Thermoelectric HVAC for Light-Duty Vehicle Applications

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Overview

Timeline

- Start: Oct. 2009
- End: Jan. 2013
- Percent complete - 42%

Budget

- Total project funding: $8.48M
  - DOE share: $4.24M
  - Contractor share: $4.24M

- DOE funding received in FY10:
  - $537,447
- DOE funding projection for FY11:
  - $1,272,704

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, BSST, NREL, ZT::Plus, Ohio State University, Amerigon
- **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

FY2010 Accomplishments:

- Selected vehicle integration platform; developed test and analysis methods / tools
- Established comfort and vehicle performance criteria & targets
- Evaluated TE HVAC system architectures using CAE and testing
- Developed candidate p-type TE material; designed proof-of-concept TE HVAC module

FY2011 Objectives:

- Select a TE HVAC architecture to fully evaluate and design
- Estimate FE savings from use of TE HVAC architecture
- Develop candidate n-type TE material; design proof-of-principle TE HVAC module
- Develop detailed systems-level component requirements and specifications

Critical-Path Milestones: FY10, FY11

Month/ Year	Milestone	Status
Jan -10	Test conditions and measures of success developed	Complete
May -10	Vehicle-level performance requirements established	Complete
Aug - 10	System architecture test and selection methodology completed	Complete
Oct - 10	TE performance model validated against current technology	Complete
Mar - 11	Final TE system architecture selected	On-Target
Apr – 11	Predictive vehicle power budget and FE models developed	On-Target
Jun – 11	Advanced TE materials device capability assessment	On-Target
Jul – 11	Thermal comfort modeling toolset functionality assessed for spot-comfort	On-Target
Aug – 11	TE HVAC assembly specification development completed	On-Target
Sep – 11	Proof-of-principle TE unit, bench study, and model comparisons completed	On-Target
Oct – 11	Detailed CAD and packaging studies completed on TE HVAC	On-Target

Go / No-Go Decision Points

Month/ Year	End of Phase Go / No-Go Decision	Status
	Phase 1	
Oct – 10	CAE modeling of zonal HVAC architecture indicates comfort criteria can be achieved	Met
Oct – 10	System modeling indicates HVAC architecture can achieve specified reductions in energy	Met
Oct – 10	TE research shows a specific path to deliver a technically and commercially viable TE HVAC sub-system	Met
	Phase 2	
Oct – 11	Thermal chamber testing validates comfort modeling predictions	
Oct – 11	Laboratory testing of prototype TE device validates model predictions	
Oct – 11	Vehicle packaging studies confirm that system can be installed into the target vehicle	
Oct – 11	Integrated CAE/TE modeling indicates that required comfort levels can be achieved	

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

Technical Approach: TE HVAC Systems 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 validate component subsystems to meet design requirements (CAE/CFD also utilized for components)

