# Thermoelectric HVAC for Light-Duty Vehicle Applications

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# Overview



## Timeline

- Start: Oct. 2009
- End: Jan. 2013
- Percent complete - 15%

## Budget

- Total project funding: $8.48M
  - DOE share: $4.24M
  - Contractor share: $4.24M
- Funding obligated in :
  - FY09: $658,303
  - FY10: $540,536

## Barriers

- Barriers Addressed
  - **Efficiency, cost-effectiveness, and packaging of thermoelectric-based HVAC systems**
  - **Migration from vehicle conditioning to occupant conditioning**
  - **Climate system accessory loads which reduce energy-efficiency of light-duty vehicles**
- Targets
  - **Achieve equivalent cost**
  - **Achieve equivalent occupant comfort**
  - **Reduce fuel consumption associated with HVAC system operation**

## Partners

- Interactions/ collaborations:
  - Visteon, BSST, NREL, ZT::Plus, Ohio State University, Amerigon
- Project lead: Ford Motor Company

# 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

**FY2010 Objectives:**

- Select vehicle and establish baseline performance
- Determine test and analysis methods / tools
- Establish comfort and vehicle performance criteria & targets
- Determine and study candidate HVAC system architectures
- Select an architecture to fully evaluate and design

# Milestones



| Month/ Year | Milestone | Status |
|---|---|---|
| Dec - 09 | Milestone: Select vehicle | Complete |
| Jan -10 | Milestone: Establish operating conditions, test methods, and comfort targets | Complete |
| Feb - 10 | Milestone: Advanced TE materials & device R&D plan developed | Complete |
| May -10 | Milestone: Vehicle-level performance requirements established | On-Target |
| June - 10 | Milestone: System architectures selected for study | On-Target |
| Aug - 10 | Milestone: TE performance model validated against current technology | On-Target |
| Aug - 10 | Milestone: Predictive vehicle power budget and FE models developed | On-Target |
| Sep - 10 | Milestone: CAE parametric modeling of baseline & proposed architectures completed | On-Target |
| Sep - 10 | Milestone: Final TE HVAC system architecture selected | On-Target |
| | **End-of-Phase Go / No-Go Decisions** | |
| Sep – 10 | CAE modeling of zonal HVAC architecture indicates comfort criteria can be achieved | |
| Sep – 10 | System modeling indicates HVAC architecture can achieve specified reductions in energy | |
| Sep - 10 | TE research shows a specific path to deliver a technically and commercially viable TE HVAC sub-system | |

# Technical Approach



- 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

# Technical Approach: Comfort-based System Design

- Successful zonal climate control will provide equivalent occupant thermal comfort compared to a conventional climate control system
- Determine the best potential AZTECS design options prior to vehicle build
- Analysis
  - Use the NREL and Visteon thermal comfort tools to optimize the AZTECS design
    - # of TEDs, Location of vents, Air Temperature, Air Flowrate
    - Assess current thermal comfort tools and use the most effective
    - Integrate thermal comfort module into CAE tools
- Test
  - Leverage Ford's extensive human subject test experience and knowledge base in designing climate control systems
  - Assess current manikins and use the most effective
    - Use manikins, limited subject testing, and climate chambers to augment thermal analysis and guide vent placement
- Validate the final AZTECS design

# Technical Approach: Zonal Climate System Design

- Conduct subjective testing to identify optimum locations for zonal climate devices and for use in architecture trade off analysis
- Utilize CAE/CFD tools for rapid evaluation of potential system architectures and confirmation of selected architecture prior to building and testing systems
- Utilize thermal manikin to conduct testing of “mocked up” system architectures to validate model output
- Design requirements will be developed to provide starting point for detailed hardware design and build activities
- Component CAE/CFD analysis enable rapid evaluation of designs prior to prototyping and testing
- Build and validate component subsystems
- Integrate zonal climate system components into vehicle
- Validate system performance to established criteria

