Thermoelectric HVAC and Thermal Comfort Enablers for Light-Duty Vehicle Applications

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Overview

Timeline

- Start: Oct. 2009
- End: Aug. 2013
- Percent complete - 68%

Budget

- Total project funding: $8.48M
  - DOE share: $4.24M
  - Contractor share: $4.24M
- DOE funding received in FY11:
  - $540,641
- DOE funding projection for FY12:
  - $600,000

Barriers#

- **Barriers**
  - Cost
  - Scale-up to a practical thermoelectric device
  - Thermoelectric device / system packaging
  - Component / system durability
- **Targets**
  - By 2015, reduce by > 30% the fuel use to maintain occupant comfort with TE HVAC systems.
  - Develop TE HVAC modules to augment MAC system
  - Integrate TE HVAC into vehicle. Verify performance and efficiency benefits.
  - Validate efficiency improvements with next-gen TE.

Partners

- **Interactions/ collaborations:**
  - Visteon, Amerigon, NREL, ZT::Plus, Ohio State Univ.
- **Project lead:** Ford Motor Company

Barriers & targets listed are from the VT multi-year program plan: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

Relevance / Objectives

Project Goal:

Identify and demonstrate technical and commercial approaches necessary to accelerate deployment of zonal TE HVAC systems in light-duty vehicles

Program Objectives:

- Develop a TE HVAC system to optimize occupant comfort and reduce fuel consumption
- Reduce energy required from AC compressor by 1/3
- TE devices achieve $COP_{cooling} > 1.3$ and $COP_{heating} > 2.3$
- Demonstrate the technical feasibility of a TE HVAC system for light-duty vehicles
- Develop a commercialization pathway for a TE HVAC system
- Integrate, test, and deliver a 5-passenger TE HVAC demonstration vehicle

Relevance / Accomplishments

FY2011 Accomplishments:

- Selected an architecture to fully evaluate and design
- Developed a proof-of-principle TE device to meet design-point targets
- Improved capability of comfort modeling tools to predict spot-cooling benefits
- Developed compatibility methods for TE HVAC system to function within whole-vehicle environment
- Completed detailed design specifications for TE HVAC system components
- Continued development of advanced p- and n-type TE heating/cooling materials

FY2012 Objectives:

- Complete TE component fabrication and bench testing
- Complete evaluation of advanced TE heating/cooling materials
- Complete advanced TE materials feasibility assessment
- Fabrication of all prototype components
- Conduct initial system and component cost analysis
- Perform ancillary loads trade-study
- Continue thermal comfort modeling toolset development
- Finalize build of all Bill-of-Material components for prototype vehicle integration

Critical-Path Milestones: FY11, FY12

Month/ Year	Milestone	Status
Oct – 10	TE performance model validated against current technology	Complete
Mar – 11	Selection of System Architecture Elements completed	Complete
Apr – 11	Baseline vehicle performance and comfort testing completed	Complete
May – 11	Predictive vehicle power budget and FE models developed	Complete
May – 11	CAE comfort studies completed	Complete
Jun – 11	Advanced TE materials device capability assessment	Complete
Sep – 11	TE HVAC assembly specification development completed	Complete
Nov – 11	Thermal comfort modeling toolset functionality assessed for spot-comfort	Complete
Nov – 11	Empirical buck-modeling validation studies completed	Complete
Dec – 11	CAE and comfort models completed on final system architecture	Complete
Feb – 12	Detailed CAD and packaging studies completed on TE HVAC	Delayed to March '12
Mar – 12	Proof-of-principle TE unit, bench study, and model comparisons completed	
Sep – 12	Bench testing completed on vehicle-intent TE device hardware	
Sep – 12	Design complete for vehicle-intent TE power supplies, air handlers and A/C system	

Go / No-Go Decision Points

Month/ Year	End of Phase Go / No-Go Decision	Status
	Phase 2	
Oct – 11	Thermal chamber testing validates comfort modeling predictions	Met
Oct – 11	Laboratory testing of prototype TE device validates model predictions	Met
Oct – 11	Vehicle packaging studies confirm that system can be installed into the target vehicle	Met
Oct – 11	Integrated CAE/TE modeling indicates that required comfort levels can be achieved	Met
	Phase 3	
Nov – 12	Vehicle-intent TE based subsystems meet bench-level performance and durability tests	
Nov – 12	Cost analyses shows that there is a potential business case for a TE HVAC system in the specified timeframe	

Technical Approach: Overall Program

- Develop test protocols and metrics that reflect real-world HVAC system usage
- Use a combination of CAE, thermal comfort models, and subject testing to determine optimal heating and cooling node locations
- Develop advanced thermoelectric materials and device designs that enable high-efficiency systems
- Design, integrate, and validate performance of the concept architecture and device hardware in a demonstration vehicle

AMERIGON

Technical Approach: TE Device Development

TE Device Development

- Develop an improved thermal interface test apparatus to generate a refined data set to update model assumptions and assess relative performance of potential dielectric material systems.
- Utilize the predictive computer models to optimize the thermoelectric engines and matching heat exchangers.
- Design and develop high performance mass producible liquid and air heat exchangers.
- Continue to develop and optimize the manufacturing methods for fabricating thermoelectric engines.