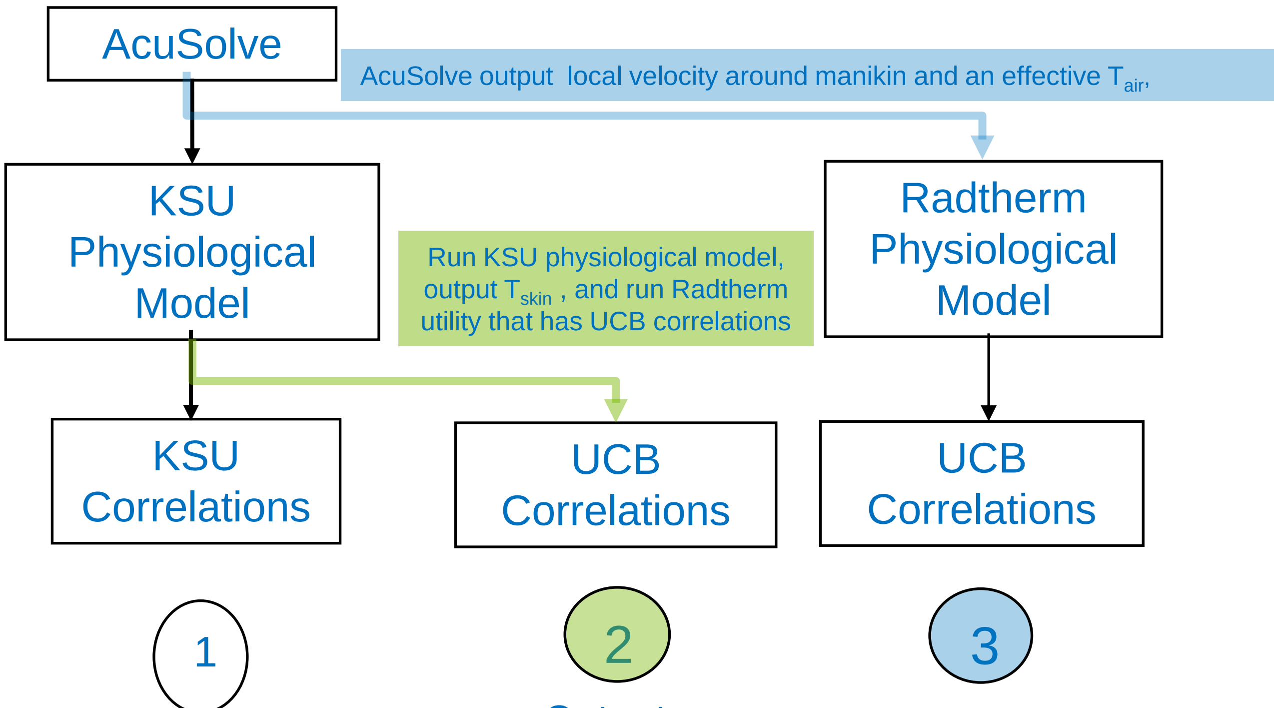
Phase 4

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

Technical Approach

Thermal Sensation/Comfort Analysis Options

- Evaluate 3 potential paths
- Compare to subject evaluations
- Select method for CAE analysis of system architecture



Outputs

- Thermal sensation
- Thermal comfort

TE Device Development Approach

TE Device Development

- Develop and supply computer models of specifically sized TE devices (TEDs) for integration into HVAC-system performance and human comfort models.
- Utilize CAE models to optimize design of TEDs for performance, size, and cost.
- Develop and refine test apparatus to confirm prototype device performance and correlate computer models to test results.
- Develop TED designs and manufacturing methods that can be transferred to mass production.

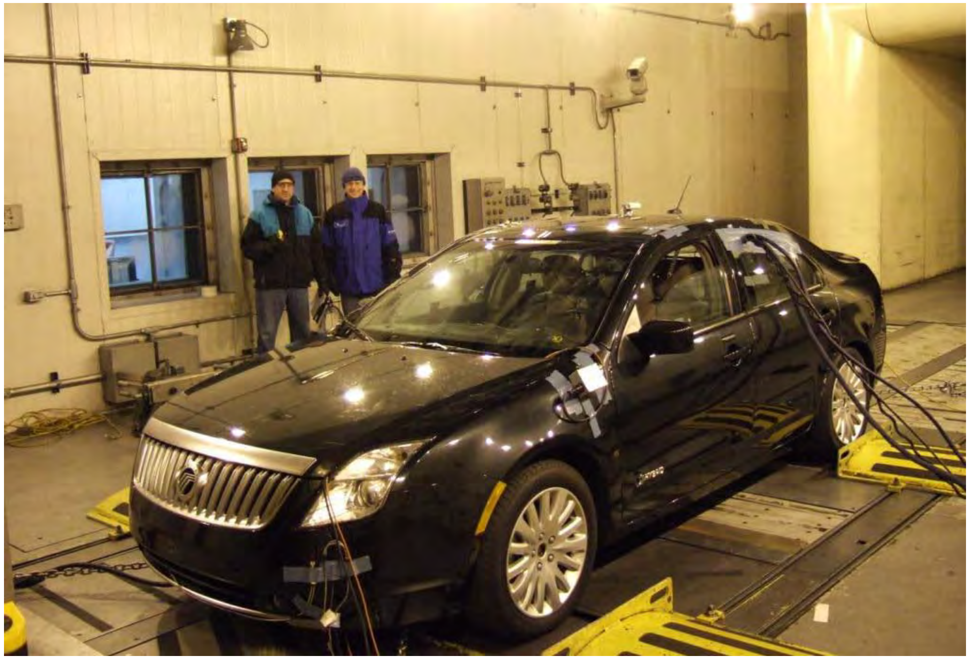
Advanced Thermoelectric Material Development

- Identify and investigate elemental impurities in p- & n-type Bi_2Te_3 to create a performance-improving resonant level.
- Coordinate manufacturing methods with ZT::Plus to develop materials with repeatable performance properties.

