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




John P. Rugh
National Renewable Energy Laboratory
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Overview

Timeline

Project Start Date: FY11
Project End Date: FY14
Percent Complete: 50%

Budget

Total Project Funding (to date): $ 1225 K *
Funding received prior to FY13: $ 750 K *
Funding for FY13: $ 475 K *
Partner In-Kind Cost Share: $ 300 K **

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

Barriers (to EDVs)

- Cost – cooling loop components
- Life – thermal effects on energy storage system (ESS) and advanced power electronics and electric motors (APEEM)
- Weight – additional cooling loops in electric drive vehicles (EDVs)

Partners

- Interactions/ collaborations
  - Delphi
  - Halla Visteon Climate Control
  - Magna Powertrain - Engineering Center Steyr
  - Ford
- Project Lead
  - National Renewable Energy Laboratory

Relevance - The PHEV/EV Thermal Challenge

- **Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) have increased vehicle thermal management complexity**
  - Separate coolant loop for advanced power electronics and electric motors (APEEM)
  - Thermal requirements for energy storage systems (ESS)
- **Additional thermal components result in higher costs**
- **Multiple cooling loops lead to reduced range due to**
  - Increased weight
  - Energy required to meet thermal requirements

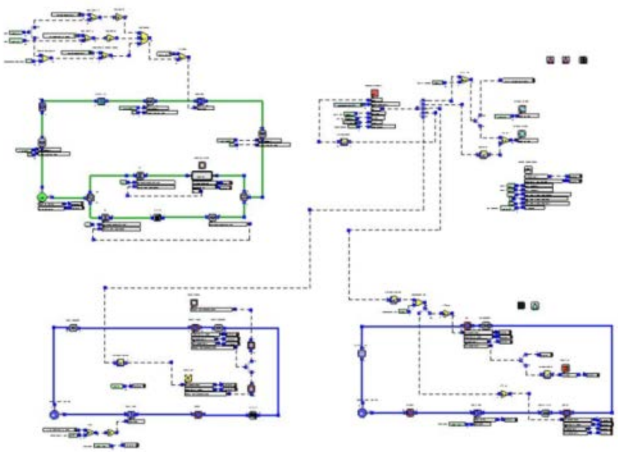
Relevance

- **Support broad VTO efforts**
  - DOE VTO MYPP
    - "…..development of advanced vehicles and components to maximize vehicle efficiency ….."
    - This projects seeks to maximize vehicle efficiency by developing combined cooling loop solutions to reduce parasitic power, improved battery temperature, and increase range.
  - President's EV-Everywhere Grand Challenge
    - A goal of EV Everywhere is to have automobile manufacturers produce a car with sufficient range that meets consumer's daily transportation needs.
    - This project is researching techniques to reduce vehicle thermal management power and improve range.
- **Task Objective**
  - Collaborate with industry partners to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains
  - Solve vehicle-level heat transfer problems, which will enable acceptance of electric drive vehicles

Approach/Strategy

- **Research benefits** of combining EV thermal management systems
- **Develop solutions** to combine vehicle-level cooling systems
- **Improve vehicle performance** (fuel use or EV range) and reduce cost
- **Reduce APEEM coolant loop temperature** (to less than 105°C) without requiring a dedicated system

Overall Approach



- **Build a 1-D thermal model (using KULI software)**
- **Conduct bench tests to verify performance and identify viable hardware solutions**
- **Collaborate with automotive manufacturers and suppliers on a vehicle-level project**

Approach/Strategy - Integration Between Vehicle Technology Programs

Hybrid Electric Systems
Dave Howell – Team Lead

Vehicle Systems
Lee Slezak
David Anderson

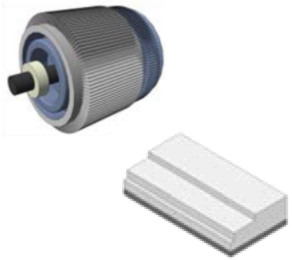
→ **Electric range and fuel consumption**

Energy Storage
Tien Duong
Brian Cunningham
Peter Faguy

→ **Battery temperature and life**

Power Electronics & Electric Motors
Susan Rogers
Steven Boyd

→ **APEEM temperatures**

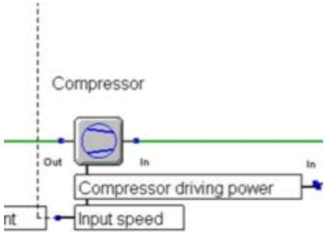


Approach - Milestones

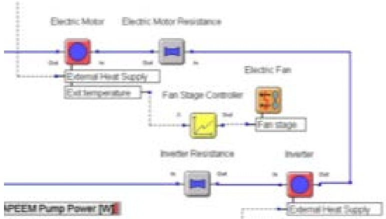
Month / Year	Description
Sept/12	Milestone • Identified advantages of combining fluid loops and strategies for bench testing Go/No-Go • Based on the successful outcome of analysis of the thermal management system concepts, build a bench test facility to evaluate combined cooling loop strategies
Sept/13	Milestone • Evaluate combined cooling loop system performance during cooling mode using bench testing Go/No-Go • Based on bench test results, design a vehicle-level test that can demonstrate vehicle system level performance using a combined cooling loop system