Advanced Thermoelectric Material Development

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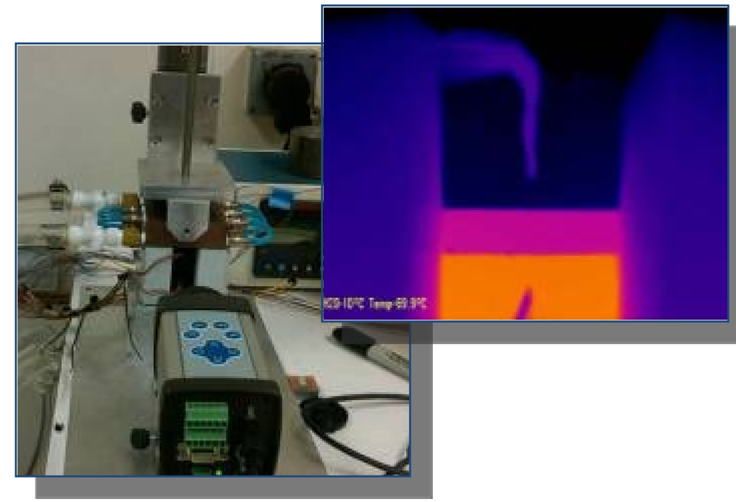
Investigate the ability of Tin & Iodine impurities in p/n-type $Bi_{2-x}Sb_xTe_{3-y}Se_y$ to create a performance improving resonant level and coordinate with ZT::Plus to develop materials with repeatable performance levels.

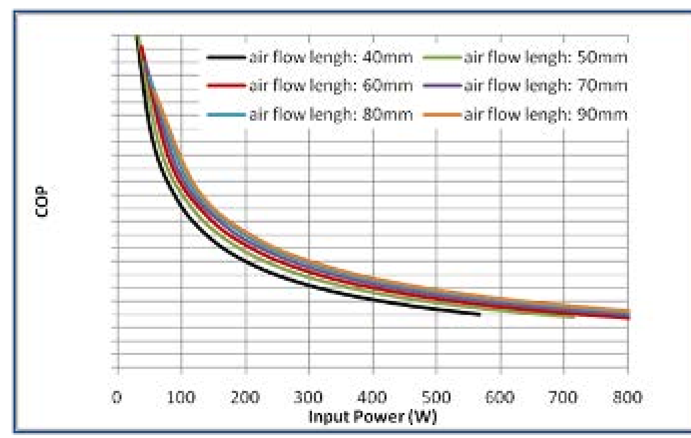
Technical Accomplishments:
TE Device Optimization

TE System Design & Optimization

- **Thermal Property Analysis:**
  - Developed test apparatus to evaluate thermal properties of dielectric material systems
  - IR camera & thermistors quantify heat flux through samples
- **Analytical optimization of concept TED:**
  - Calculated ideal TE element size & # of elements
  - Air fin depth optimization
  - Dielectric system selection



Thermal Interface Test Apparatus

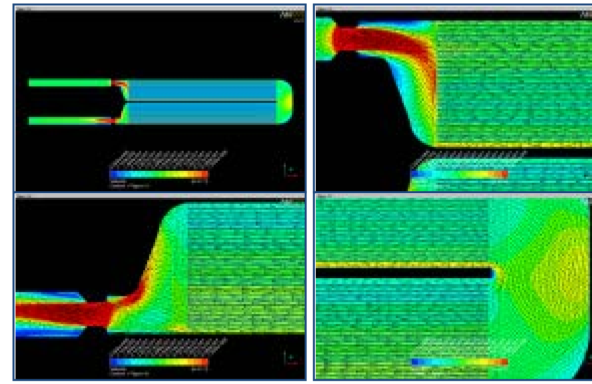


Air Fin Flow Depth vs. COP

Technical Accomplishments:
TE Device Fabrication

Key Accomplishments –

- Designed/fabricated custom liquid heat exchanger, optimized to meet design requirements
- Fabricated HEX using production processes and assembly lines
- Analyzed, fabricated, and tested several air fin variants for performance, manufacturing feasibility, and impact on device final assembly process
- TE engine manufacturing processes further refined for improved cycle rate and quality
- TE engine assembly performed on existing production assembly lines.