# Technical Approach: TE Device Development

## 2nd Generation TE Device Development

- Develop Computer models to predict TE device performance and direct design optimizations
- Replace the “waste” side air fin with a liquid tube to increase power density, approximately double for given package space, and enable waste heat & cold to be rejected outside the passenger compartment
- Use Thermal isolation to maximize TED efficiency. Focus on high density designs that reduce parasitic losses and increase power density (Qc/gram of BiTe)

## Advanced Thermoelectric Material Development

- Attempt to increase the ZT values of commercially available $Bi_2Te_3$ through the addition of impurities that create a resonant level, starting with P-type material in Phase 1

# Technical Accomplishments and Progress



- 2010 Ford Fusion HEV selected for demonstration program

- Electric A/C Compressor
- EATC Climate System
- High-Voltage Electrical System
- Flexible 12-V Architecture
- Existing CAD / CAE / Test Data

Fusion HEV is a flexible and relevant platform to demonstrate the concept of TE HVAC

# Technical Accomplishments and Progress



## Test Conditions and Metrics Established

– Based on analysis of 3 primary factors:
  - Population Density, Weather Conditions, Driving Patterns

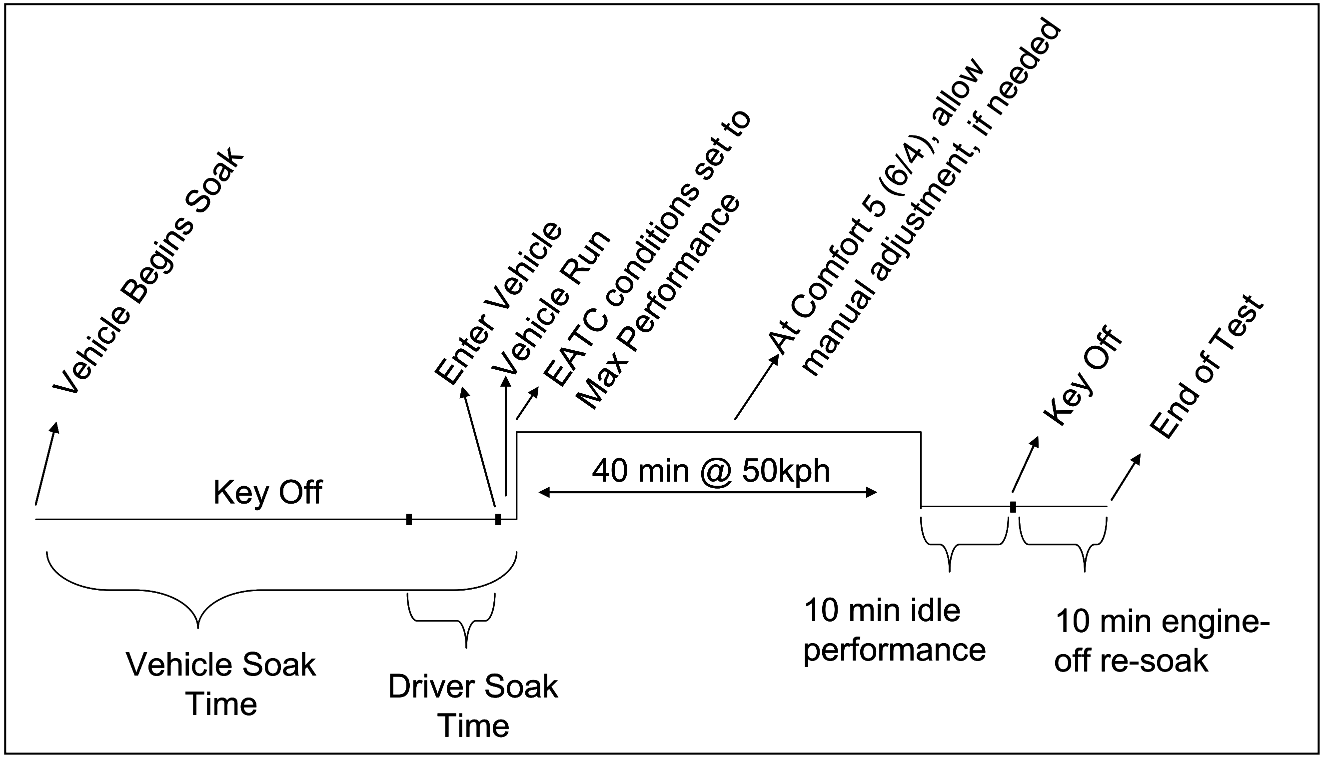
| | Hot Test 1 | Hot Test 2 | Hot Test 3 | Cold Test 3 | Cold Test 2 | Cold Test 1 |
|---|---|---|---|---|---|---|
| Ambient Conditions | 43° C (104° F)<br>40% RH<br>1000 W/m² Solar | 32° C (90° F)<br>70% RH<br>1000 W/m² Solar | 28° C (82° F)<br>70% RH<br>1000 W/m² Solar | 5° C (41° F)<br>No Solar | -5° C (23° F)<br>No Solar | -18° C<br>(0° F)<br>No Solar |
| Energy Consumption Weighting Factor | 6% | 13% | 31% | 33% | 11% | 6% |
| Comfort Target | 5<br>Comfortable | 6<br>Slightly Warm | 5<br>Comfortable | 5<br>Comfortable | 4<br>Slightly Cool | 5<br>Comfortable |