Accomplishments

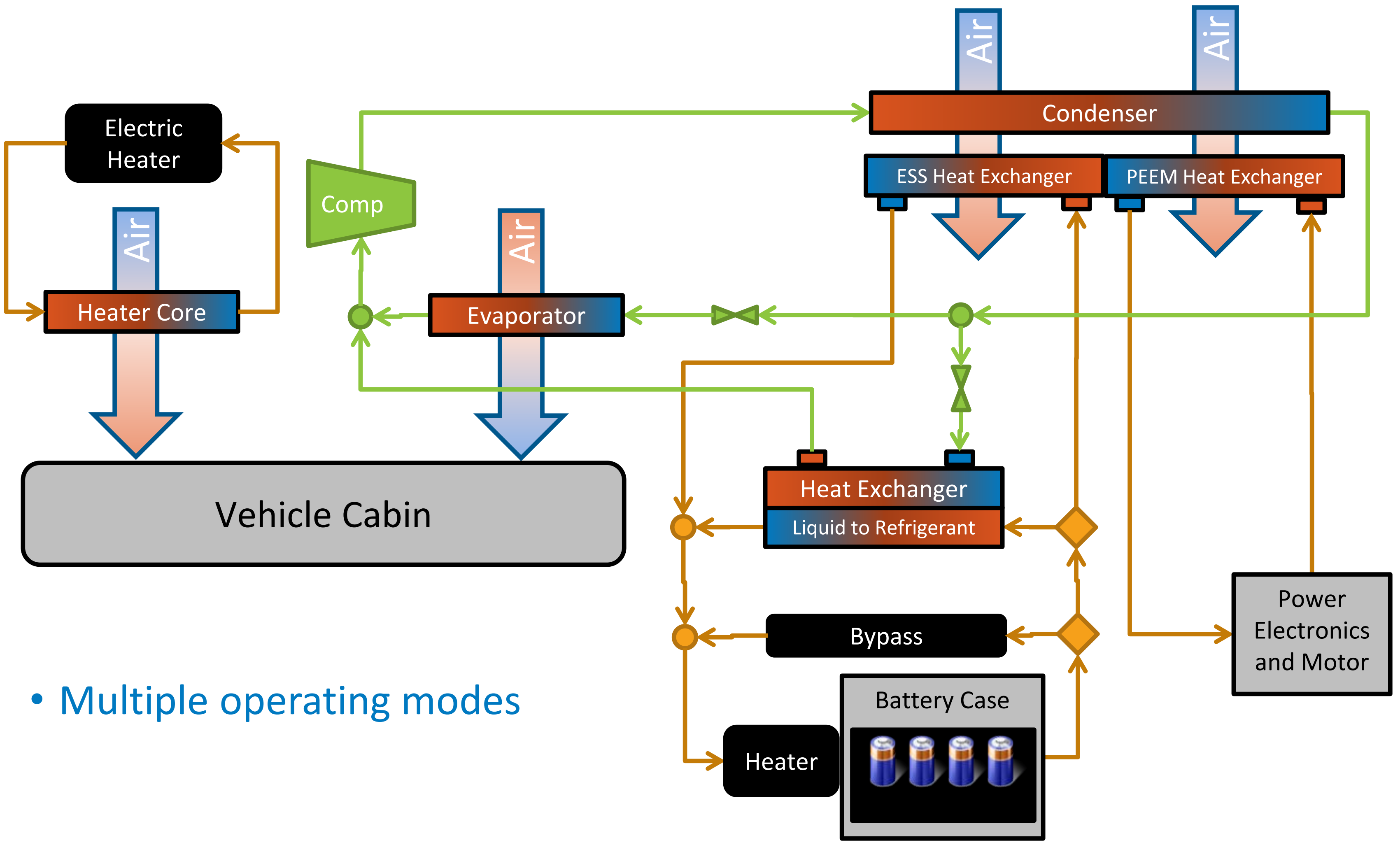
Improvements to Baseline Models (March/12 – March/13)



- **Improved air conditioning (A/C) compressor control**
  - Blower speed
  - Compressor rpm
  - The control state is determined by the ambient environment, target temperatures, and the component temperatures.
  - Developed control logic with anti-windup
- **Added inverter model (based on feedback from Electrical and Electronics Technical Team)**
- **Updated battery thermal model based on review with the NREL ESS group (battery properties and thermal performance)**
- **Added ability to heat battery coolant to improve warmup**
- **Created component models for cabin heater core and electrical fluid heater for cabin heating**
- **Built a cabin heating loop**
- **Added controls for battery temperature**
  - Pump speed
  - Valve position
  - Developed control logic with anti-windup proportional integrator controllers