CFD of liquid heat exchanger

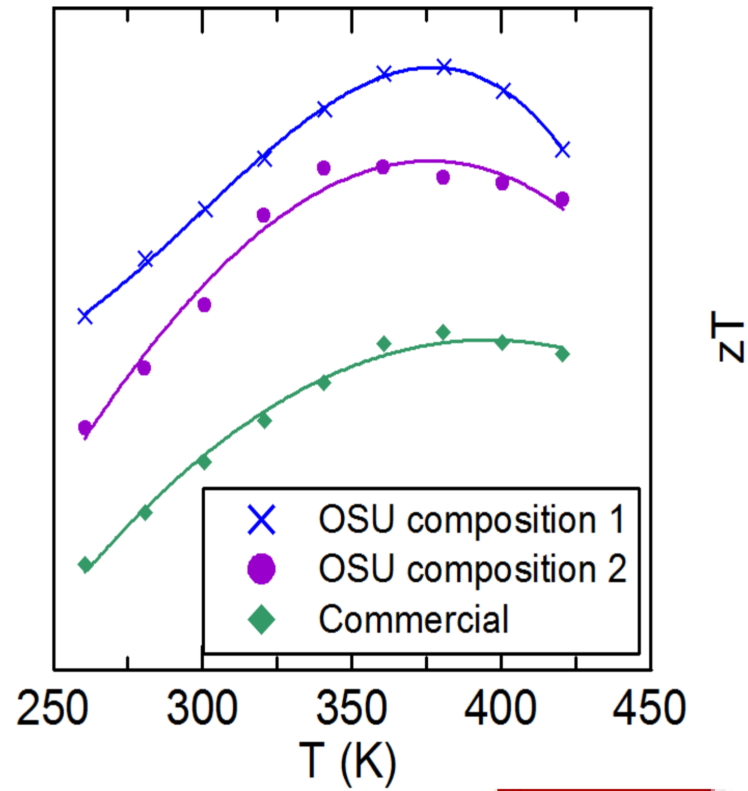
Liquid Heat Exchanger

AMERIGON

Technical Accomplishments: Advanced TE Materials Development

p-type TE Materials

- Attempts at incorporating Sn into commercial p-type $Bi_{2-x}Sb_xTe_3$ material have shown promise in several samples
  - Increase in zT of ~25% over commercially available p-type Bi_2Te_3
  - Repeating this success underway at OSU and ZT::Plus using two different processing techniques
  - OSU team building device out of porous material to confirm max ΔT performance



n-type TE Materials

- Repeat material processing techniques that led to successful p-type material for standard n-type $Bi_2Te_{3-y}Se_y$ composition

- Pursuing new composition for n-type Bi_2Te_3 to understand property changes

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zt :: plus

Technical Approach: Climate System Development

The approach to develop a zonal climate system has been broken into 4 phases:

Phase 1

- ✓ Developed test conditions, measures of success and test methodology
- ✓ Benchmarked testing of conventional HVAC configurations.
- ✓ Evaluated perceived comfort for multple configurations of a zonal climate system

Phase 2

- ✓ Utilize CAE/CFD tools , including comfort models, for rapid evaluation of potential system architectures and confirmation of selected architecture before building & testing
- ✓ Conduct subjective tesing for perceived comfort in vehicle buck to confirm CAE/CFD
- ✓ Develop design requirements for TED and base system

Phase 3

- Build and bench validate component subsystems to meet design requirements (CAE/CFD also utilized for components)

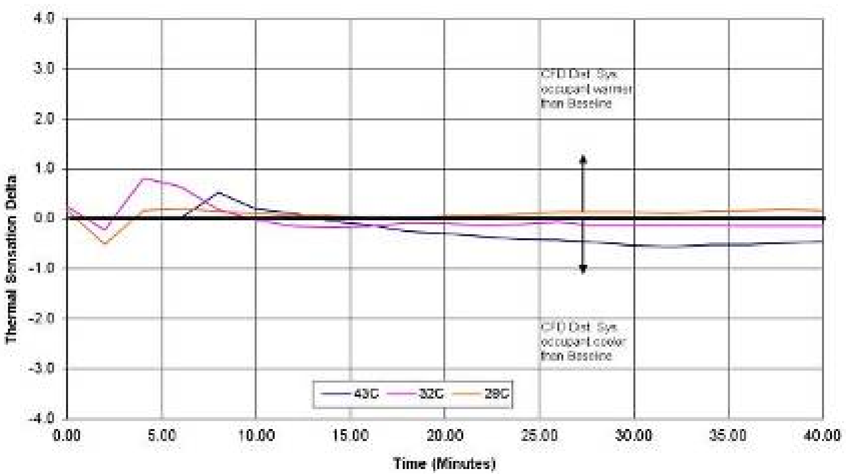
Phase 4

- Integrate zonal climate system components into vehicle & validate system performance

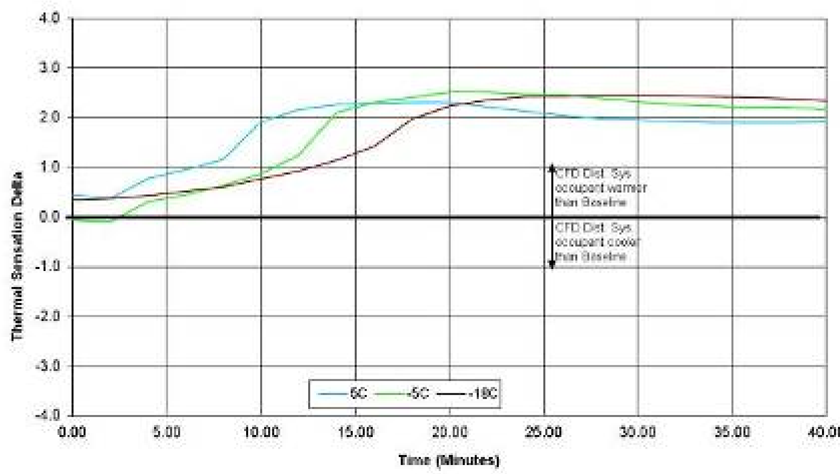
Technical Accomplishments: HVAC System Modeling

Thermal sensation modeling has been completed for the baseline vehicle climate system and the proposed distributed climate system consisting of 4 elements. Results have indicated the distributed system can achieve comparable or improved thermal sensation ratings with less overall power consumption.