Technical Accomplishments: Baseline Testing

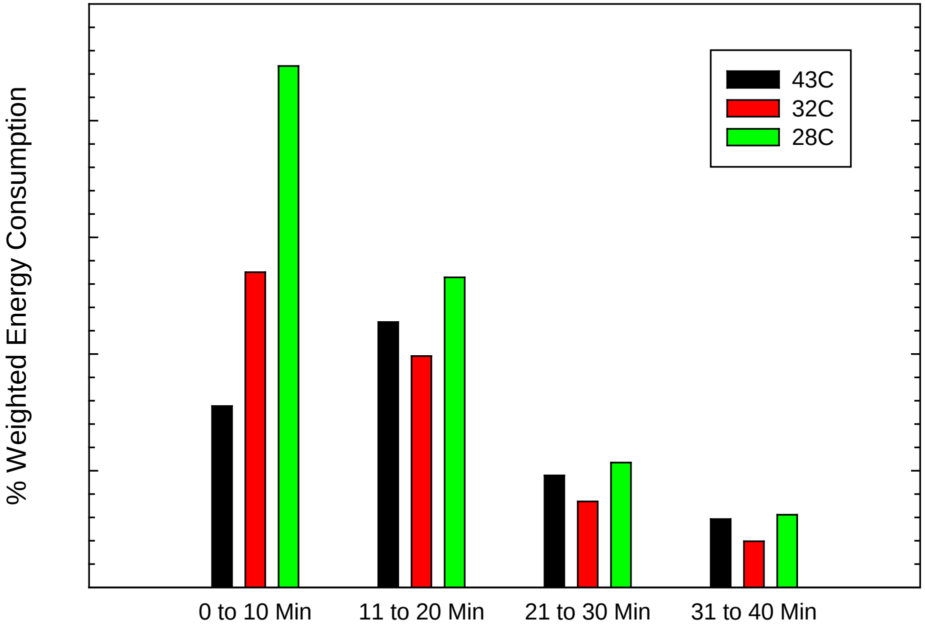
Hot Ambient Testing

Cold Ambient Testing

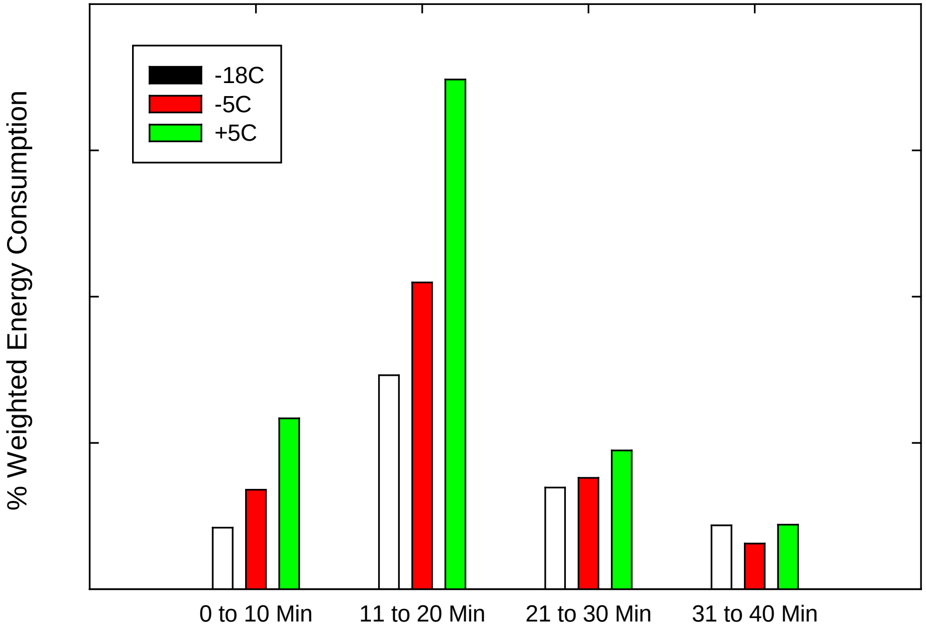


Technical Accomplishments: Energy Usage

A/C Compressor:
Weighted Energy Consumption



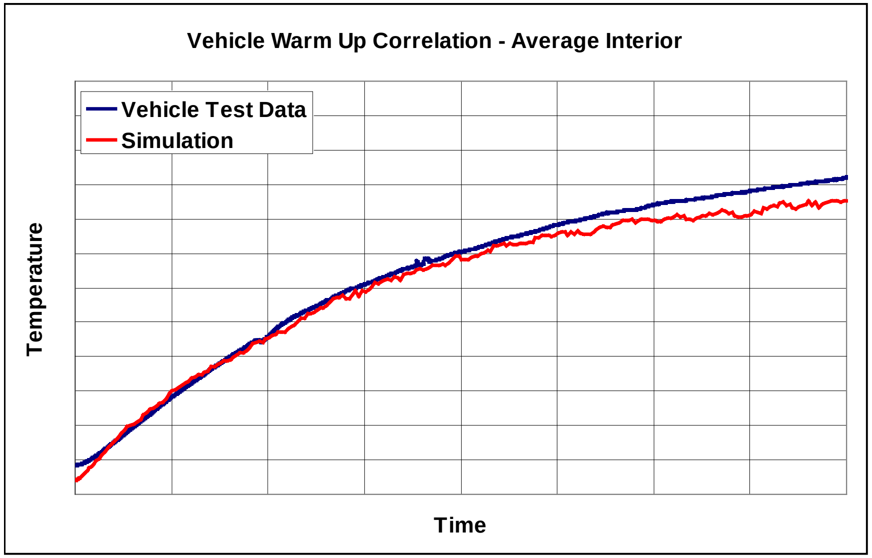
Heater System:
Weighted Energy Consumption