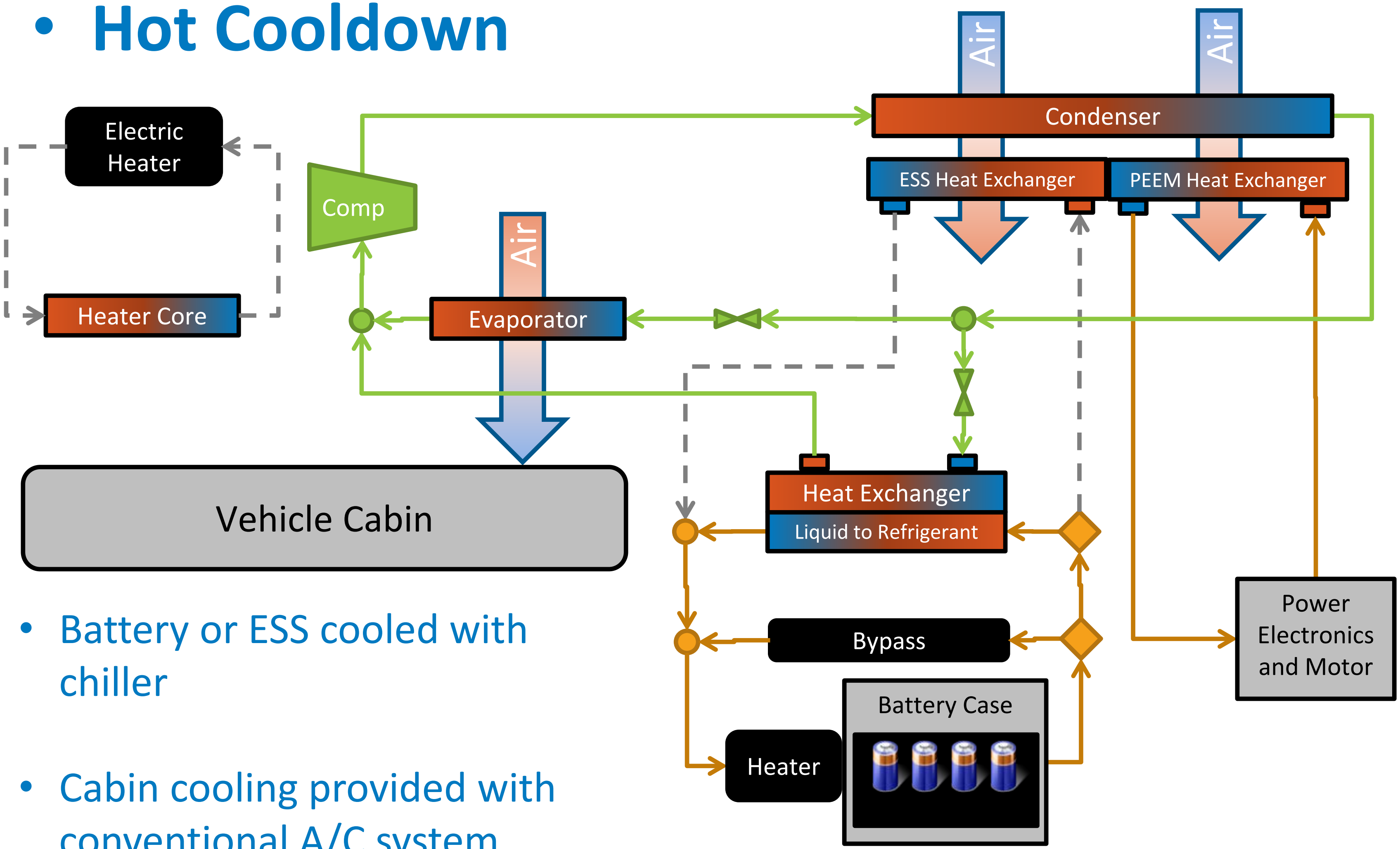
EV Baseline Thermal Management System



- Multiple operating modes

EV Baseline Thermal Management System

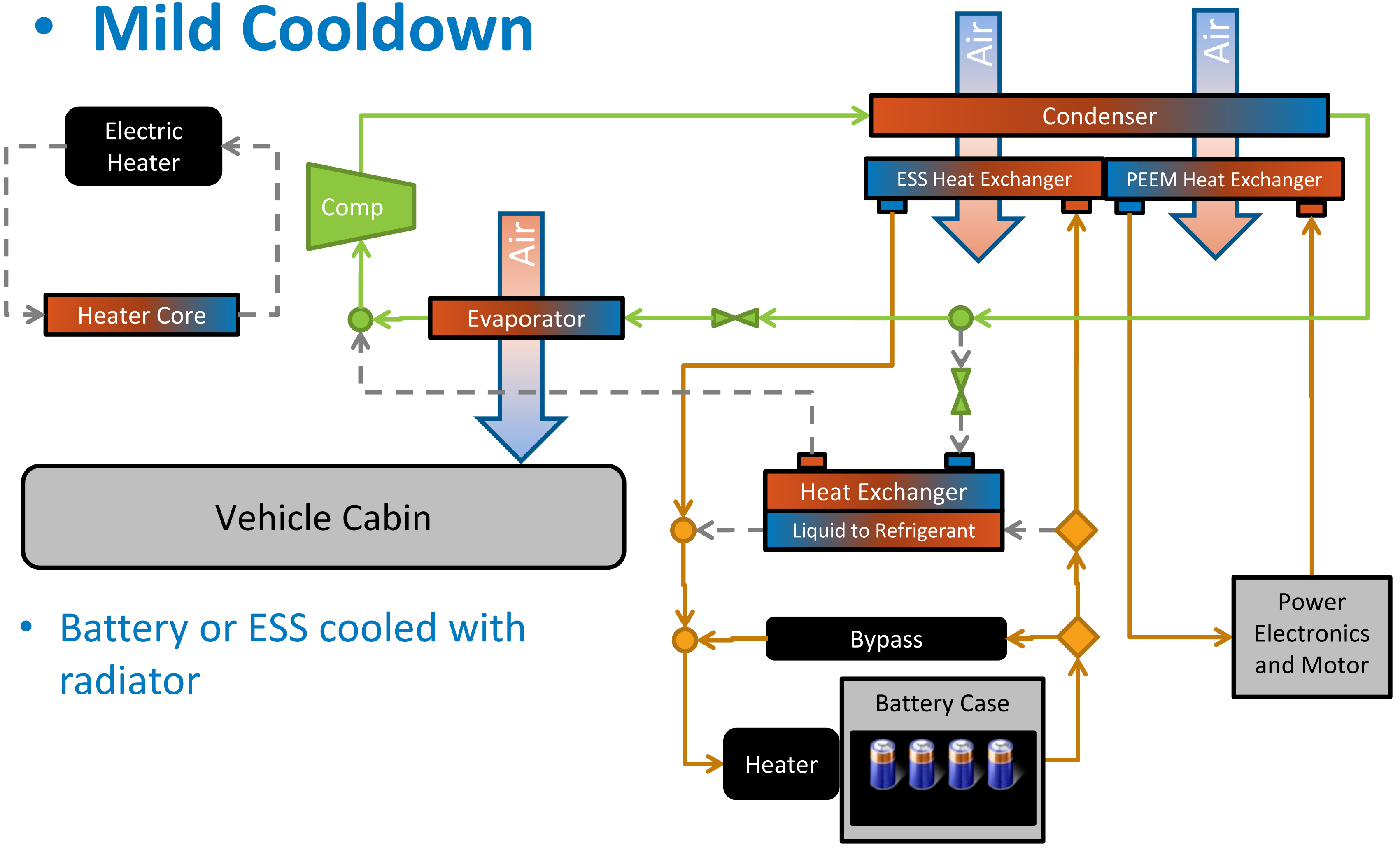
- Hot Cooldown



- Battery or ESS cooled with chiller
- Cabin cooling provided with conventional A/C system