Hot Ambient Testing



Cold Ambient Testing

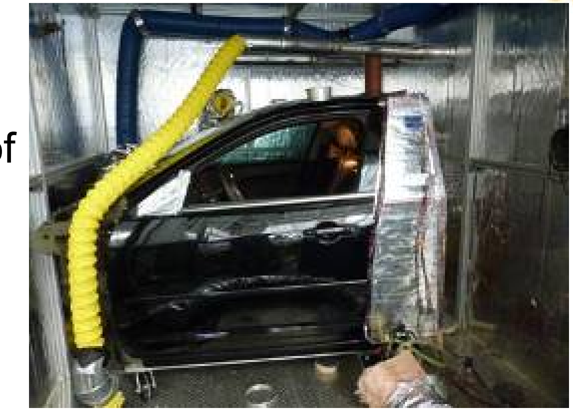


Graphs show the delta in Modeled Thermal Sensation Ratings for the Distributed System compared to the Baseline System. Values above zero indicate the Distributed System is producing warmer thermal sensation.

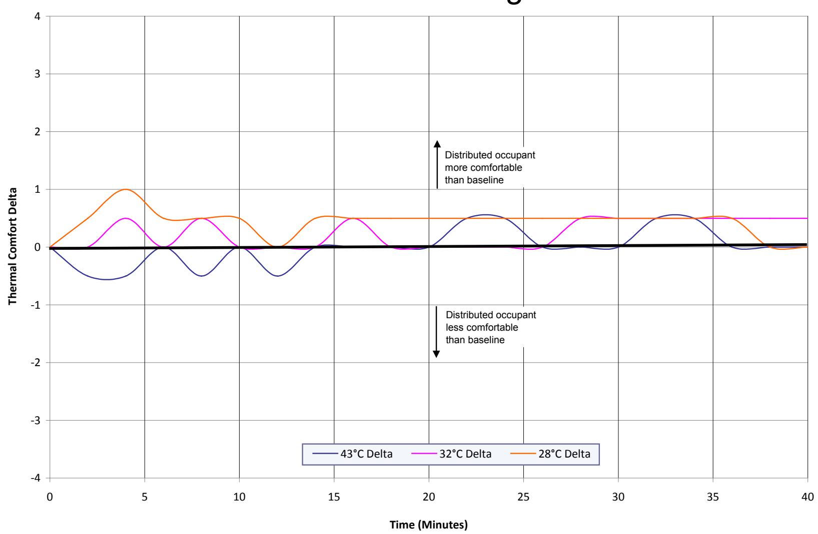
Technical Accomplishments: Vehicle Buck Validation

The Air Chamber Evaluation System (ACES) is an environmental chamber with the ability to independently control chamber temperature, buck temperature and the temperature of the various elements in the distributed climate system.

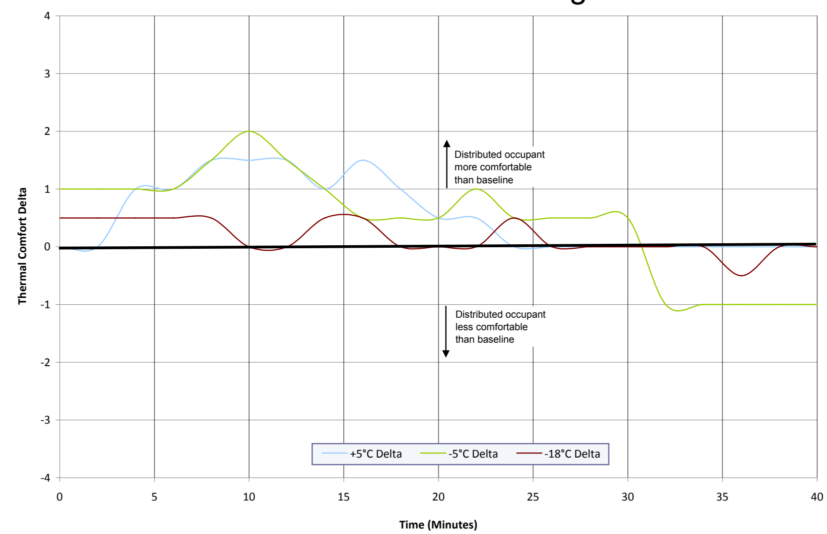
Results show similar to improved thermal comfort ratings (subjective) for the distributed climate system (consisting of 4 elements) when compared to the baseline climate system.