It is critical to evaluate system efficiency in real-world operating conditions

# Technical Accomplishments and Progress



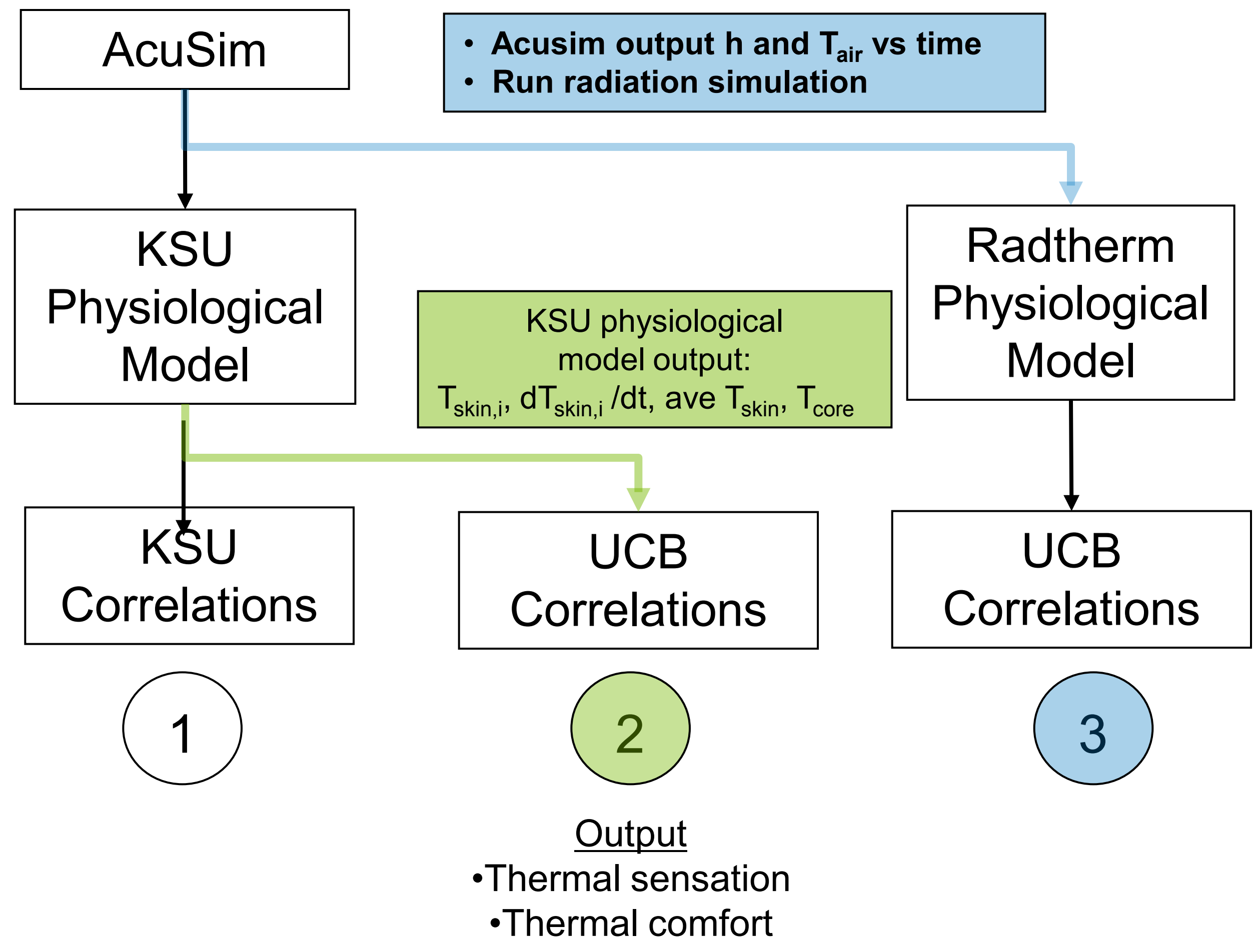
- Basic test protocol developed to determine impact of HVAC system on efficiency