EV Baseline Thermal Management System

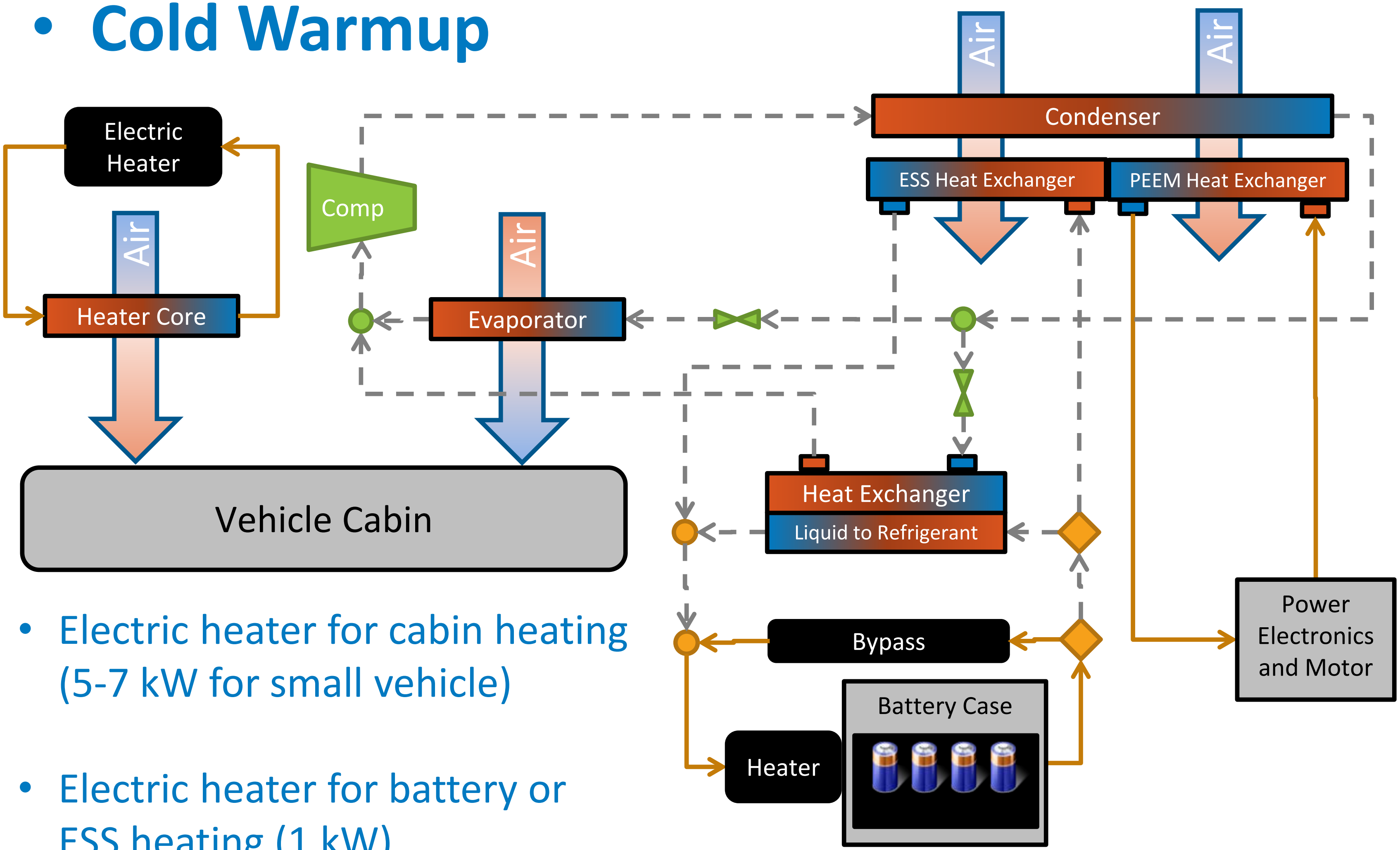
- **Mild Cooldown**



- Battery or ESS cooled with radiator

EV Baseline Thermal Management System

- **Cold Warmup**



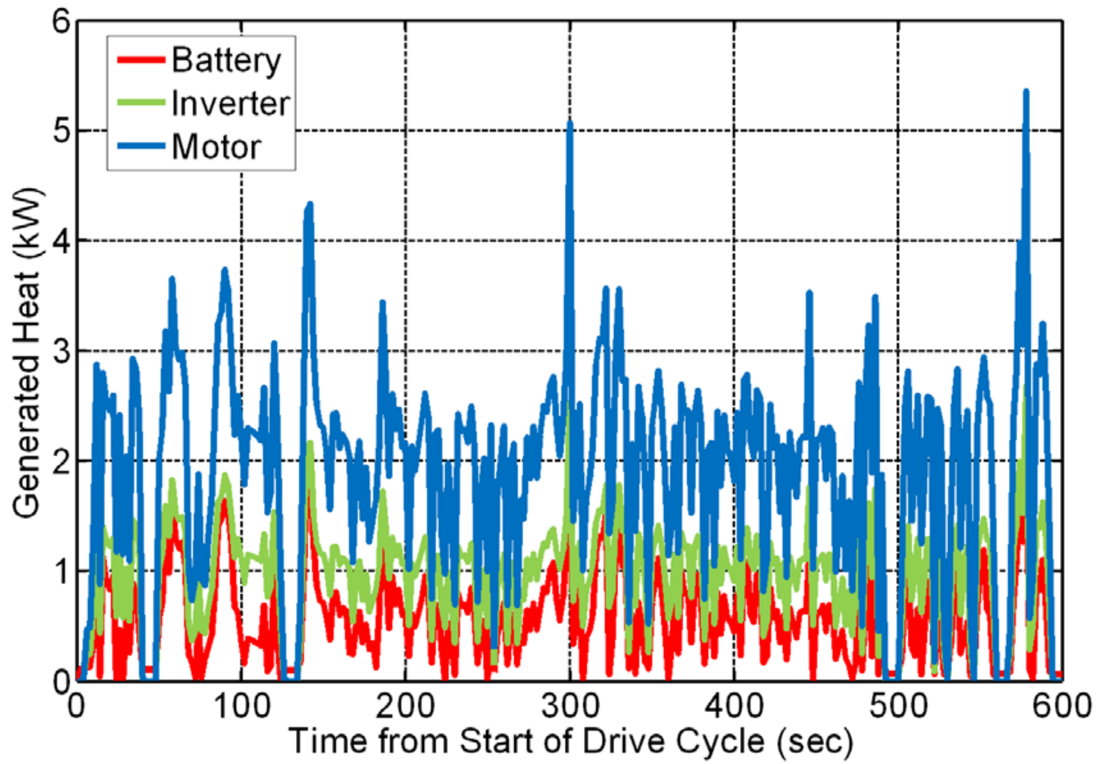
- Electric heater for cabin heating (5-7 kW for small vehicle)

- Electric heater for battery or ESS heating (1 kW)