Hot Ambient Testing



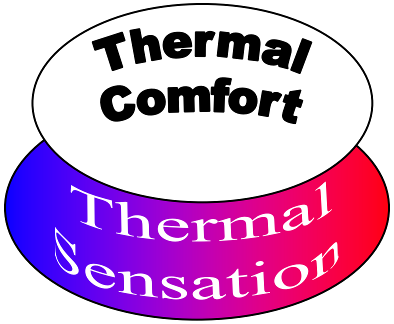
Cold Ambient Testing



Graphs show the delta in observed thermal comfort rating for the Distributed System compared to the Baseline System. Values above zero indicate the Distributed System is producing a more comfortable rating.

Technical Approach: Model Integration

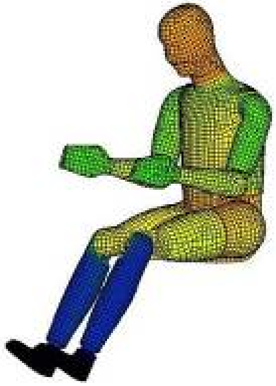
Thermal manikin compared to trained climate control observer
Temperature, sensation, comfort



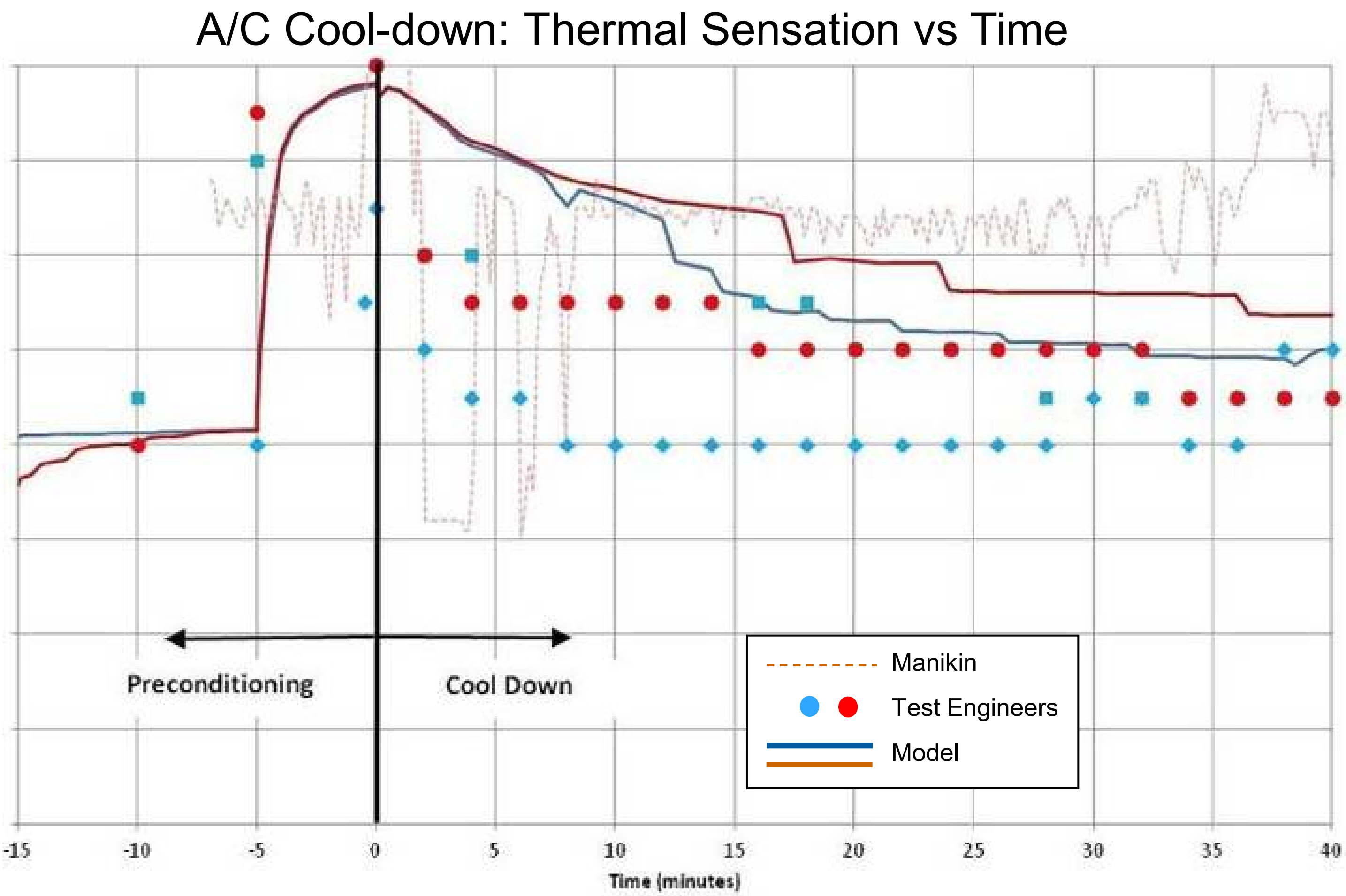
Design impacts performance
Design for comfort