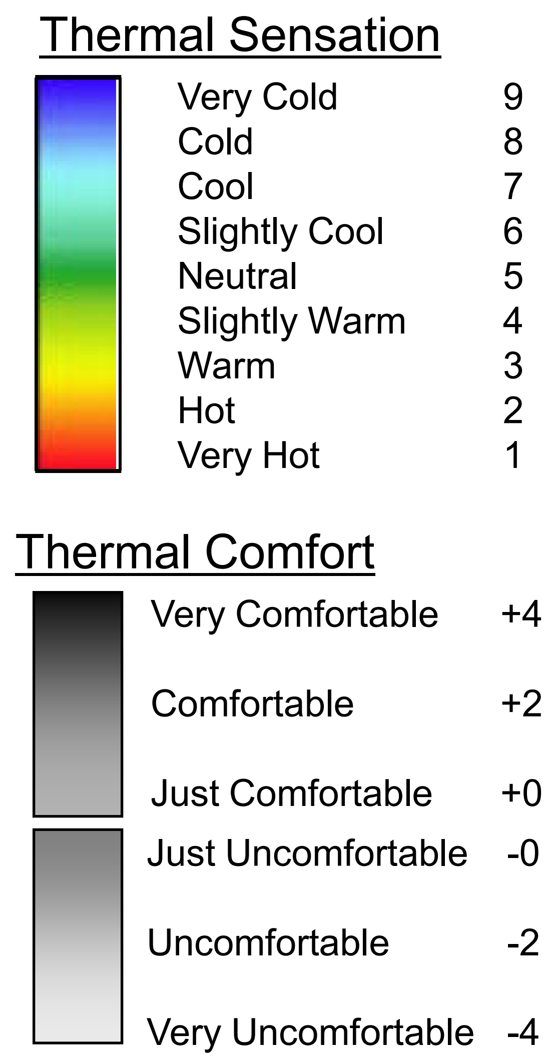



A simple evaluation drive cycle minimizes convolution with engine efficiency effects.

