Integrated Vehicle Thermal Management – Combining Fluid Loops in Electric Drive Vehicles

U.S .Department of Energy
Annual Merit Review

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National Renewable Energy Laboratory

June 17, 2014

Project ID: VSS046

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Overview

Timeline

Project Start Date: FY11
Project End Date: FY14
Percent Complete: 80%

Barriers

- **Complexity:** integrated multi-valve system for multiple thermal loads
- **Low temperature operation:** cabin heating at very low temperatures
- **Front-end heat exchanger frosting:** heat pumping below 0°C ambient

Budget

Total Project Funding (to date):	$ 1,575 K *
Funding for FY13:	$ 575 K *
Funding for FY14:	$ 250 K
Partner In-Kind Cost Share:	$ 375 K **

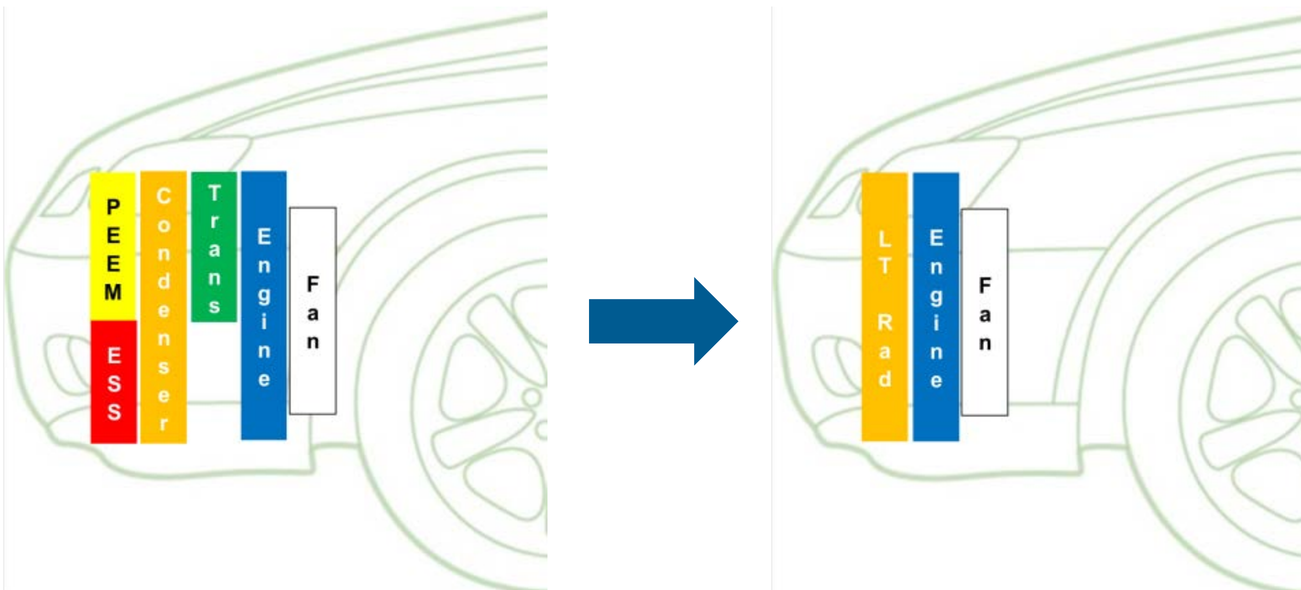
Partners

- Interactions/collaborations:
  - Delphi
  - Halla Visteon Climate Control
- Project Lead: NREL

* Shared funding between VTO programs: VSST, APEEM, ESS
** Not included in total

Relevance: Project Objectives

- **Combine electric drive vehicle (EDV) fluid loops to reduce weight, cost, and energy consumption**
- **Integrated thermal solution to increase EDV range at national level**



- **Recent focus: bench testing**

ESS = energy storage system
PEEM = power electronics and electric motors

Relevance: Support Broad VTO Efforts

- **DOE VTO Multi-Year Program Plan**
  - "… development of advanced vehicles and components to maximize vehicle efficiency …"
- **EV Everywhere Grand Challenge**
  - A goal of EV Everywhere is to have automobile manufacturers produce a car with sufficient range that meets consumers' daily transportation needs
- **Combined Fluid Loop (CFL) Project**
  - Develop CFL system to maximize vehicle efficiency and range by reducing auxiliary loads and improving battery thermal management

VTO = Vehicle Technologies Office

Relevance: VTO Integration

Hybrid Electric Systems
Dave Howell – Program Manager

Vehicle Systems
Lee Slezak
David Anderson

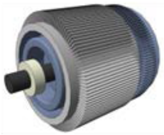
→ **Vehicle electric powertrain model**

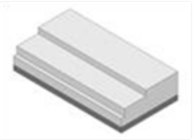
Energy Storage
Tien Duong
Brian Cunningham
Peter Faguy

→ **Battery thermal and efficiency models**

Power Electronics & Electric Motors
Susan Rogers
Steven Boyd

→ **Power electronics and electric motor thermal models**

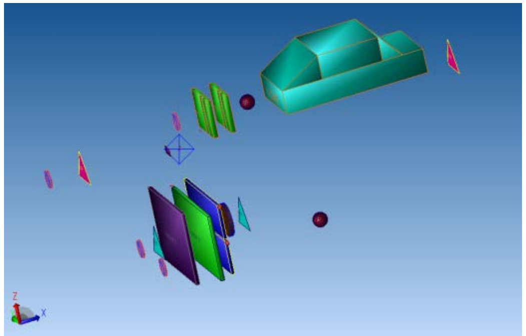




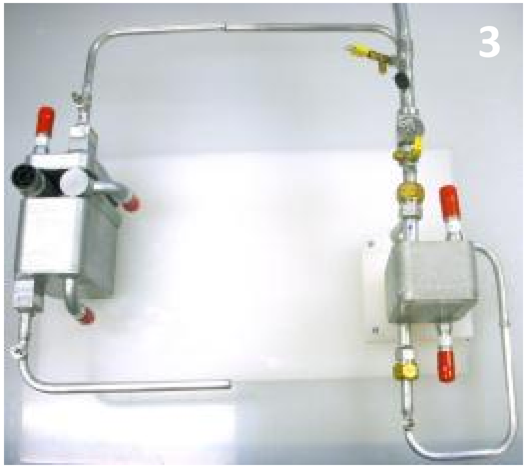
Approach/Strategy: Overview

- Evaluate with 1-D thermal model
- Bench test verification of performance and address technical barriers
- Collaborate with industry on vehicle-level demonstration

Modeling (FY11 & FY12)



Bench Testing (FY13 & FY14)

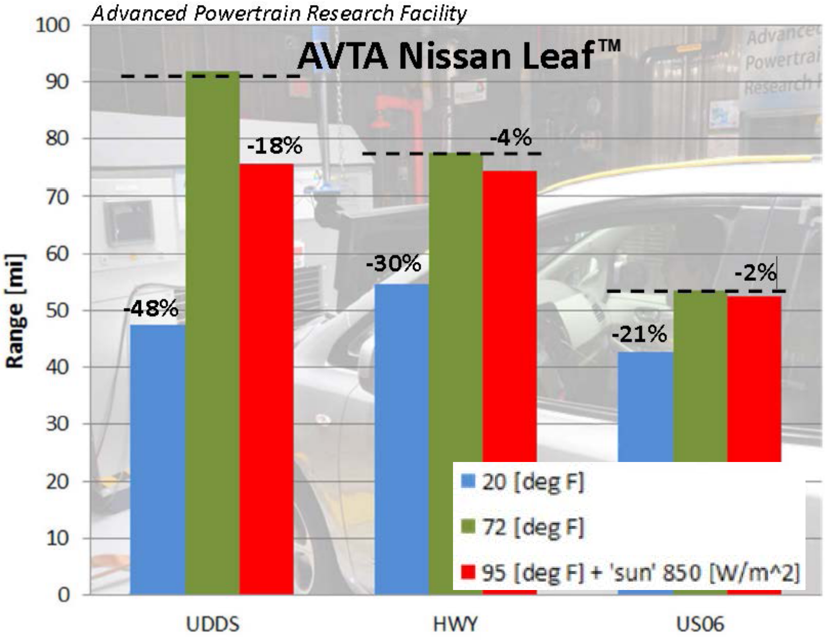


Vehicle Testing (Future)