Thermal manikin helps to validate virtual manikin
Segment temperature, sensation, comfort

CAE tool guides design
Zonal climate control



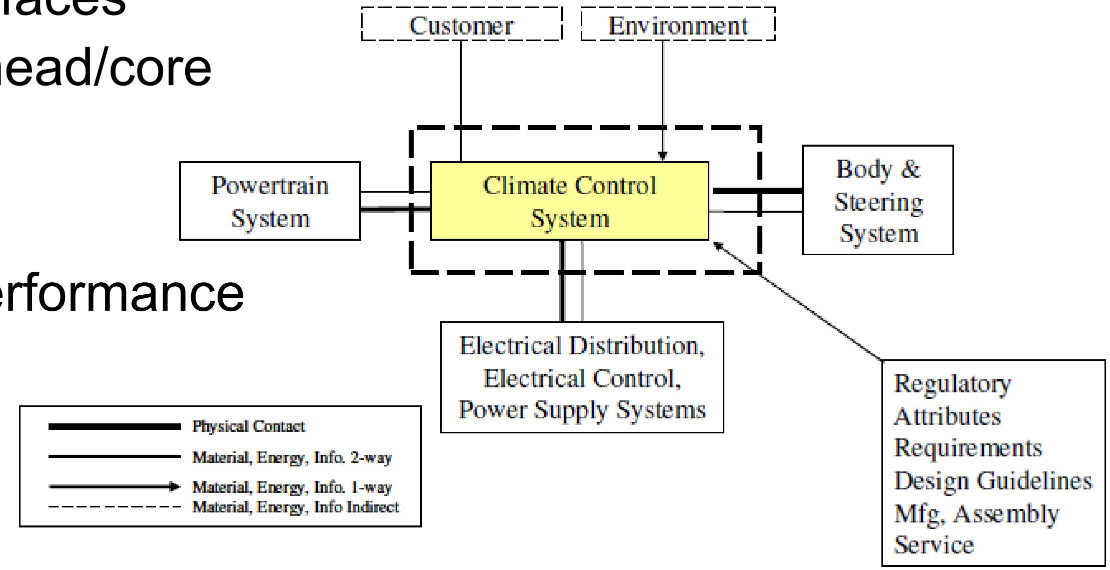
Technical Accomplishments: Comfort Model Validation



Excellent correlation between models, manikin, and test subjects

Technical Accomplishments:
Develop System Architecture & Requirements

- **Zonal Architecture**
  - Reduced reliance on central HVAC system
  - Seat-based heating & cooling
  - Thermally-conditioned surfaces
  - Distributed TE nodes for head/core
- **System Requirements**
  - Heating/cooling/defrost performance
  - Occurrence efficiency
  - Package, NVH, Electrical, Materials, Serviceability



Collaborations and Project Coordination

- Ford Motor Company: Prime Contractor, Vehicle OEM, Systems Integrator
- Visteon: Climate Systems Tier-1 Supplier, Power Electronics
- NREL: Occupant Comfort Modeling / Testing
- Amerigon: Advanced Thermoelectric Device and Module & Climate-Controlled Seat Module and Integration
- ZT::Plus: Production Thermoelectric Materials Scale-Up and Manufacturing
- Ohio State University: Advanced Thermoelectric Materials Research

Broad industry/government/academia collaboration with expertise in all aspect of the project

Remaining Critical-Path Activities for FY12 and FY13

FY12 (4Q11 – 3Q12)

- CAD study for component packaging
- Proof-of-principle TE unit design, build, test, model
- Ancillary load trade-off study
- Thermal comfort model and measurement sensitivity study
- TE-HVAC system component design, build, and test
- System Cost Analysis

FY12 (4Q12 – 3Q13)

- Complete installation of TE HVAC system and analysis equipment into test vehicle
- Wind tunnel and field testing performance of TE HVAC system
- Commercialization analysis of system
- Deliver test vehicle to DOE

Demonstration Vehicle Selection

- Electric a/c compressor
- EATC climate system
- High-voltage electrical system
- Flexible 12-V architecture
- Existing CAD / CAE / Test Data

- Baseline vehicle available for test / verification throughout project
- Front heated/cooled seats in production
- Packaging ducting is largest issue

Summary

- **Relevance**:
  - Climate control systems are a large auxiliary load on the powertrain and energy optimization can result in overall vehicle fuel economy improvement
- **Approach**:
  - Project focus is on developing methods to optimize climate system efficiency while maintaining occupant comfort at current levels using new technology, architecture, and controls approaches
- **Technical Accomplishments**:
  - On target to meet Phase 3 milestones and deliverables
  - System architecture design study completed, advanced TE materials research results encouraging, TED liquid-to-air device results on-track, thermal comfort modeling predictions validated by test results
- **Collaborations**:
  - Cross-functional team working well together. Good mix of skills and resources to address the technical tasks in this project.
- **Future Directions**:
  - Continue to progress towards a vehicle demonstration of the technology

Acknowledgements

- We acknowledge the US Department of Energy and the California Energy Commission for their funding support of this innovative program

- A special thank you to John Fairbanks (DOE-EERE), Reynaldo Gonzales (CEC), and Carl Maronde (NETL) for their leadership

- Thanks to the teams at Ford, Visteon, NREL, OSU, Amerigon, and ZT::Plus for their work on the program.