# Technical Accomplishments: Evaluation of Comfort Tools

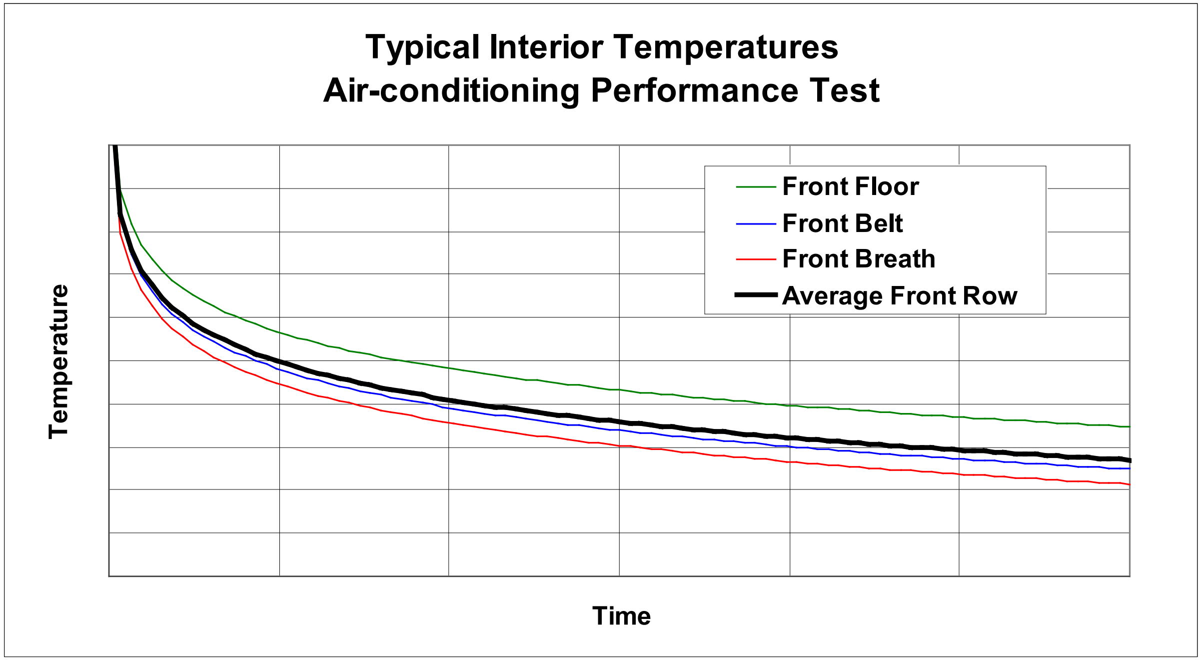
## TE HVAC Vehicle Thermal Sensation/Comfort Analysis Options