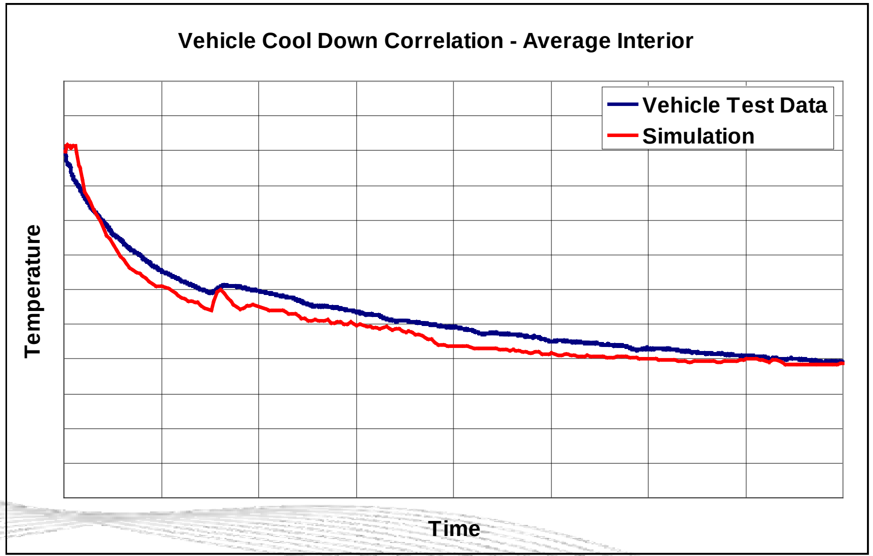


- Cooling energy consumption is initially high due to large demand on blower and A/C compressor
- Heating energy consumption is delayed due to delay in heater core warm-up

Technical Accomplishments – Correlation Modeling

Status:
Objective correlation between vehicle test data and CFD (Computational Fluid Dynamics) simulation is within +/- 3°C on average. All test conditions completed for baseline modeling.
(43°C, 32°C, 28°C, 5°C, -5°C, & -18°C)





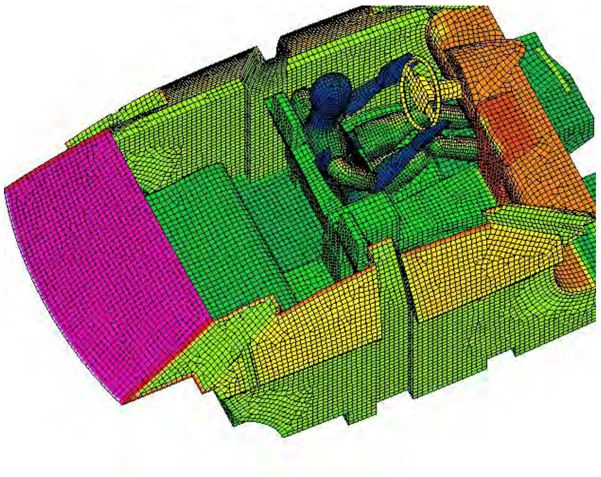
Next Steps:
Run comfort models and compare results to wind tunnel jury evaluation results prior to modeling the selected architecture.

Good correlation achieved enabling good predictive analysis prior to building vehicle