Approach/Strategy: Challenges

- **Investigate performance over wide range of conditions**
- **Enable heat pump operation and waste heat recovery**
- **Identify efficiency versus complexity trade-offs to develop solutions for cost reduction and EDV range improvement**

Impact of Temperature on Range



*ANL climate chamber dynamometer testing of stock 2012 Nissan Leaf

ANL = Argonne National Laboratory
AVTA = Advanced Vehicle Testing Activity

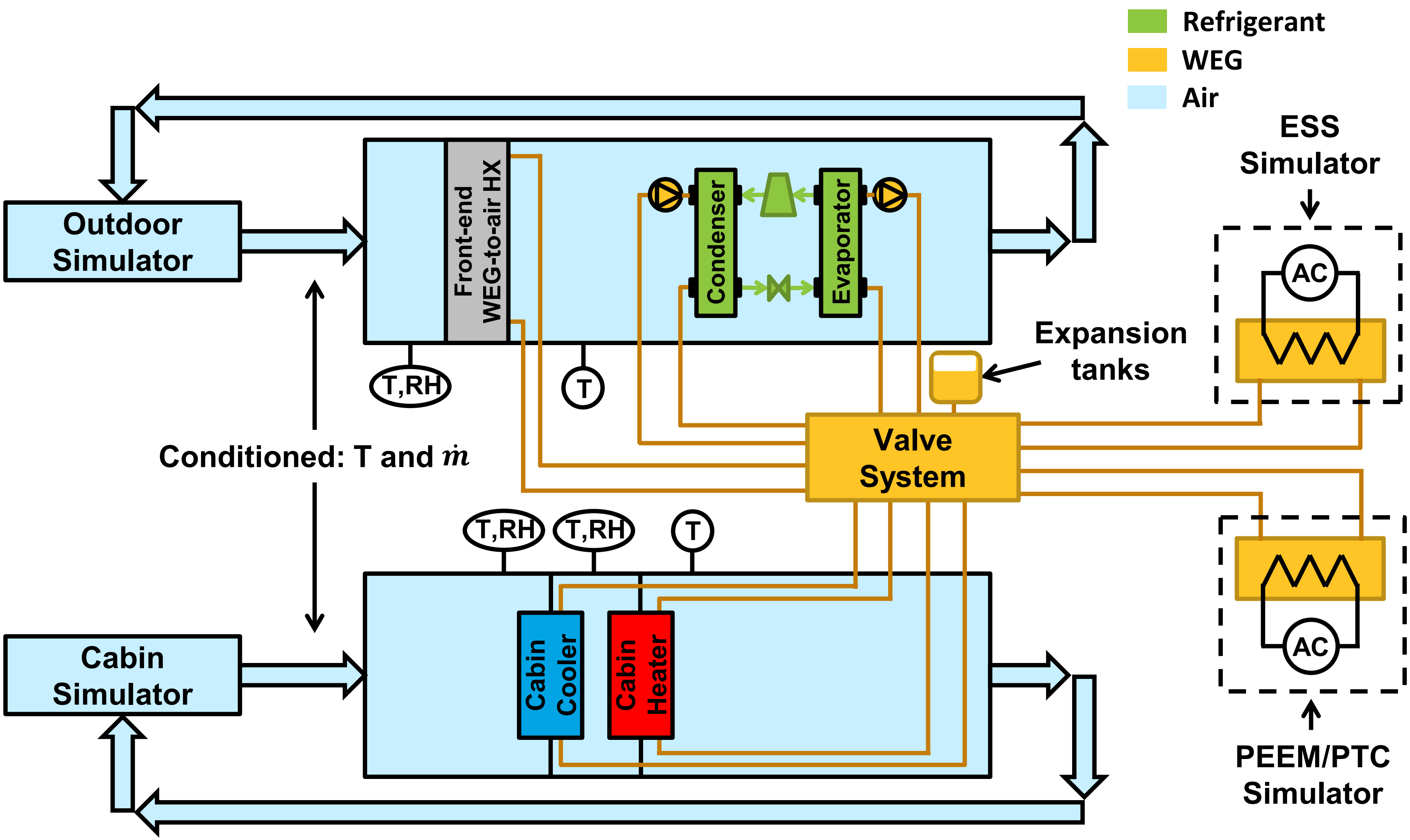
Milestones

Month/Year	Description
Q3 June 2014	Milestone: • Complete modifications of bench test apparatus for cold weather operation and test the CFL concept in a cold environmental chamber
Q4 Sept. 2014	Milestone: • Submit a summary of the project results in the DOE annual report format

Technical Accomplishments and Progress: Overview

- **March 2013 to March 2014 – Bench testing**
  - Constructed bench test apparatus
  - Integrated vehicle, power electronics, electric motor, battery, and cabin models into LabVIEW data acquisition and control system
  - Constructed CFL system using prototype heat exchangers from Delphi and an electric compressor from HVCC
  - Completed hot weather steady-state testing
  - Near completion of hot weather drive-cycle testing

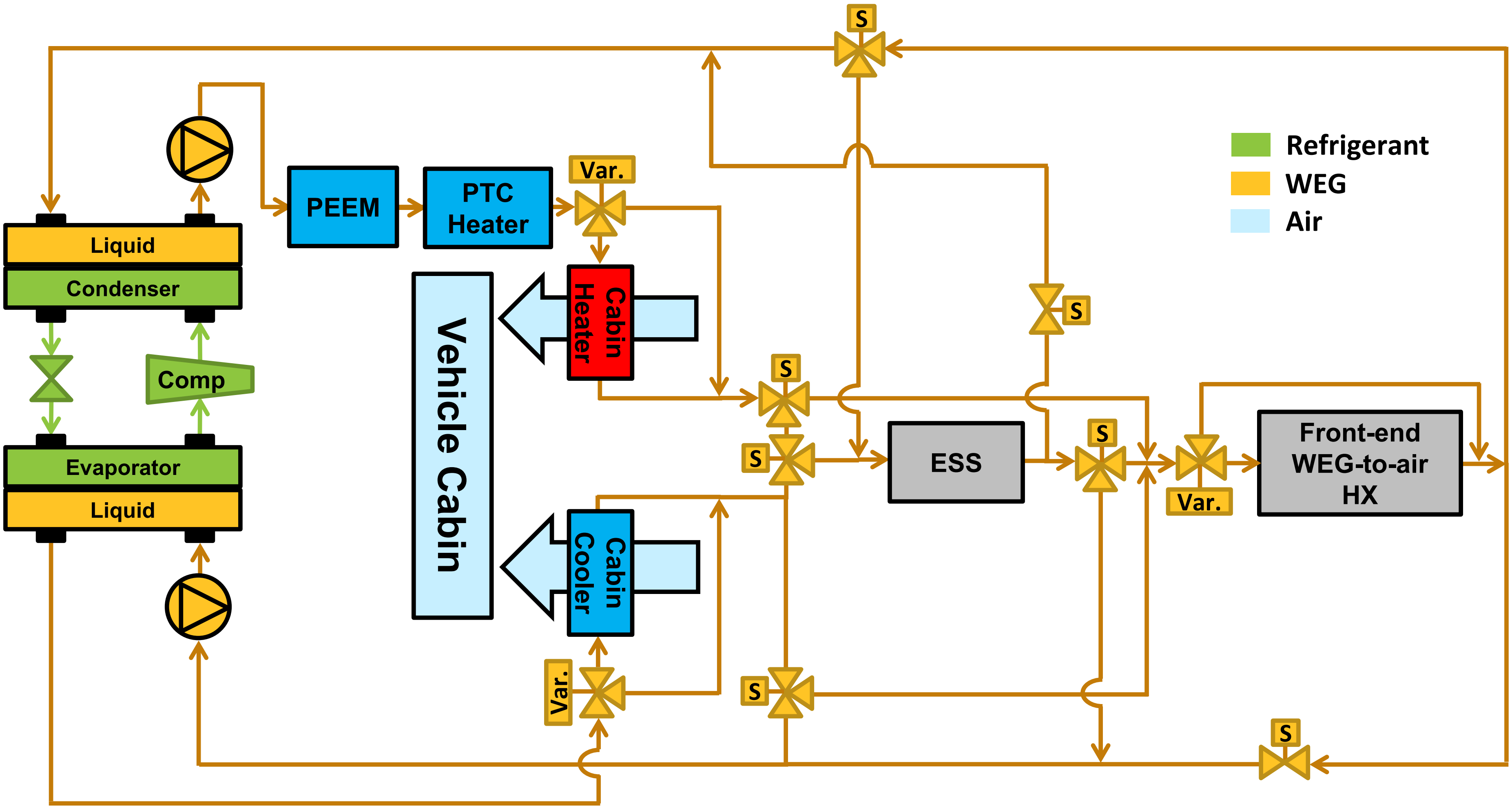
Technical Accomplishments and Progress: Test Apparatus