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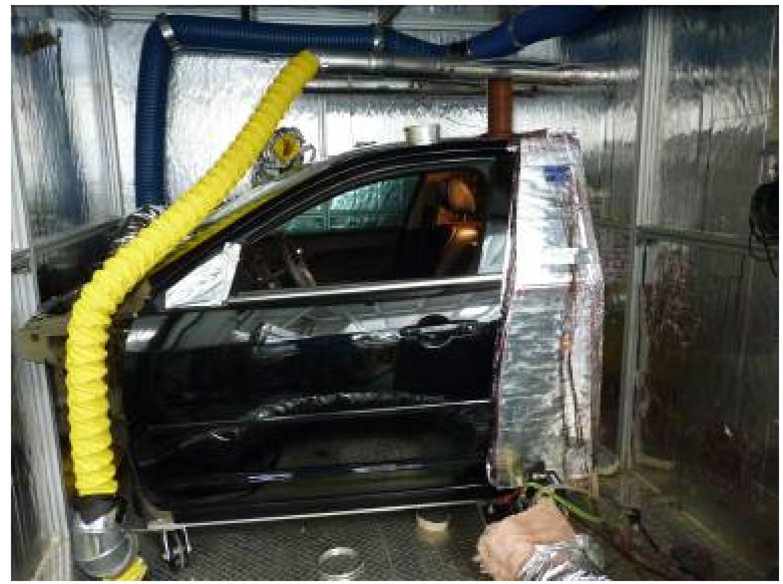
Technical Back-up Slides