Baseline EV Thermal Management System

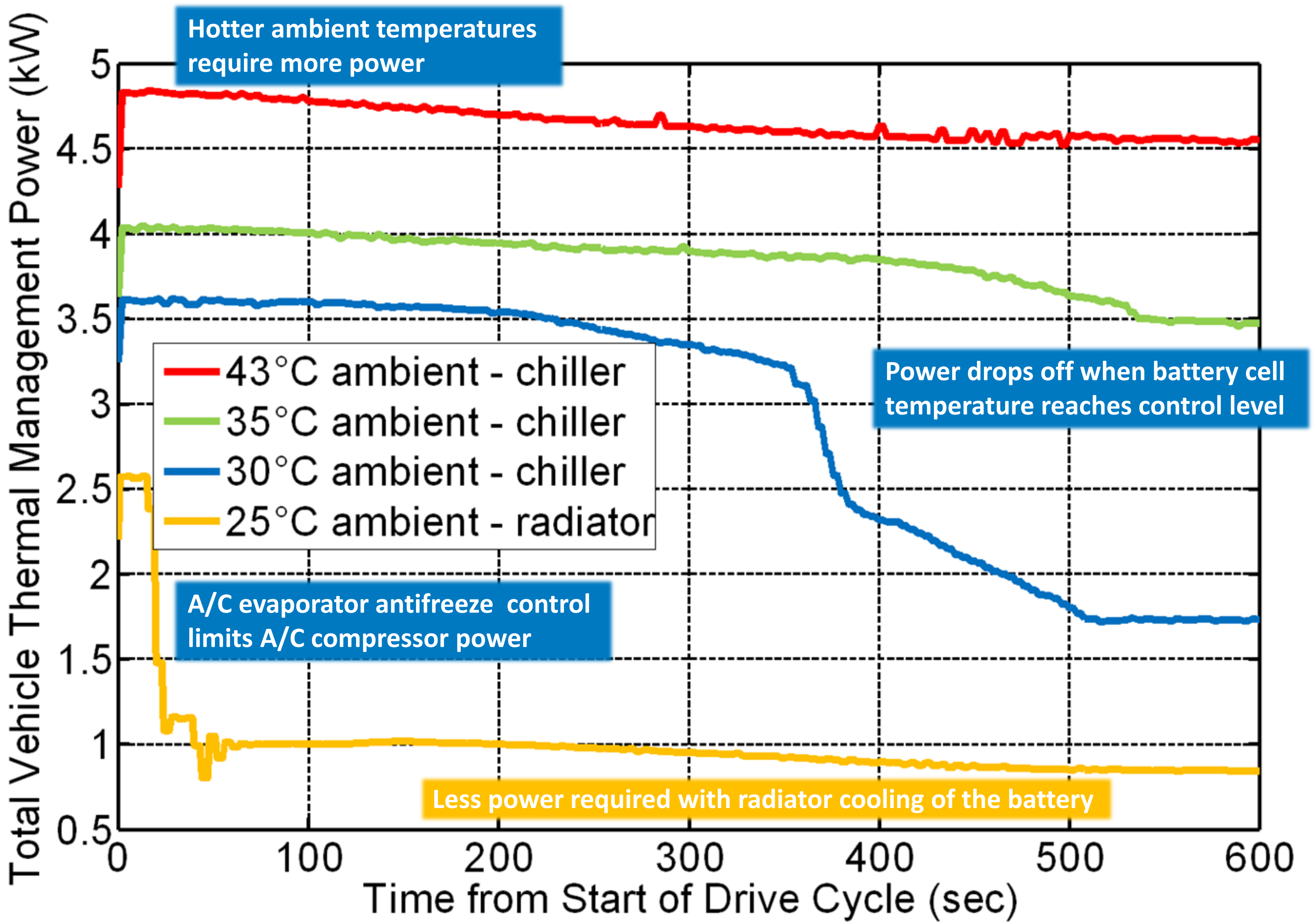
EV Test Case at Four Ambient Temperatures

- **24-kWh EV**
- **Environment**
  - 43°C, 35°C, 30°C, 25°C
  - 25% relative humidity
  - 850 W/m²
- **0% recirculation**
- **US06 drive cycle**
- **Cooldown simulation from a hot soak**
- **ESS – cooling loop with chiller and low temperature radiator**
- **Waste heat load from FASTSim simulations**



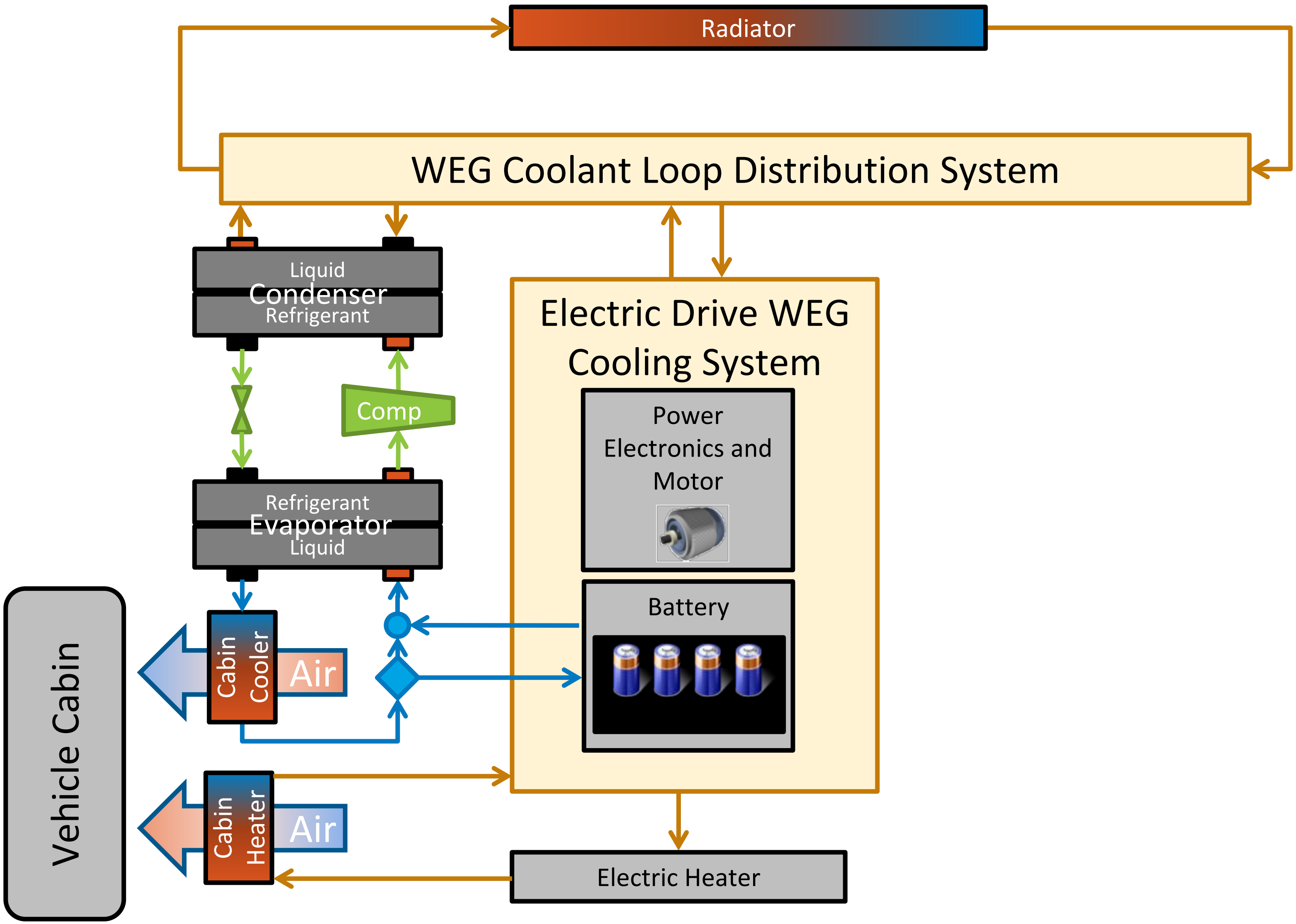
Baseline System

Total Vehicle Thermal Management Power Including Compressor, Fans, Blowers, Pumps