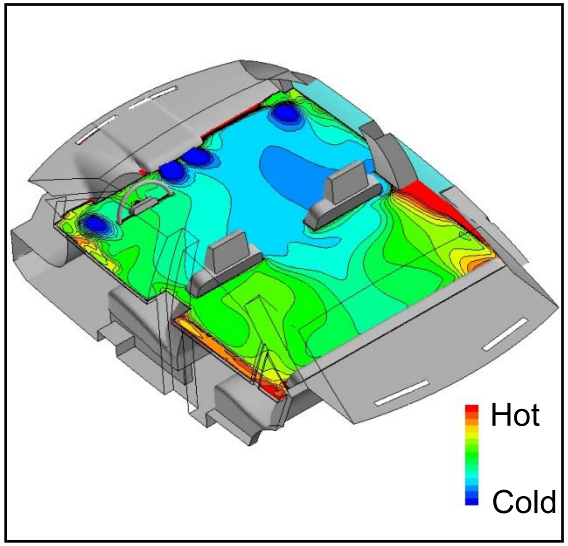


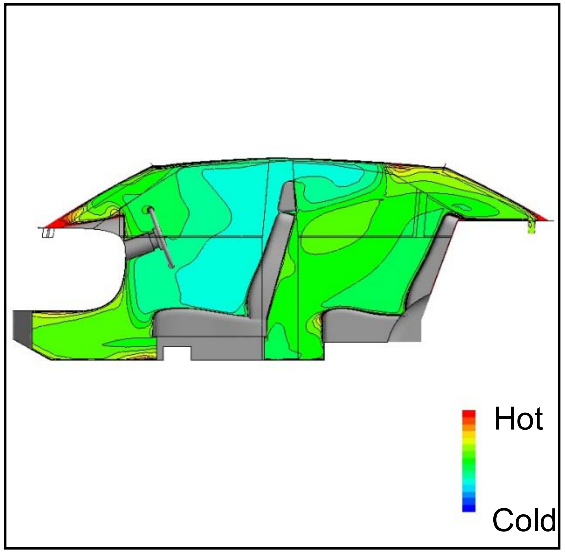




Scale forces a determination of comfort / discomfort and reason

# Evaluation of Transient Interior Environment Using CFD - Computational Fluid Dynamics

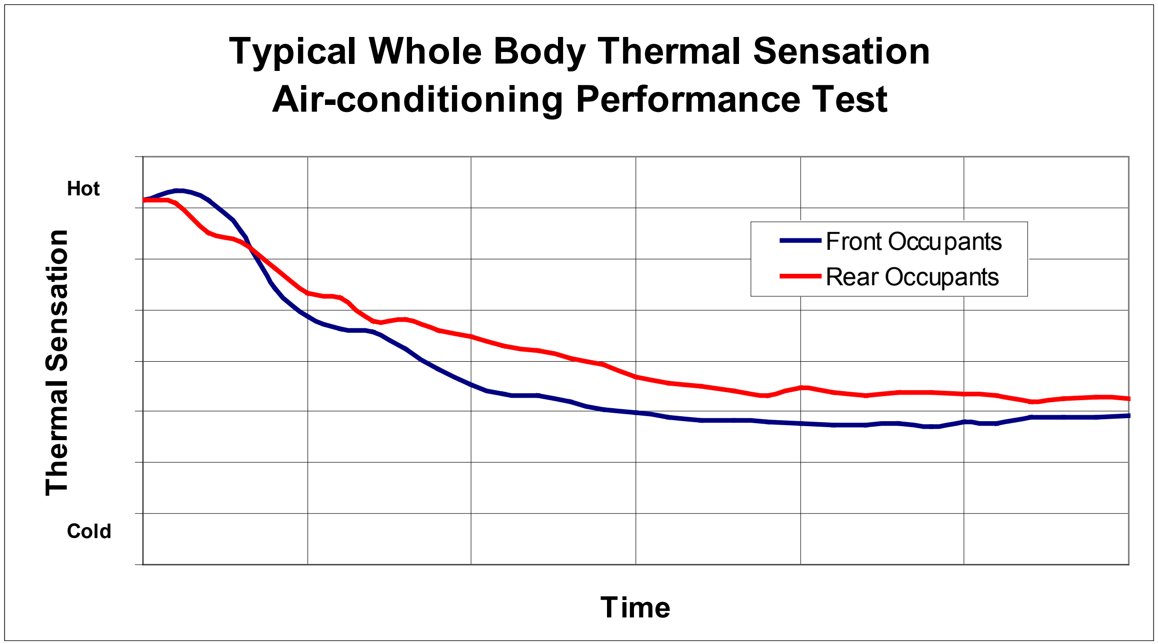


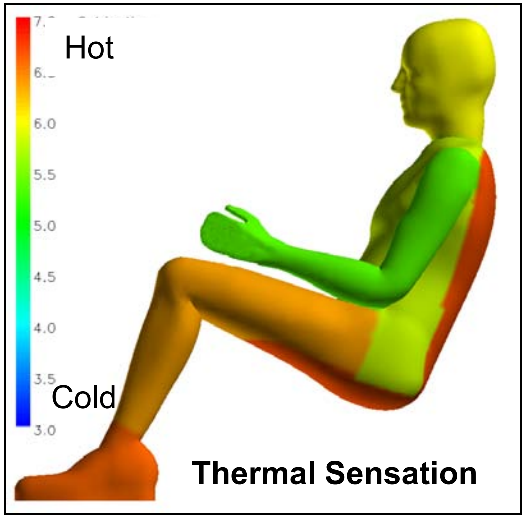

- Completed build of baseline vehicle CFD model using parametric geometry
- Began correlation of model simulations with A/C pull down and heater warm up test data
- Started building CFD model using vehicle CAD geometry