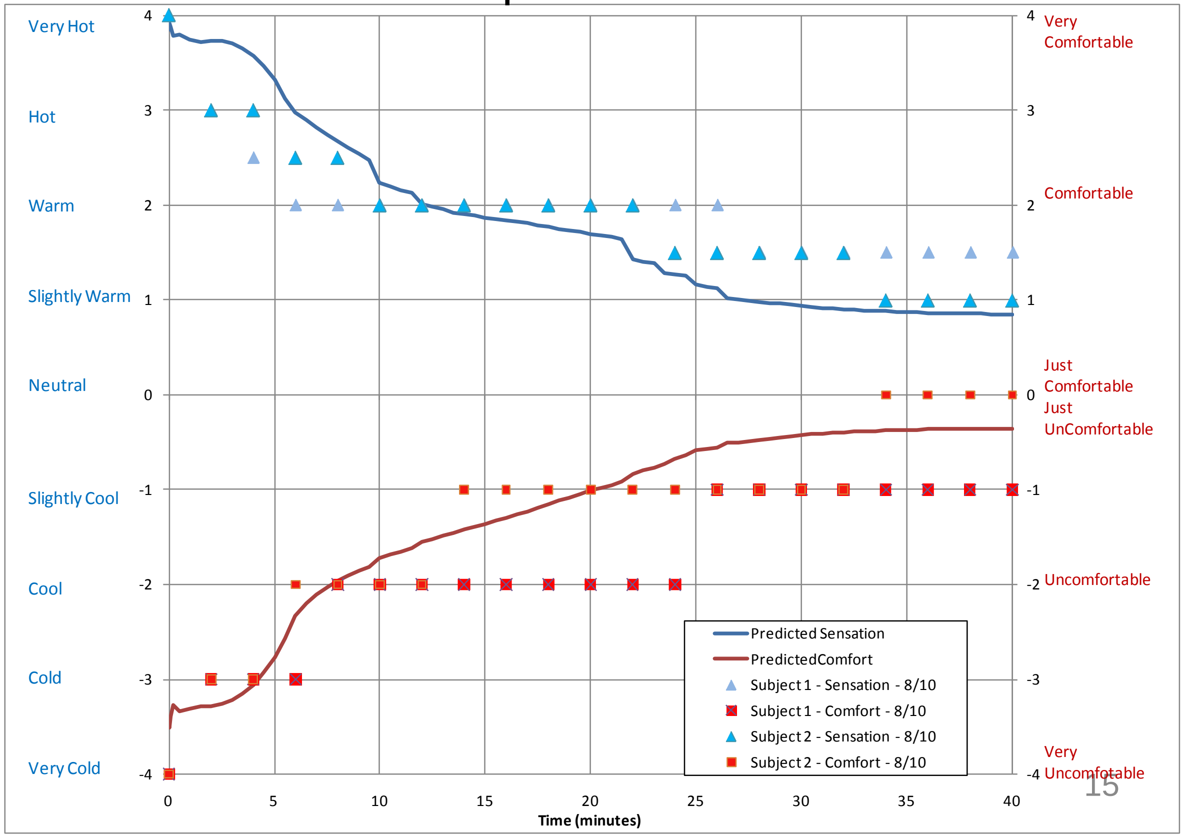
Technical Accomplishments:

Thermal Sensation/Comfort Analysis Options

- Evaluated 3 potential paths
- AcuSolve / RadTherm path show potential for prediction of thermal sensation and comfort



AC pull down test



Technical Accomplishments – ACES Testing

The Air Chamber Evaluation System (ACES) is an environmental chamber with the ability to independently control chamber temperature and the temperature of one or more outlets to simulate a zonal climate system.

Test setup:

- Full instrument panel
- Heated/cooled driver's seat
- Multiple outlet configurations (location & size)

Objective:

- Evaluate multiple distributed outlet configurations to identify high potential climate zonal system architectures with largest impact on thermal comfort.

Results:

- After 100+ trials, zonal climate system architectures were identified for further CAE and jury evaluations in a representative vehicle buck.

Feature Combinations Evaluated

Test #	Test Condition	Weighting %	Feature 1	Feature 2	Feature 3	Feature 4	Feature 5	Feature 6	Feature 7	Feature 8	Feature 9	Feature 10	Feature 11	Feature Delta	Weighted Delta
1	Hot 1	6%	X											0.0	0.00
2		6%	X	X										1.0	0.06
3		6%	X	X	X									1.0	0.06
4		6%	X	X	X	X								0.5	0.03
5	Hot 2	13%	X											0.0	0.00
6		13%	X	X										1.0	0.13
7		13%	X	X	X									0.5	0.07
8		13%	X	X	X	X								0.5	0.07
9	Hot 3	31%	X											0.5	0.16
10		31%	X	X										0.5	0.16
11		31%	X	X	X									1.0	0.31
12		31%	X	X	X	X								0.0	0.00
13	Cold 1	6%	X											0.0	0.00
14		6%	X	X										0.0	0.00
15		6%	X	X	X									0.0	0.00
16		6%	X	X	X	X								0.0	0.00
17	Cold 2	11%	X											1.5	0.17
18		11%	X	X										0.0	0.00
19		11%	X	X	X									0.5	0.06
20		11%	X	X	X	X								0.0	0.00
21	Cold 3	33%	X											1.5	0.50
22		33%	X	X										0.5	0.17
23		33%	X	X	X									0.0	0.00
24		33%	X	X	X	X								1.0	0.33

Individual Features Evaluated

Test #	Test Condition	Weighting %	Feature 1	Feature 2	Feature 3	Feature 4	Feature 5	Feature 6	Feature 7	Feature 8	Feature 9	Feature 10	Feature 11	Feature Delta	Weighted Delta
25	Cold 3	33%	X											1.5	0.50
26		33%		X										1.0	0.33
27		33%			X									0.5	0.17
28		33%				X								0.5	0.17
29	Hot 3	31%	X											0.5	0.16
30		31%		X										0.5	0.16
31		31%			X									1.5	0.47
32		31%				X								1.5	0.47