- **Designed for hardware-in-the-loop drive cycle testing with vehicle load simulation**

HX = heat exchanger
PTC = positive temperature coefficient
WEG = water/ethylene glycol

Technical Accomplishments and Progress: CFL System

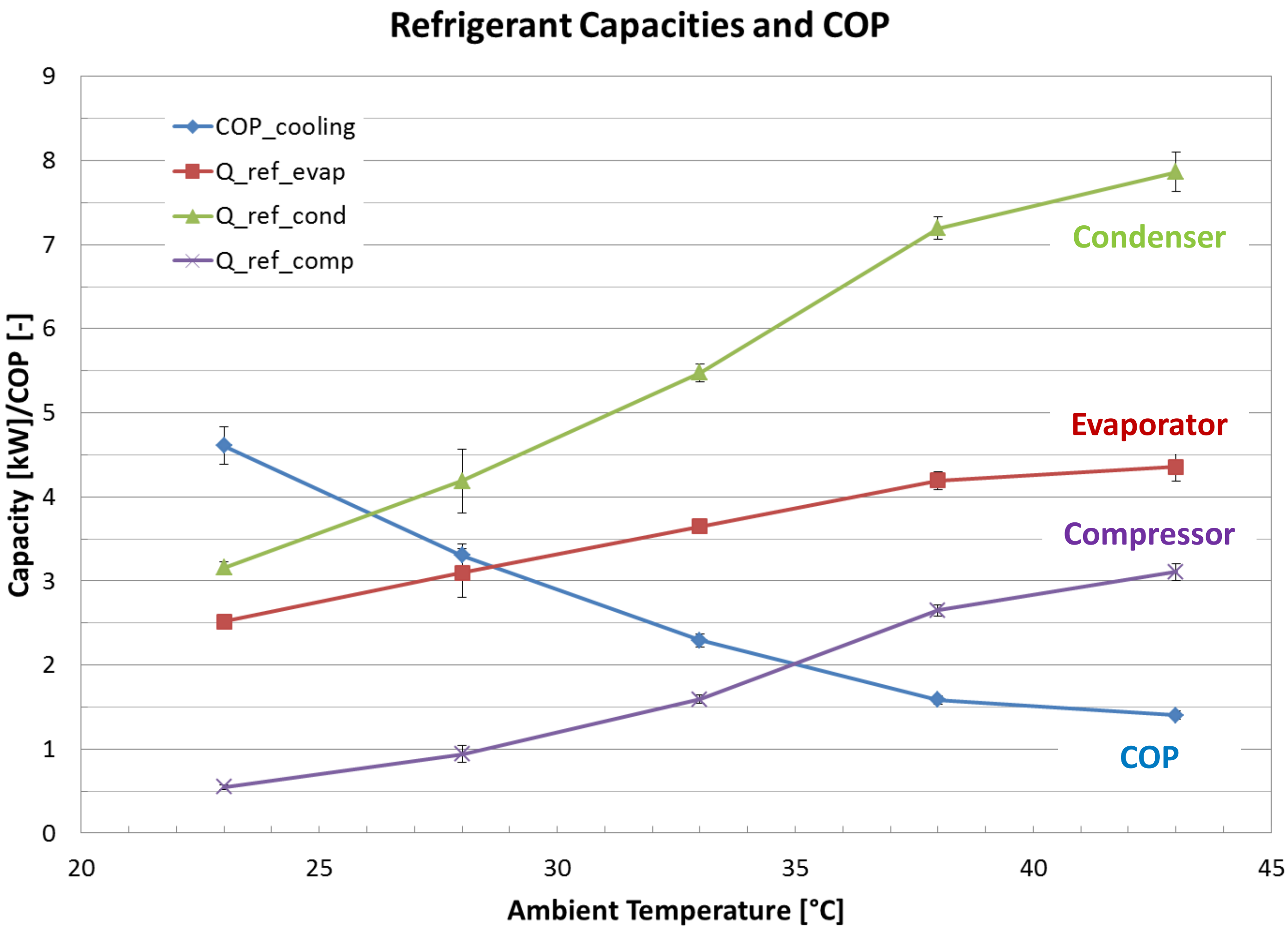


- Allows multiple configuration strategies, including waste heat recovery and heat pumping

Technical Accomplishments and Progress: Test Apparatus

- **Most important technical accomplishment was successful design, construction, and operation of CFL test bench**

Technical Accomplishments and Progress: Steady-State Cooling

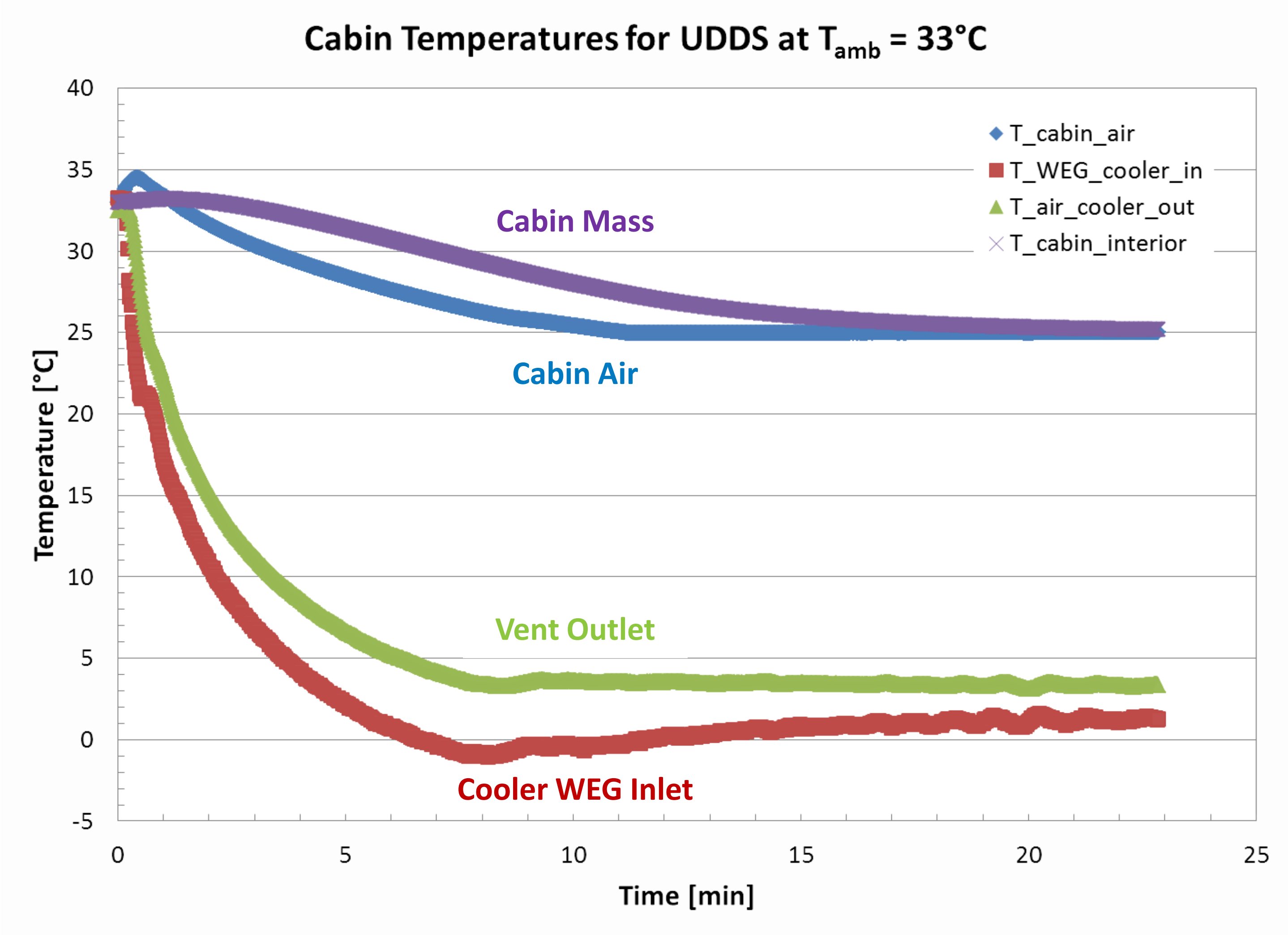


- **Stable system operation, reasonable energy balances and errors, and performance meeting expectations**