Combined System

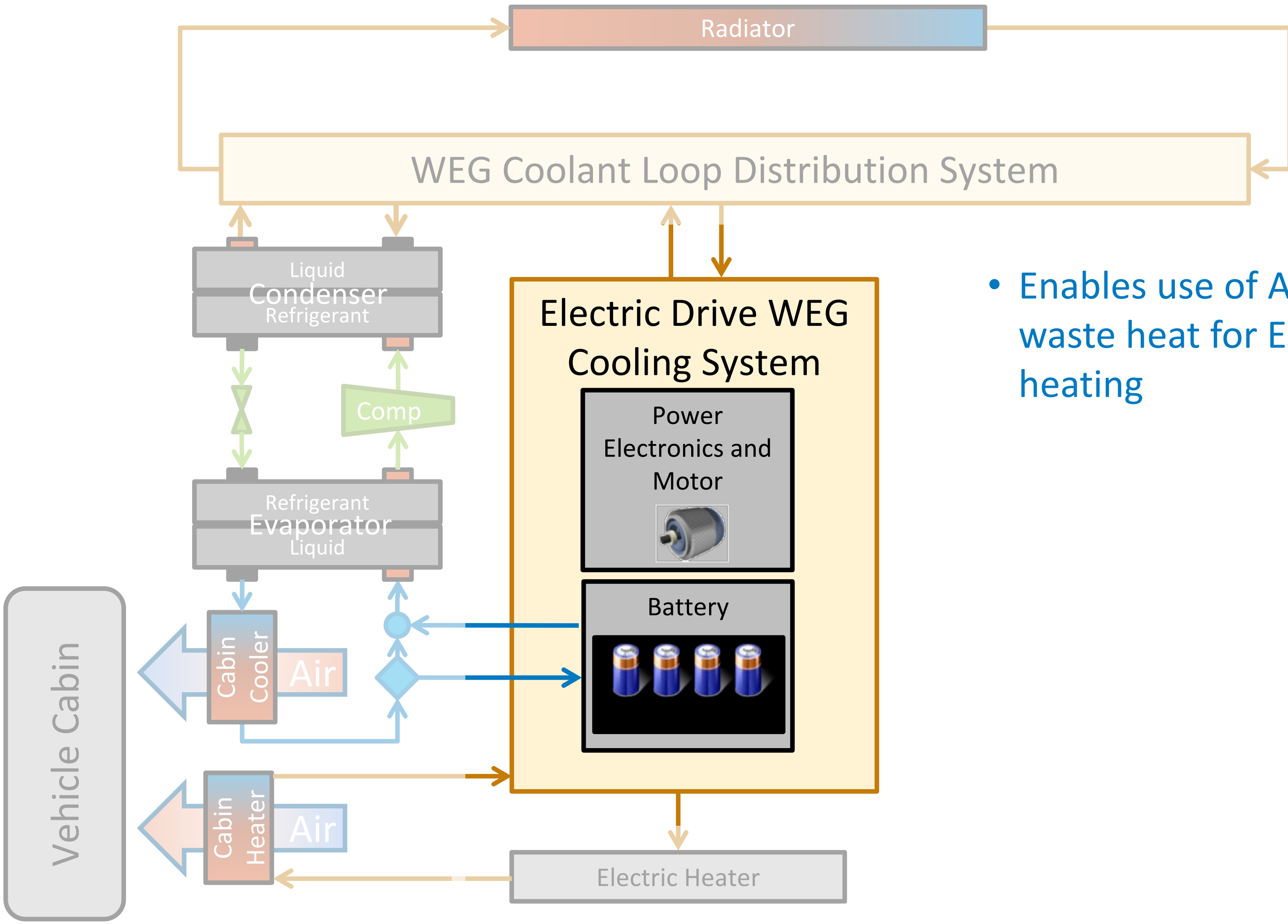
Combining APEEM and ESS Cooling Loops



WEG = Water/Ethylene Glycol

Combined System – Configuration 1

Combining APEEM and ESS Cooling Loops

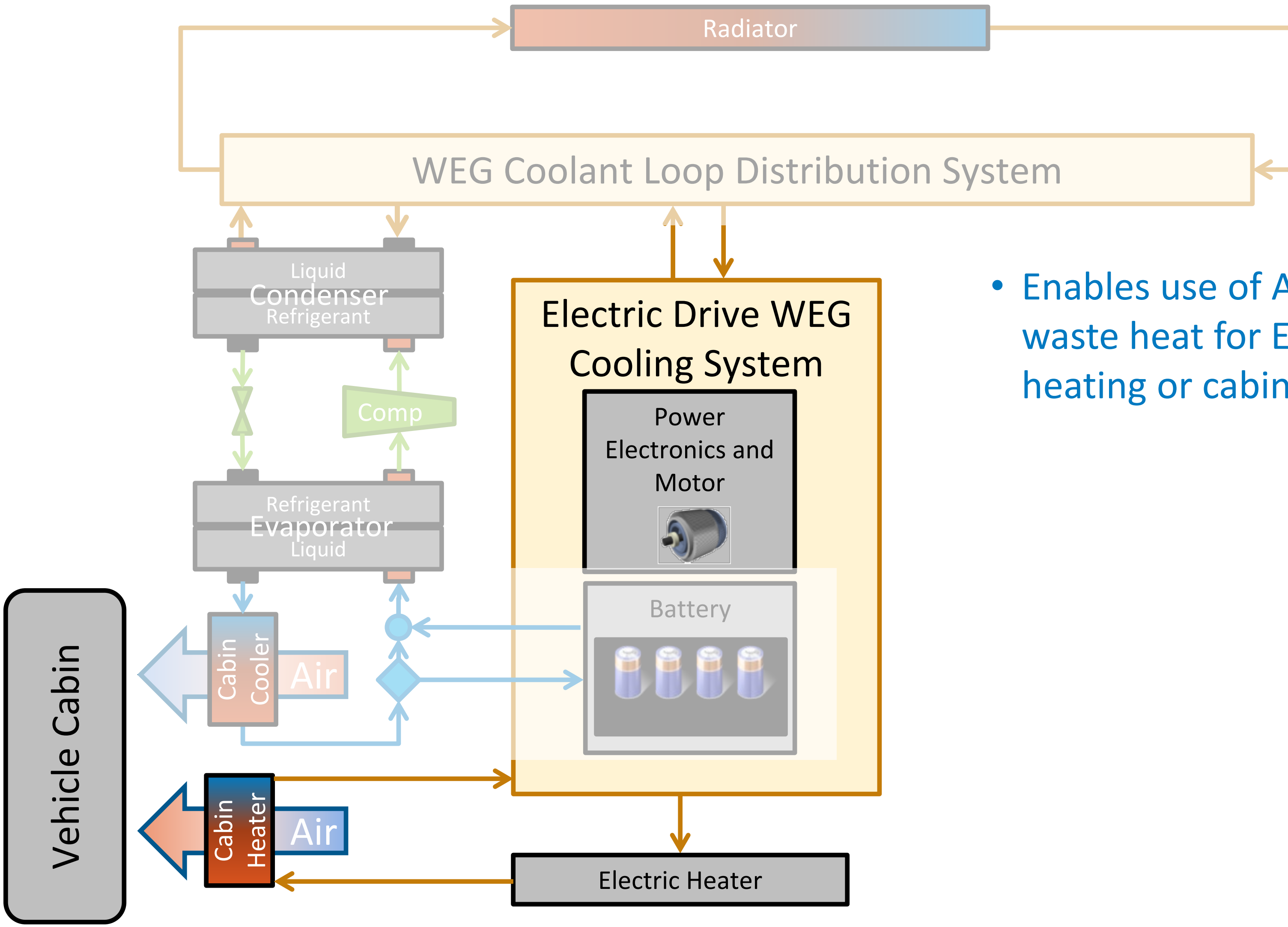