# CFD Solution Data Converted into Transient Occupant Thermal Sensation Predictions




**Occupant Thermal Sensation Predictions are a Function of:**

- Temperature
- Velocity
- Solar Load
- Surface Radiation
- Humidity




Initiated trial runs of comfort model based on CFD simulation

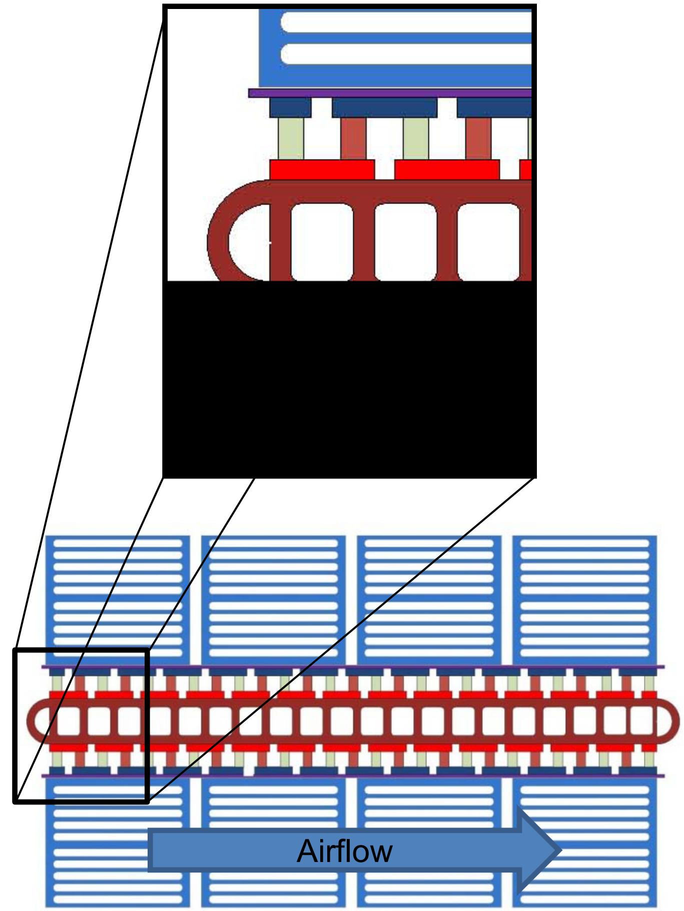
AMERIGON

BSST

# 2nd Generation TE Device Development

Status to Date

- Computer performance modeling of a modular (scalable up or down) device is ongoing.
- TE material selection has been narrowed down to 2 commercial sources and 2 TE pellet sizes for the Phase 1 prototype device.
- Preliminary electrical circuits have been established and designed with flexibility to allow the current draw to be maintained with-in acceptable limits for a range of potential system voltages.
- Initial TE engine builds have been conducted. Bonding quality studies are in progress.




Conceptual cross-section of a High Density "Liquid to Air" TE device

zt plus Thermoelectric Materials



THE OHIO STATE UNIVERSITY

# Advanced TE Material Development

Status to date

- Initial evaluation of Sn as a resonant impurity in pure $Bi_2Te_3$ material showed a doubling of the thermoelectric power factor.
- First attempts at directly integrating Sn as a resonant impurity into a commercial grade $Bi_2Te_3$ p-type material with no other modifications were unsuccessful to date.

Next Steps

- Adjust ratio of Sb to Bi and Sn resonant impurity concentration and evaluate performance effects.
- Bibliographic studies to find a candidate impurity which forms a resonant level in n-type $Bi_2Te_3$

# 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
- BSST: Advanced Thermoelectric Device and Module
- Amerigon: 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 Activities for Fiscal Year 2010