COP = coefficient of performance

Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary

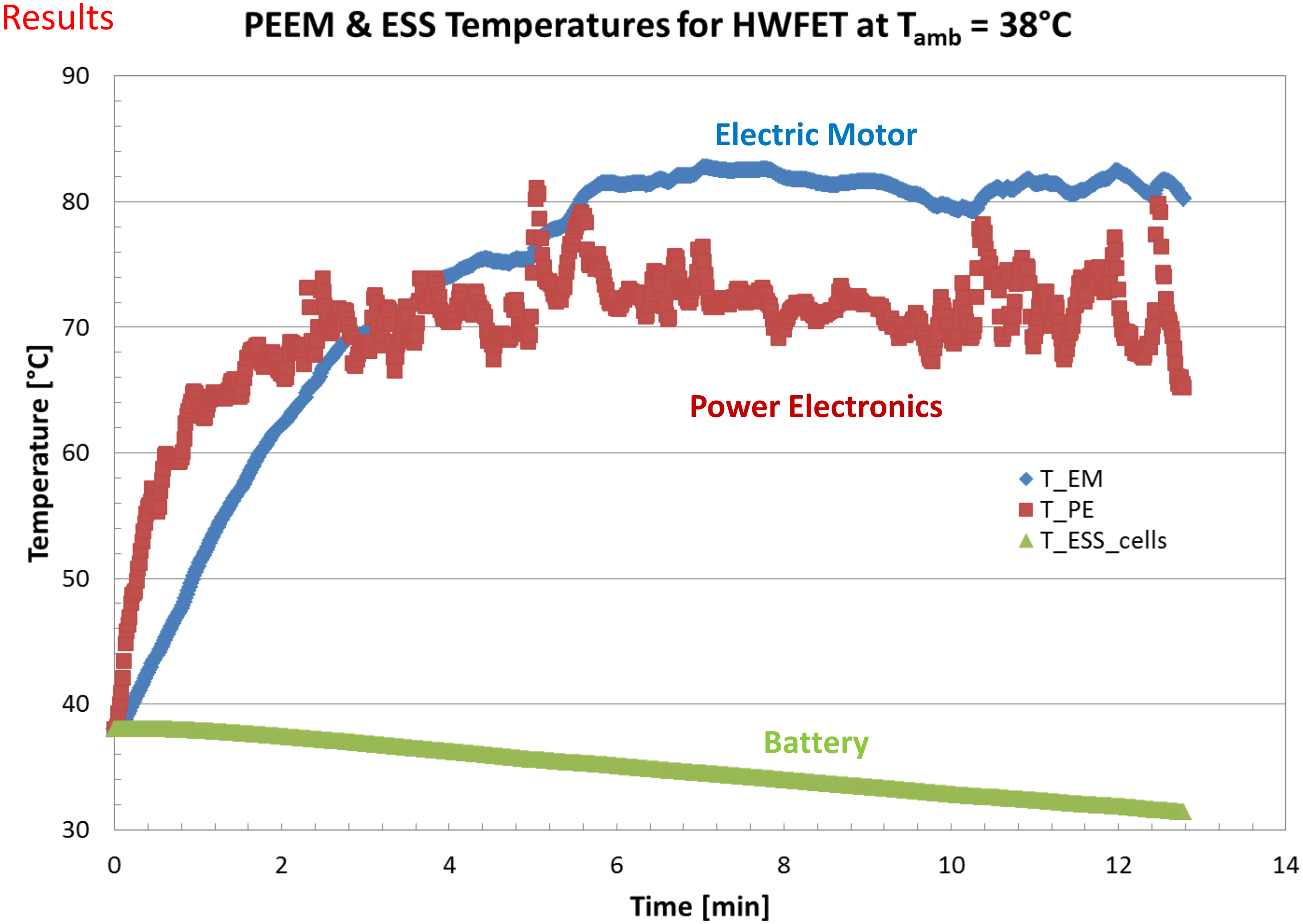


- **Cabin pull-down penalty due to experiment thermal mass – real system more compact**

UDDS = Urban Dynamometer Driving Schedule

Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results

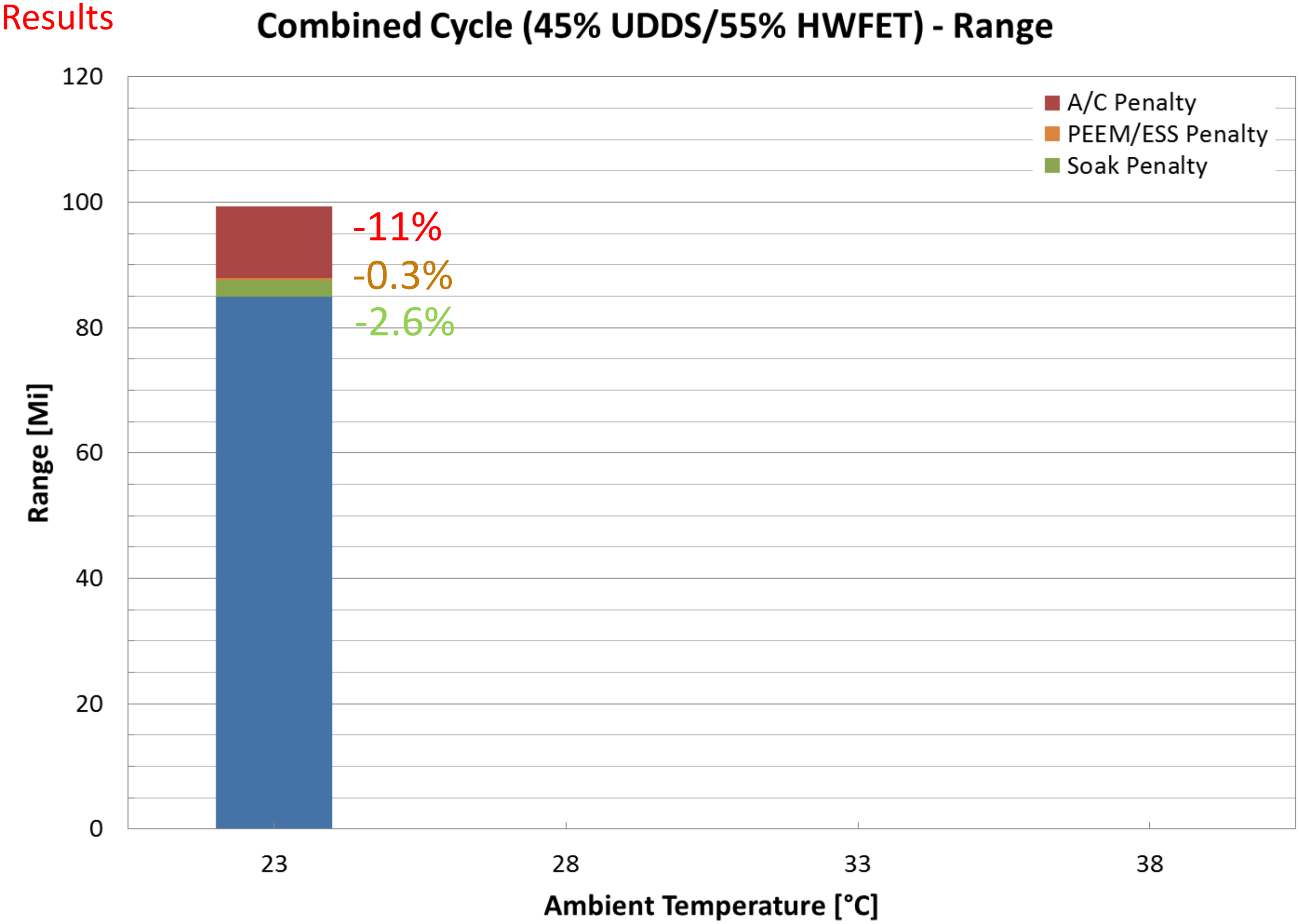


- **PEEM temperatures within thermal limits, ESS control strategy needs further investigation**