- Enables use of APEEM waste heat for ESS heating

WEG = Water/Ethylene Glycol

Combined System – Configuration 2

Combining APEEM and Cabin Heating Loops



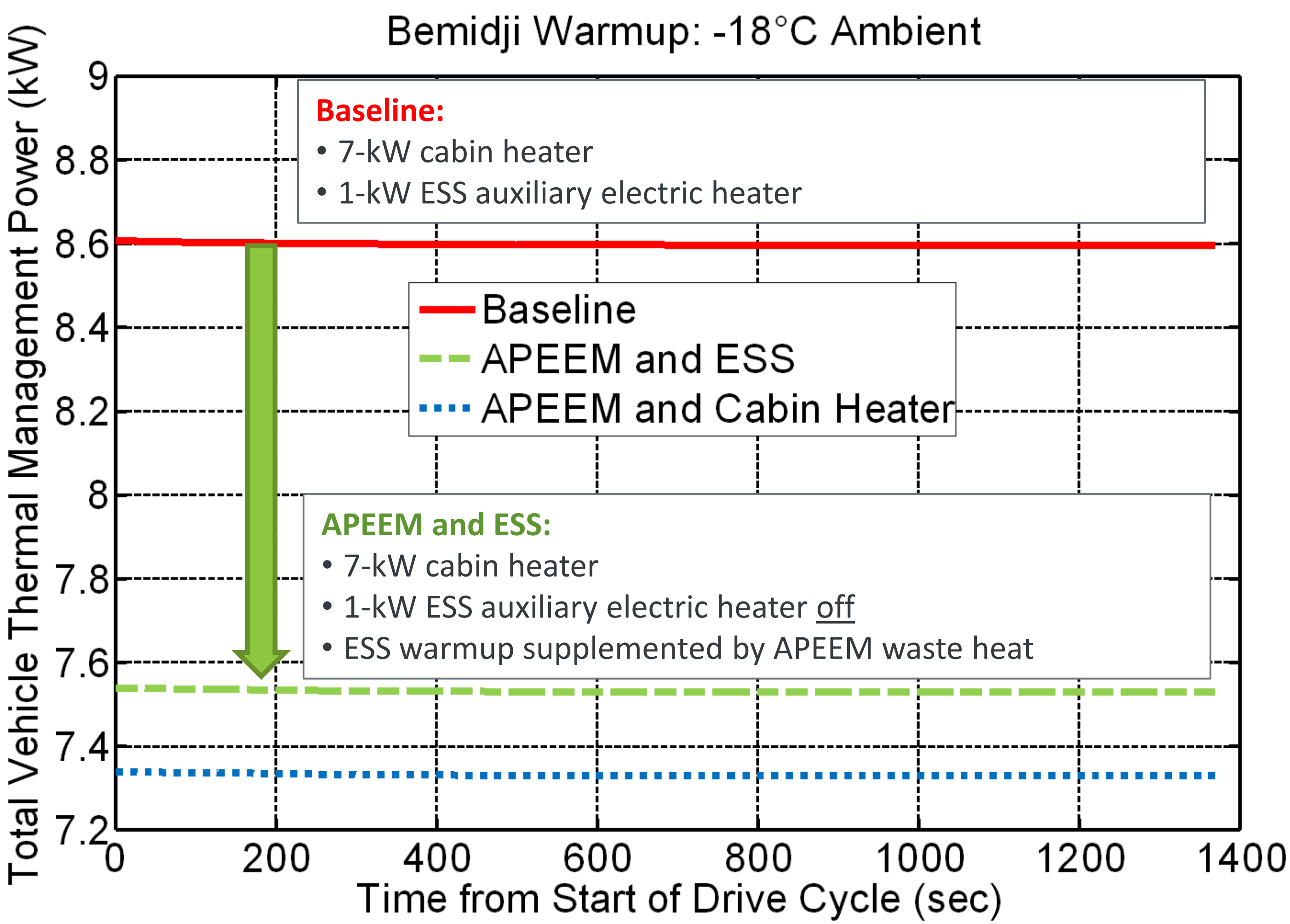
- Enables use of APEEM waste heat for ESS heating or cabin heating