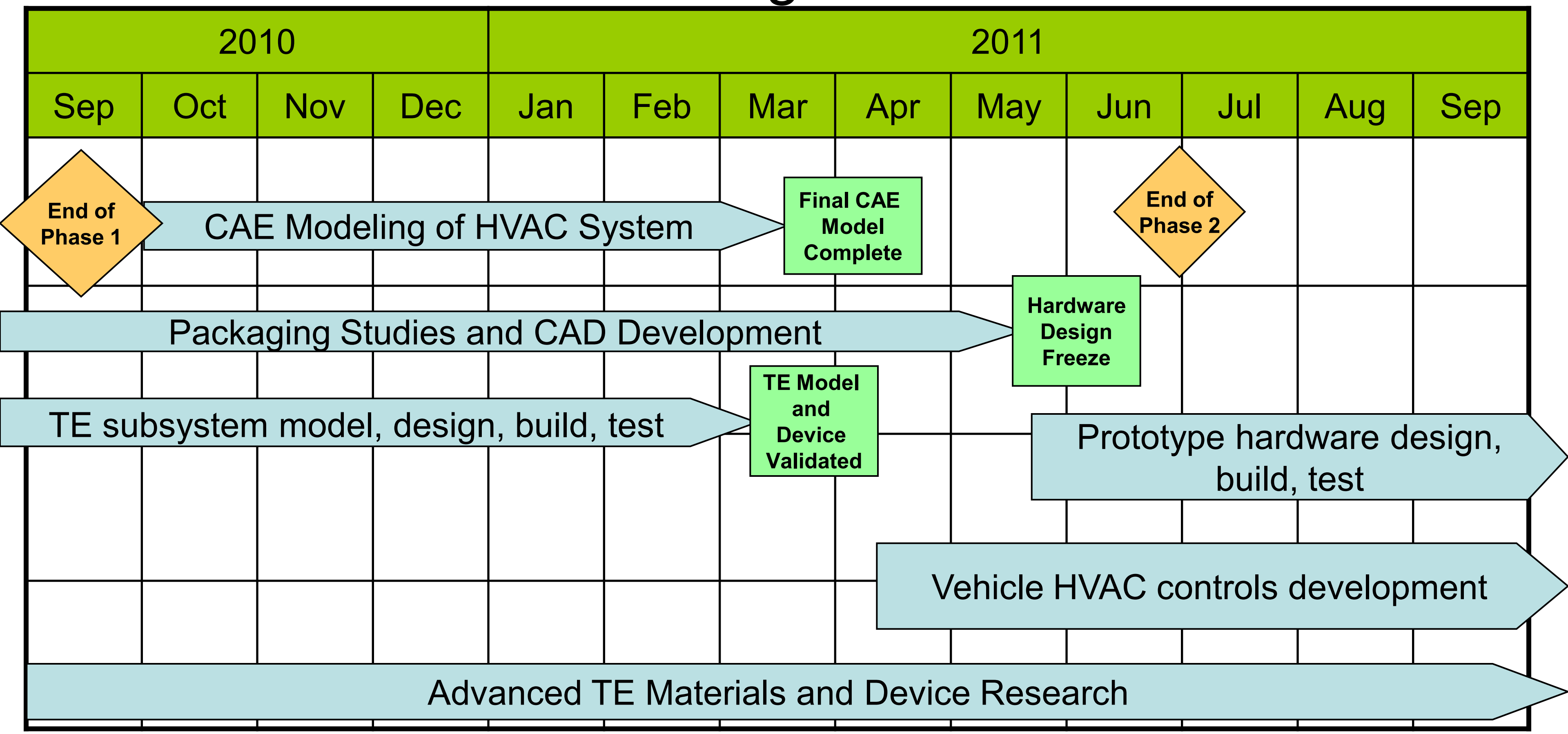


- Perform baseline wind-tunnel testing of target vehicle
- Occupant subject testing to refine thermal node locations for occupant comfort response model
- Develop and validate parametric model of target vehicle against test data
- Synthesize advanced p-type heating/cooling thermoelectric materials
- Develop transient TE model and validate results using a prototype device
- Determine heating/cooling node locations and target output requirements
- Develop systems-level vehicle model to estimate vehicle performance change with TE HVAC architecture
- End Phase 1 of program and Go/No-Go decision point

# Activities for FY2011



## Phase 2 scheduled to begin in FY2011



# 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 1 milestones and deliverables
  - Test conditions established, climate system and comfort modeling has been started, baseline testing and advanced thermoelectrics research is underway
- **Collaborations**:
  - Cross-functional team is 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
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