HWFET = Highway Fuel Economy Driving Schedule

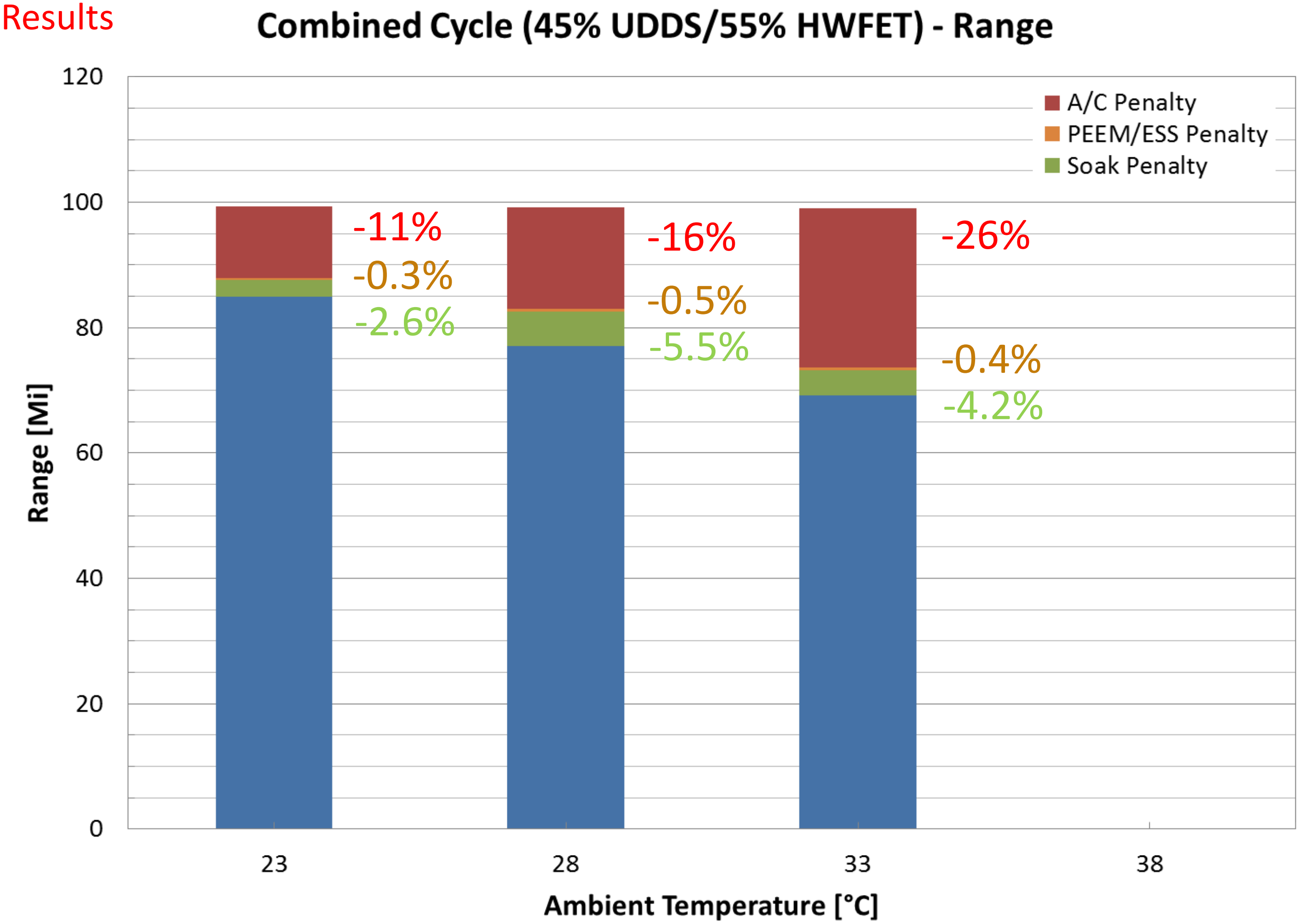
Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results



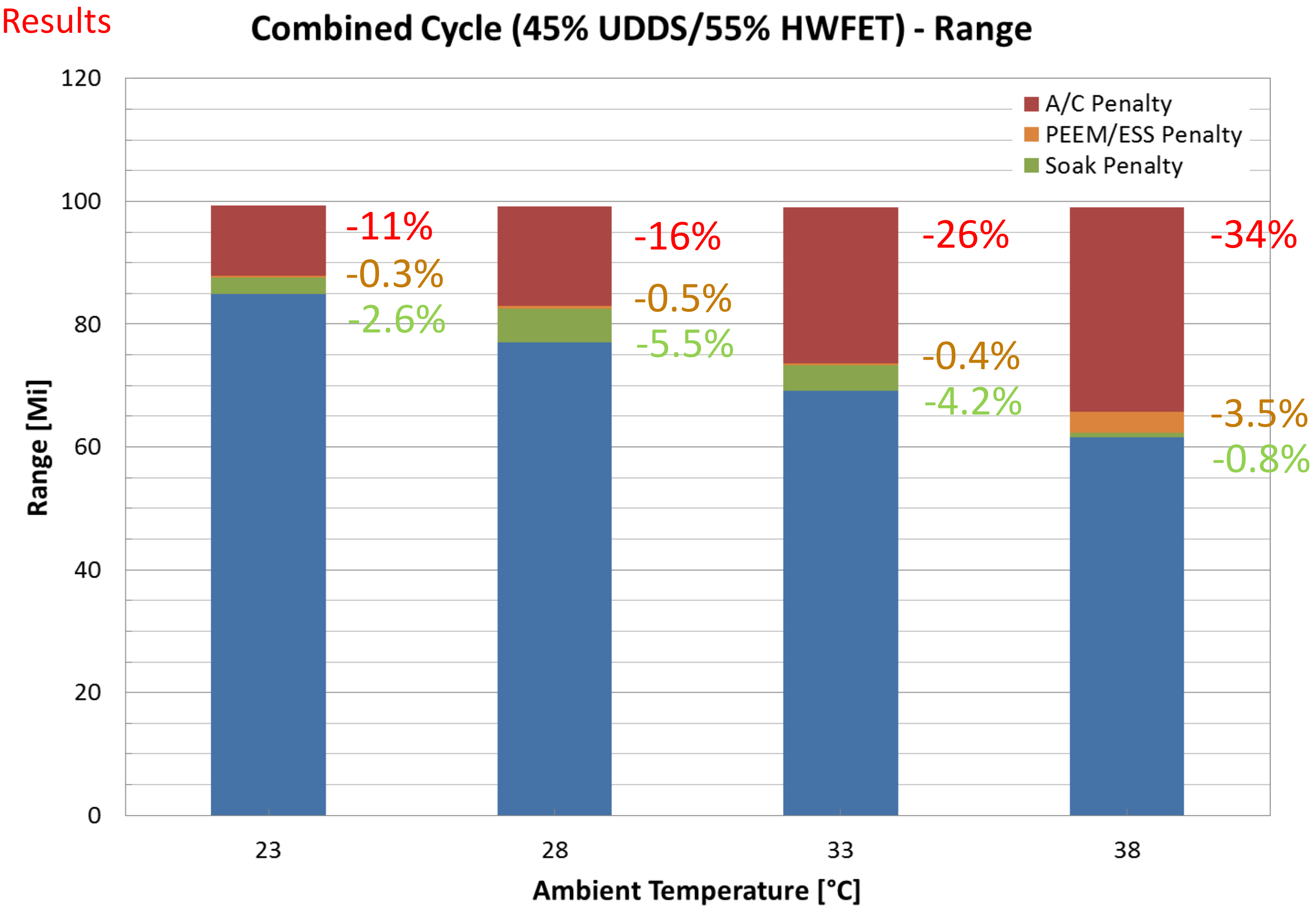
Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results



