) with localized TEDs to reduce the climate control induced variation in battery operating range between -10 to 32^{o}C (14 to 90^{o}F)
  - Determine coolant mode change logic for transparent high to unitary efficiency switch
  - Determine integration energy opportunity afforded by TE coolant heater

Summary – TE HVAC Project

- Relevance - The climate control system is the largest vehicle parasitic load with strong FE and mass impact.
- Approach - Optimize localized HVAC components using a refined Thermal Comfort model. Develop TE components that provide efficient localized heating & cooling of occupants. Manage thermal stratification/fogging risk with central system operating energy
- Accomplishments – VTCE and personal computer tool refined to aid in evaluation of localized heat transfer. Control strategy developed for TE components
- Collaboration – UCB, Delphi, Faurecia, Intrepid CS and GM meet frequently to refine daily activity. The UCB comfort tool integration allows rapid optimization of distributed HVAC components. GM developing TE material systems & modules with UNLV, ORNL, and Marlow.
- Future Direction
  - Commercialization of TE integrated system (the critical few) and further vehicle power train control system optimization
  - High Watt density cabin coolant heater development for efficient annualized heating and defrosting performance in a Chevrolet Volt

Acknowledgements