Additioan Features Evaluated

Test #	Test Condition	Weighting %	Feature 1	Feature 2	Feature 3	Feature 4	Feature 5	Feature 6	Feature 7	Feature 8	Feature 9	Feature 10	Feature 11	Feature Delta	Weighted Delta
33	Cold 3	33%					X							0.0	0.00
34	Hot 3	31%					X							0.0	0.00
35	Cold 3	33%						X						0.0	0.00
36	Hot 3	31%						X						0.0	0.00
37	Cold 3	33%							X					0.0	0.00
38	Hot 3	31%							X					0.0	0.00
39	Cold 3	33%								X				0.0	0.00
40	Hot 3	31%								X				0.0	0.00
41	Cold 3	33%									X			0.0	0.00
42	Hot 3	31%									X			0.0	0.00
43	Cold 3	33%										X		0.0	0.00
44	Hot 3	31%										X		0.0	0.00
45	Cold 3	33%											X	0.0	0.00
46	Hot 3	31%											X	0.0	0.00

Preliminary Architecture Identified for Verification in Vehicle Buck (CAE & subjective)

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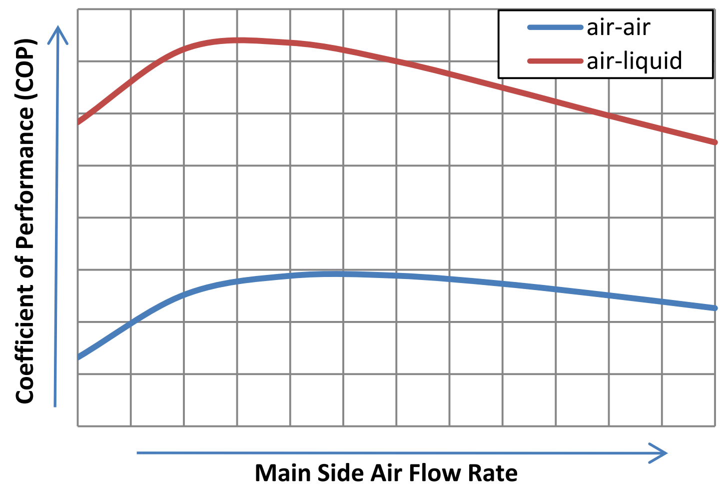
Technical Accomplishments:
Device Optimization Modeling

TED CAE Model Development –

- Developed and used model to perform initial sizing calculations to set over all dimensions of the Phase 1 Liquid-to-Air devices.
- Successfully integrated TED models into a HVAC system performance model.
- Identification & Pareto of the following performance improvement opportunities:
  - Optimization of the liquid size heat exchanger
  - Increase device depth in the airflow direction
  - TE element size
  - Implement thermal isolation
  - Improved dielectric systems



Simulation results compare an Air-to-Air Device vs an Air-to-Liquid device for cooling performance. Both devices have same package volume, TE engines, and are delivering the same Q_c (W). Waste & Main side inlet temperature conditions are constant.

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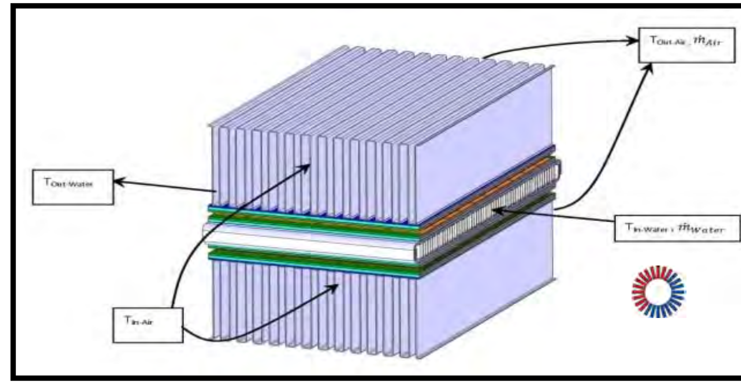
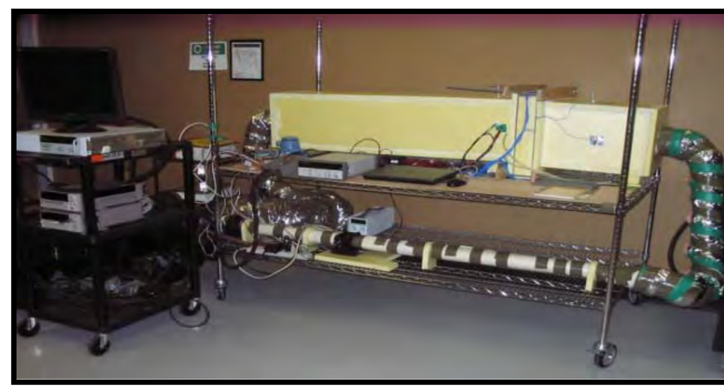
Technical Accomplishments:
TE Device Testing & Model Correlation