Technical Accomplishments and Progress: Drive Cycle Cooling

*Preliminary Results



- **PEEM cooling <1% penalty to range, ESS cooling penalty significant at higher ambient temperatures**

Responses to FY13 AMR Reviewers' Comments

Comment:	Consider defog and defrost
Response:	• Without vehicle cabin, direct testing is not possible, but heating capacity matches conventional vehicle • If vehicle test is pursued, direct evaluation is possible
Comment:	Collaborate with vehicle OEM
Response:	• Bench testing in close collaboration with Delphi • Interest from Delphi and a vehicle OEM to develop technology for vehicle demonstration
Comment:	Characterize baseline for "extreme" environments
Response:	• Bench testing at ambient temperatures from -30°C to 43°C

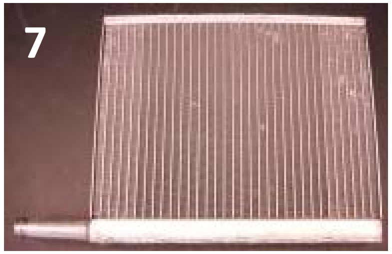
OEM = original equipment manufacturer

Collaboration: Delphi

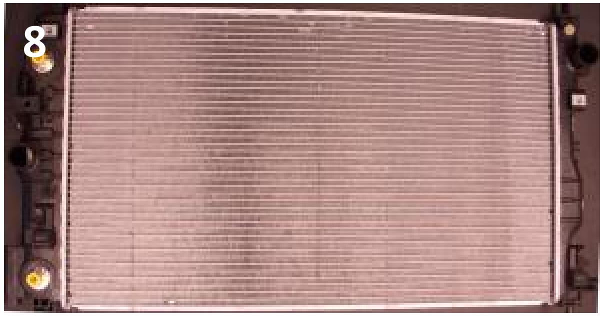
- **Delphi provided prototype refrigerant-to-coolant, and coolant-to-air heat exchangers**

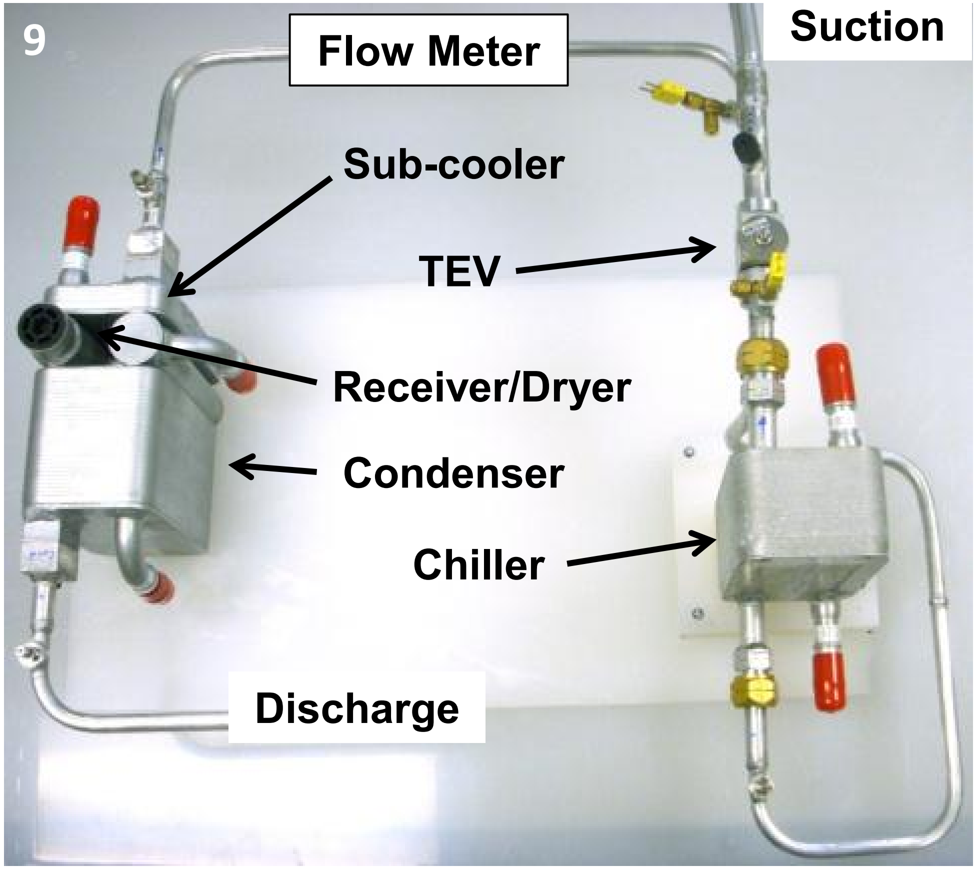
Heater Core

Cooler Core



Front-end Heat Exchanger

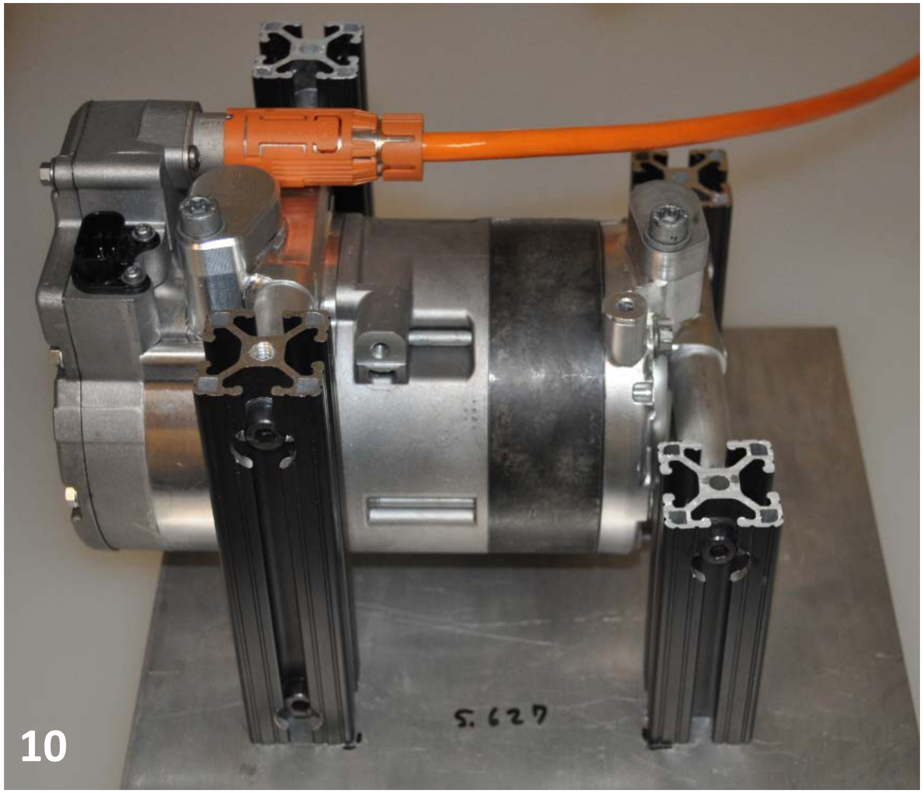




TEV = thermostatic expansion valve

Collaboration: Halla Visteon Climate Control

- **Halla Visteon Climate Control provided high-voltage DC electric compressor capable of heat pump operation**