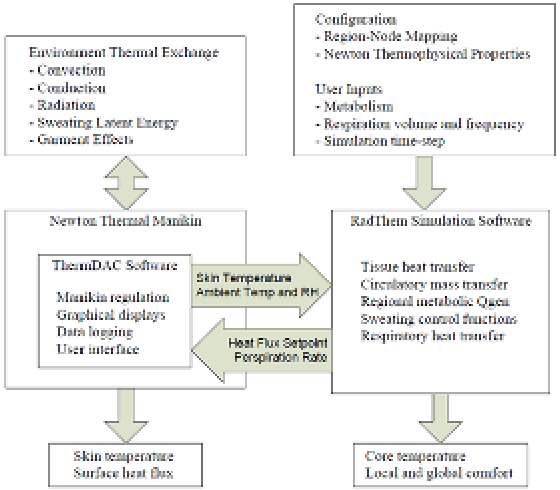
Climate System Validation Test Method

Man in Box – Phase 1

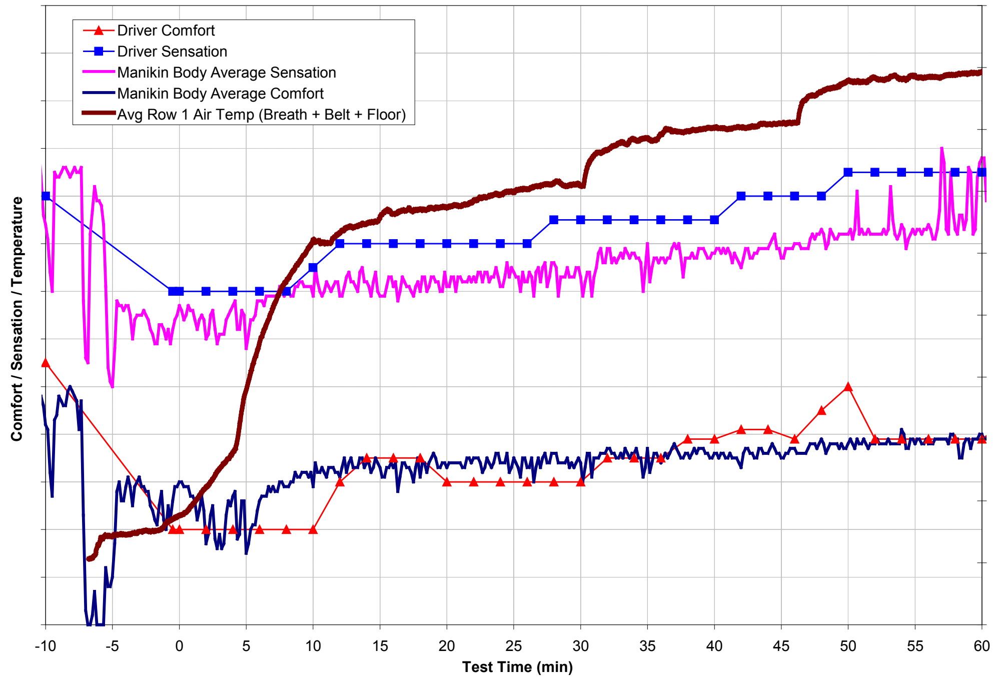


½ Buck in Box – Phase 2

Thermal Comfort Performance Analysis

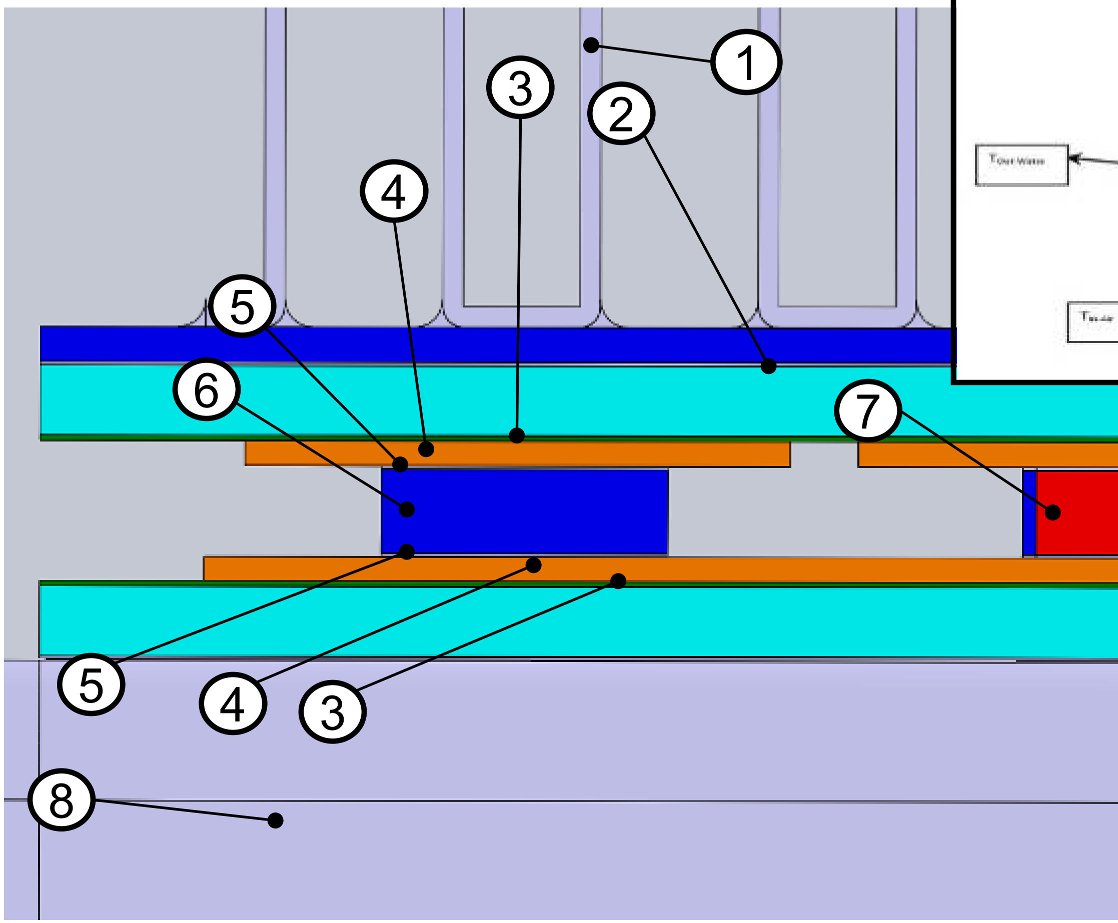


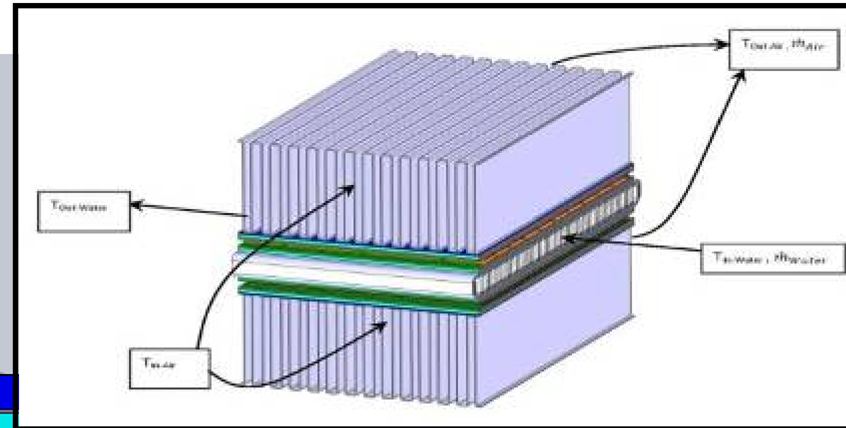
Typical results: -5 C Ambient Test



Good correlation on comfort and sensation between manikin and test subject

Thermoelectric Device Description





	Part Description
1	Air Fin
2	Fin Base
3	Dielectric Layer (Insulator)
4	Shunt
5	Solder & Metallization Layers
6	N-Type Pellet (BiTe)
7	P-Type Pellet (BiTe)
8	Liquid Heat Exchanger