Key Accomplishments –

- Calorimeter test apparatus designed and built, enabling validation of device performance:
  - Achieving acceptable energy balances in Cooling mode. Heat mode needs further refinement.
- Correlation study conducted to compare actual test results against CAE model predicted performance. Key issues identified:
  - Improved dataset for interfacial (boundary layer) thermal resistance.
  - More precise coefficient of convective heat transfer for liquid-side HEX is needed.
- Confirmed that with improved inputs, existing model can reliably predict device performance and provide input for system sizing models.



Critical Measurements



Calorimeter Apparatus

Technical Accomplishments:
Advanced TE Material Development

Current Research:

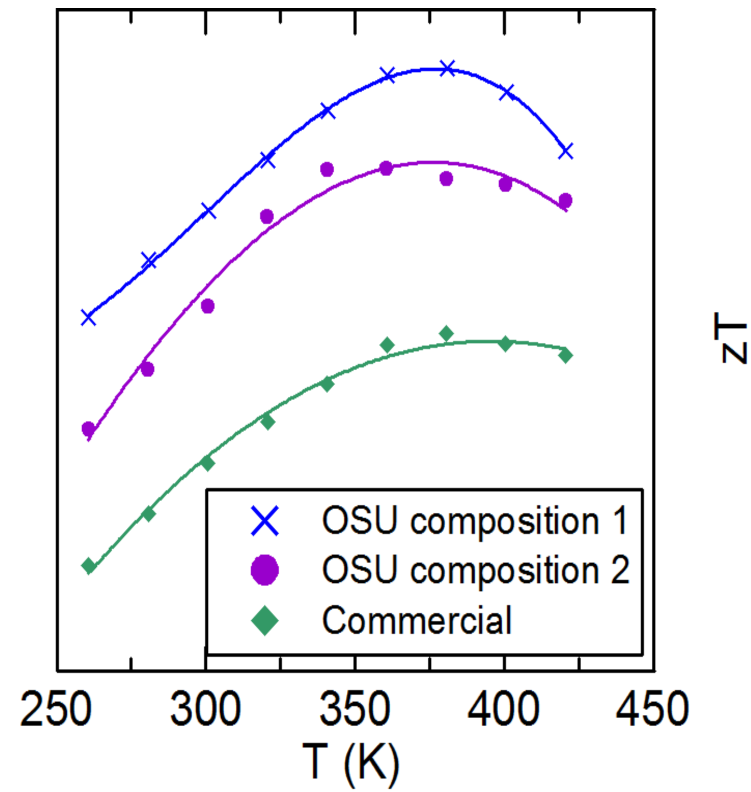
p-type TE materials research

- Attempts at incorporating Sn into commercial p-type Bi_2Te_3 material have shown promise
- Increase in peak zT of ~50% over commercially available p-type Bi_2Te_3
- Confirmation studies underway at OSU and ZT::Plus using different processing techniques

Next Steps:

n-type TE materials research

- Repeat p-type material processing techniques for standard n-type Bi_2Te_3 composition
- Complete literature review to identify unexplored chemical composition region for 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