Collaboration: Summary

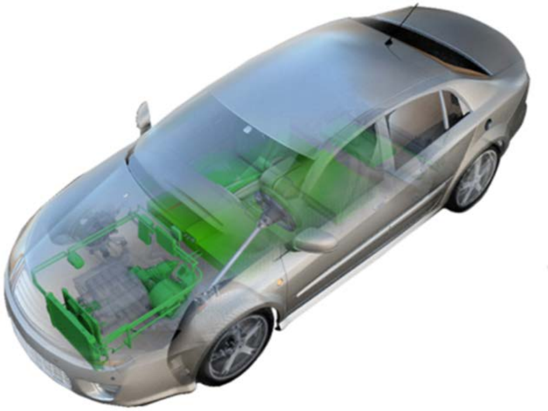
- **Industry**
  - Delphi
  - Halla Visteon Climate Control
- **VTO Tasks**
  - Advanced Power Electronics and Electric Motors
    - PEEM thermal models
  - Vehicle Systems
    - FASTSim vehicle powertrain model
  - Energy Storage Systems
    - Battery thermal and efficiency (voltage vs. temperature) models

Remaining Challenges and Barriers

- **Complexity**
  - Must define trade-offs between complexity and efficiency for industry buy-in
- **Low temperature operation**
  - Cold weather testing must demonstrate sufficient heat pump performance when supplemented with waste heat
- **Front-end heat exchanger frosting**
  - Testing must measure impact of hot coolant defrost cycling

Proposed Future Work

- **Remainder of FY14**
  - Complete hot weather drive cycle testing
  - Conduct cold weather drive cycle testing
  - Identify best practices for system design and control
  - Analyze technology impact on EDV range and thermal management
- **FY15 and beyond**
  - Work with industry partners (suppliers and an OEM) to demonstrate technology at vehicle level



Summary

- Designed and built test apparatus to validate potential of CFL to reduce cost, weight, and volume of thermal system while increasing vehicle range
- Hot weather testing almost complete, cold weather testing to begin soon
- Looking to work with industry partners on a vehicle-level demonstration to develop the technology and reduce national energy consumption

Acknowledgments and Contacts

Special thanks to:

Vehicle Technologies Office
U.S. Department of Energy
Lee Slezak
David Anderson

Industry collaborations:

Delphi
Halla Visteon Climate Control

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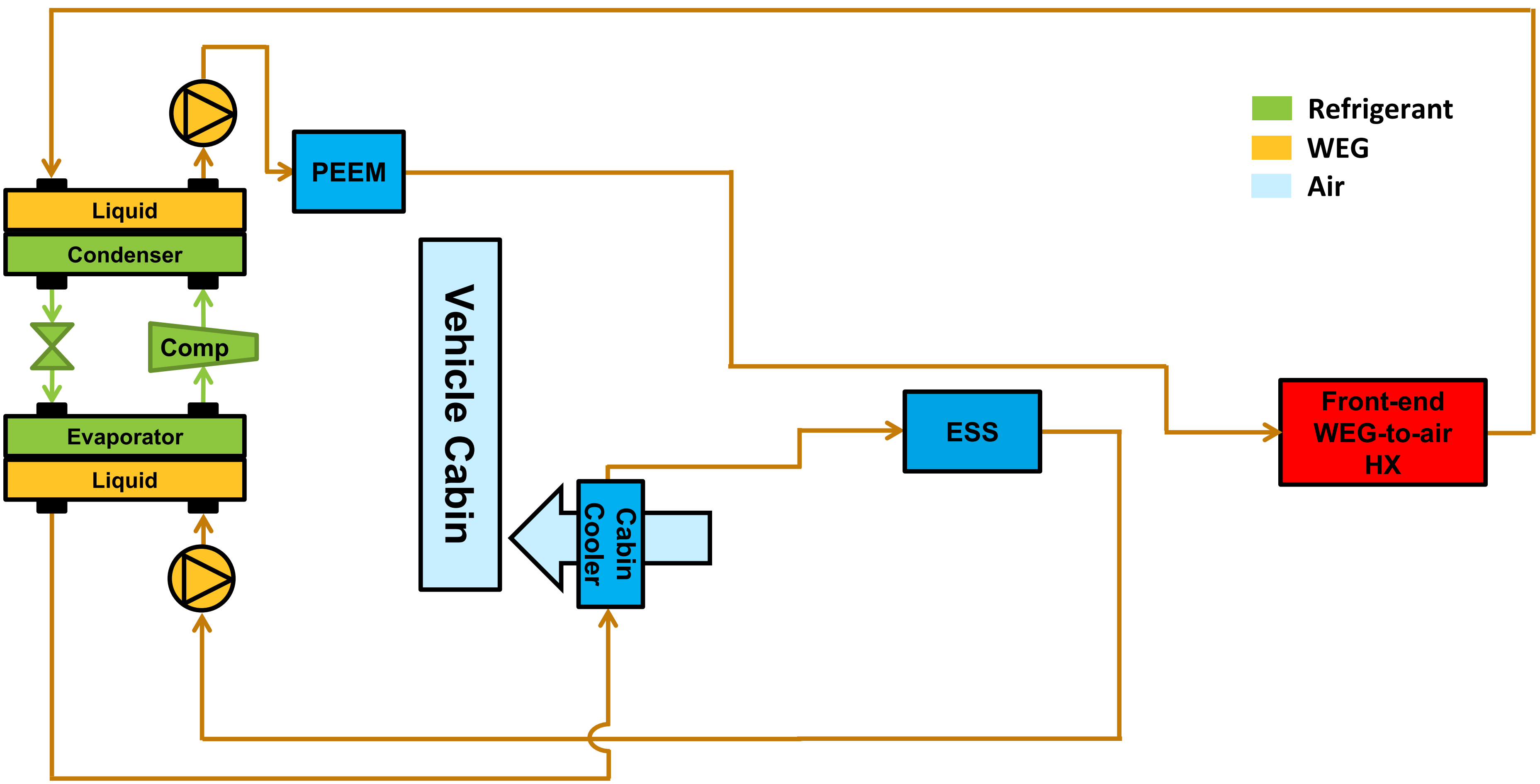
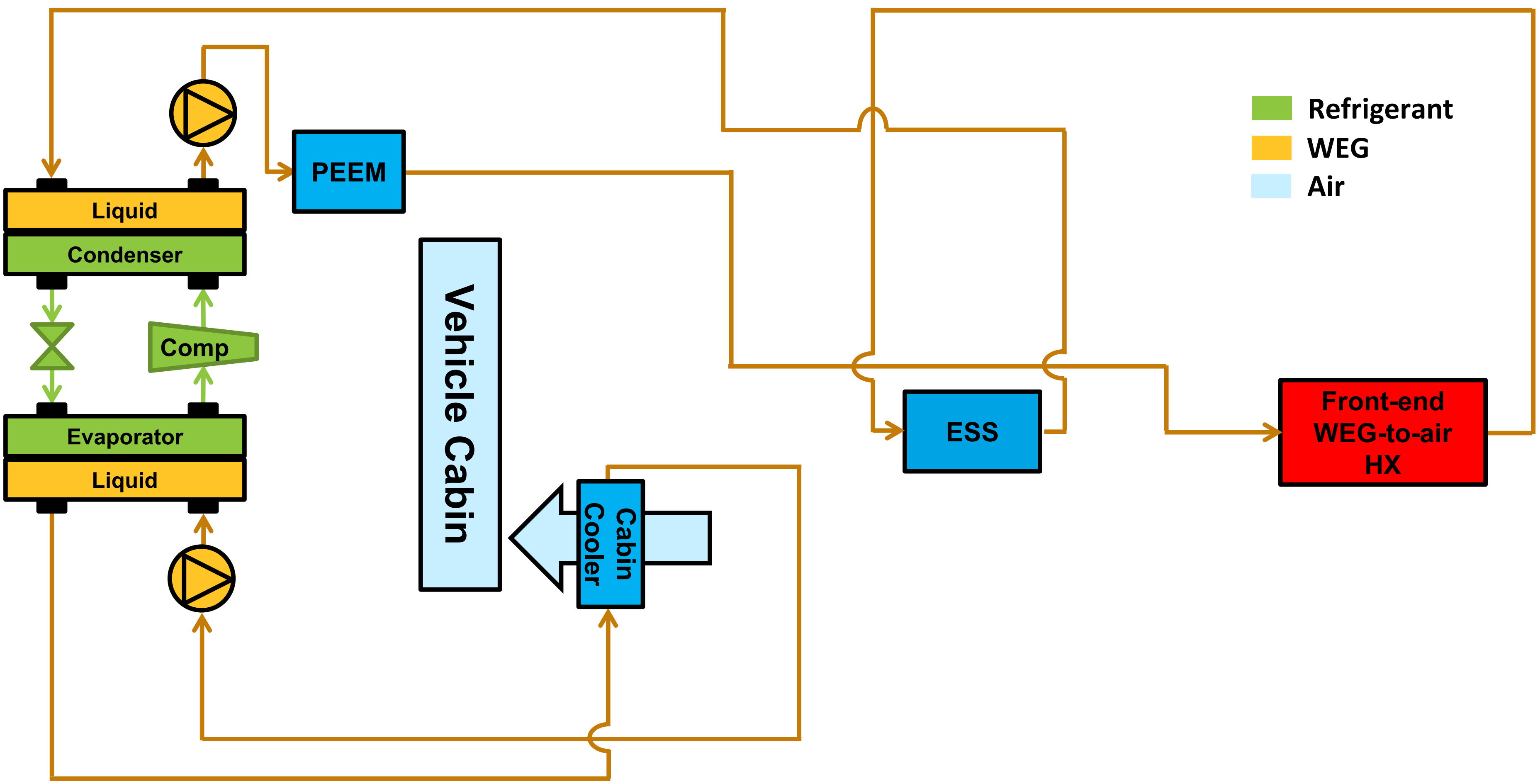
Technical Back-Up Slides

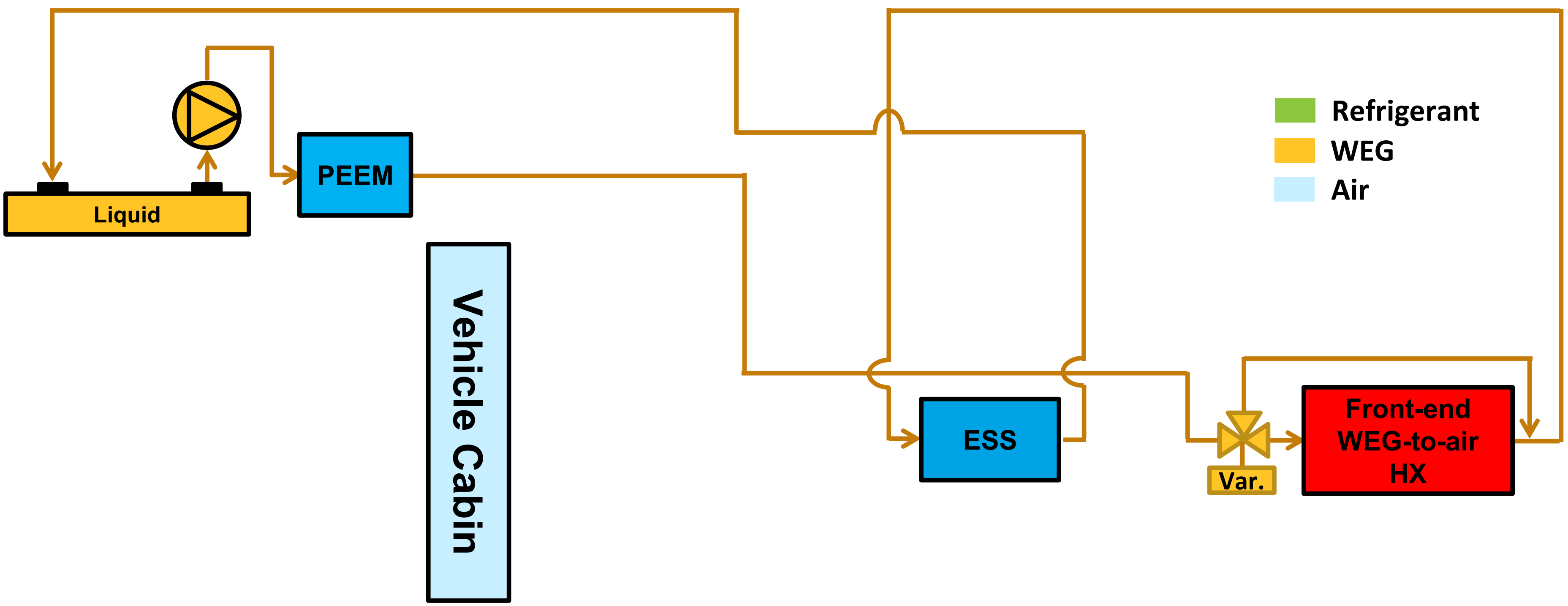
Cooling Mode (Active ESS Cooling)



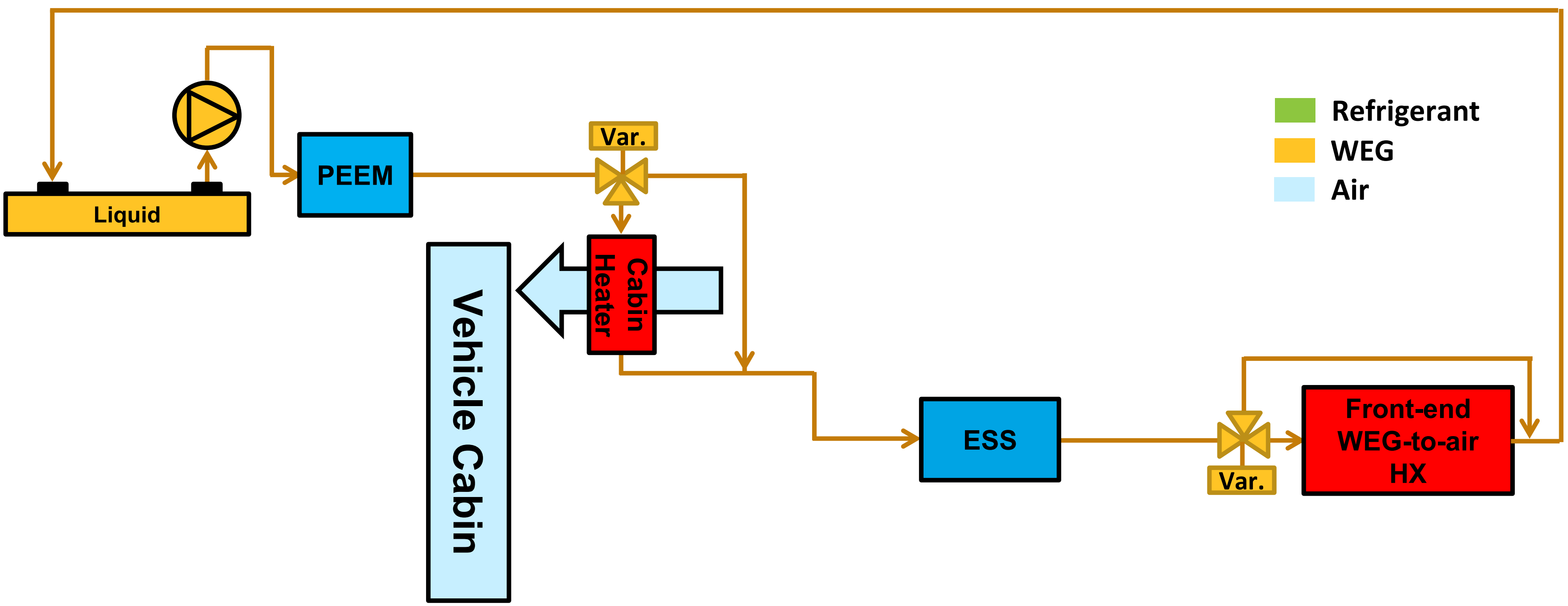
Cooling Mode (Passive ESS Cooling)



"Free" Cooling Mode



Mild Heating Mode (Only Heat Recovery)



Heating Mode