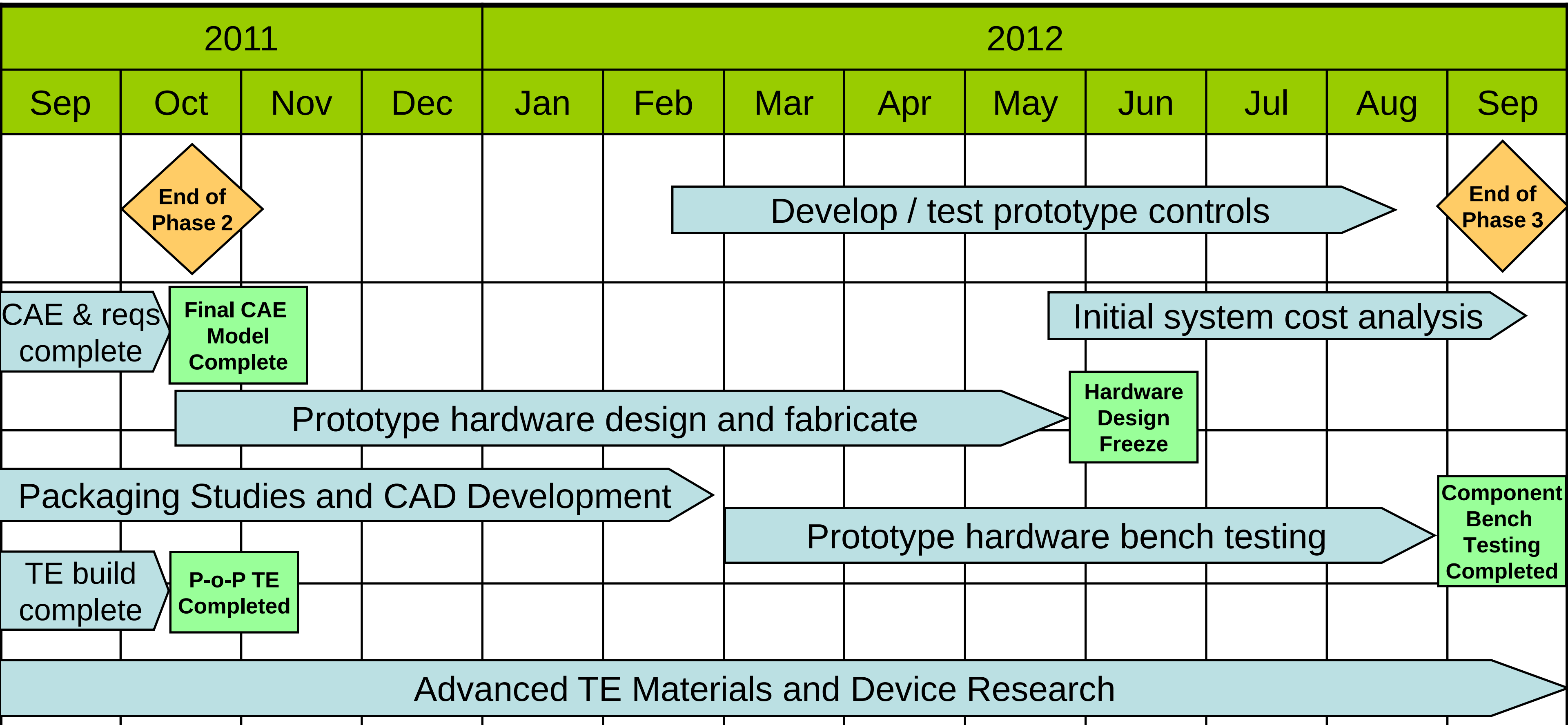
Broad industry/government/academia collaboration with expertise in all aspect of the project

Remaining Critical-Path Activities for FY 2011

- Determine heating/cooling node locations and target output requirements
- Develop systems-level vehicle model to estimate vehicle performance change with TE HVAC architecture
- Conduct CAD study for component packaging
- Complete proof-of-principle TE unit, bench study, and model
- Conduct TE materials research to identify candidate n-type material
- Develop recommendations for advanced comfort model and test validation methodology
- Develop detailed requirements for HVAC system components (blowers, ducts, power supplies, controls, pumps, A/C compressor, HEX, etc…)
- Complete TE HVAC vehicle system specifications and attribute requirements
- End program phase 2 and Go/No-Go decision point

Activities for FY2012

Phase 3 scheduled to begin in FY2012



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 2 milestones and deliverables
  - Baseline testing completed, system architecture design study completed by AMR, advanced p-type TE materials research results encouraging, TED concept device results on-track
- **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

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

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Technical Back-up Slides

Technical Accomplishments and Progress

Test Conditions and Targets 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) 40% RH 1000 W/m^2 Solar	32° C (90° F) 70% RH 1000 W/m^2 Solar	28° C (82° F) 70% RH 1000 W/m^2 Solar	5° C (41° F) No Solar	-5° C (23° F) No Solar	-18° C (0° F) No Solar
Energy Consumption Weighting Factor	6%	13%	31%	33%	11%	6%
Time to Achieve Comfort	16 minutes	12 minutes	8 minutes	8 minutes	12 minutes	17 minutes

TE HVAC Vehicle Thermal Sensation/Comfort Scales

Thermal Sensation

Very Cold	1
Cold	2
Cool	3
Slightly Cool	4
Neutral	5
Slightly Warm	6
Warm	7
Hot	8
Very Hot	9

Thermal Comfort

Very Comfortable	+4
Comfortable	+2
Just Comfortable	+0
Just Uncomfortable	-0
Uncomfortable	-2
Very Uncomfortable	-4

Scales used to assess occupant thermal comfort

Air Chamber Evaluation System - ACES

External View of ACES Chamber with controls

Internal of ACES Chamber with mannequin

Device Optimization Modeling

- Simulation results compare an Air-to-Air Device to a Air-to-Liquid device. Both devices have with the same package volume and utilize the same TE engines. Waste & Main side inlet temperature conditions are also constant for the 2 simulations.

- The Air-to-Liquid device has significantly more cooling capacity for a given set of conditions and in turn can delivery significantly larger temperature differentials.