WEG = Water/Ethylene Glycol

Warmup: Auxiliary Load Power

VTM Power Reduced by Using APEEM Waste Heat

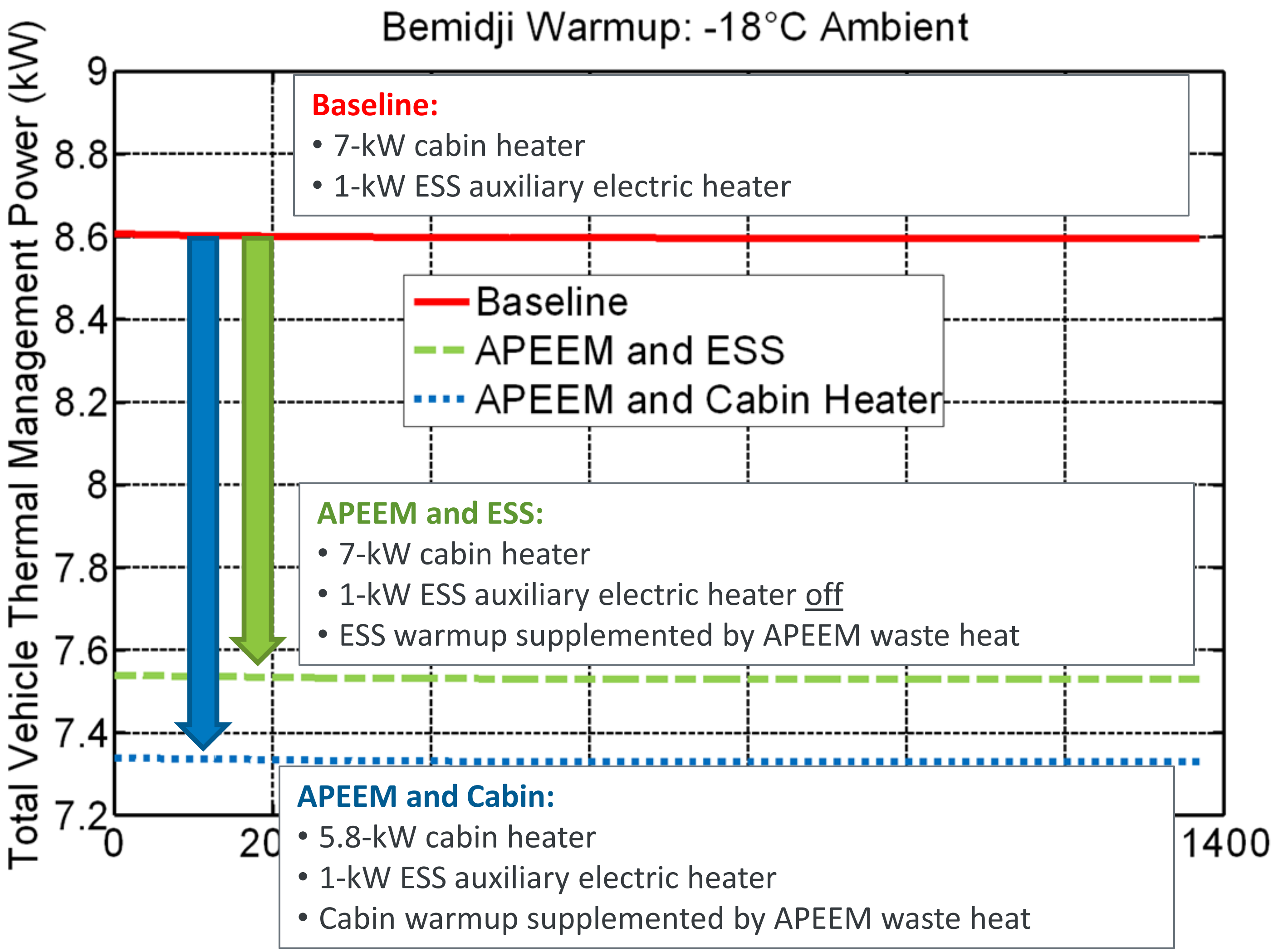
Configuration 1 (APEEM and ESS)



Warmup: Auxiliary Load Power

VTM Power Reduced by Using APEEM Waste Heat

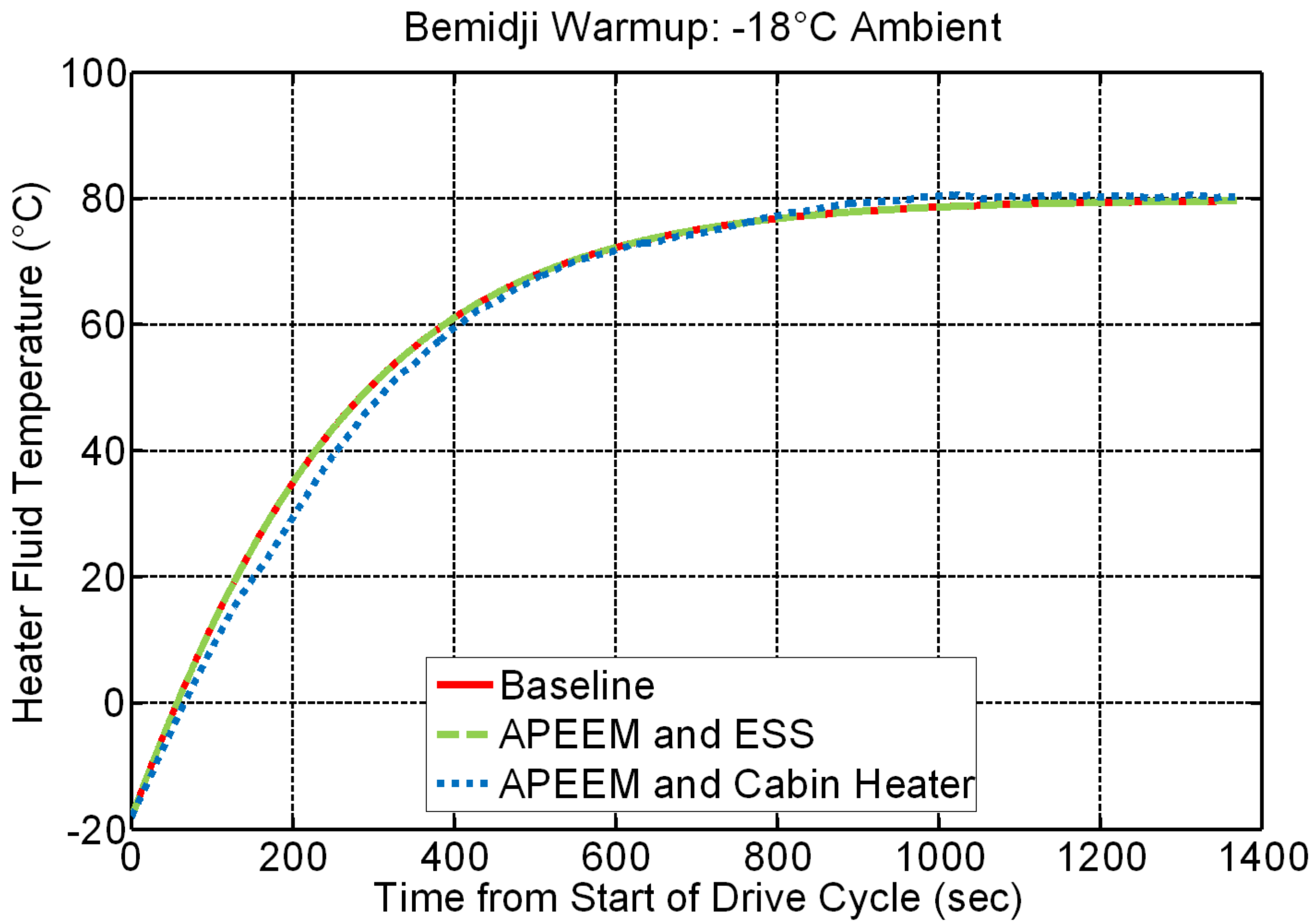
Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)



Warmup: Cabin Heater Fluid Temperature

Cabin Heater Fluid Temperatures Are Very Similar

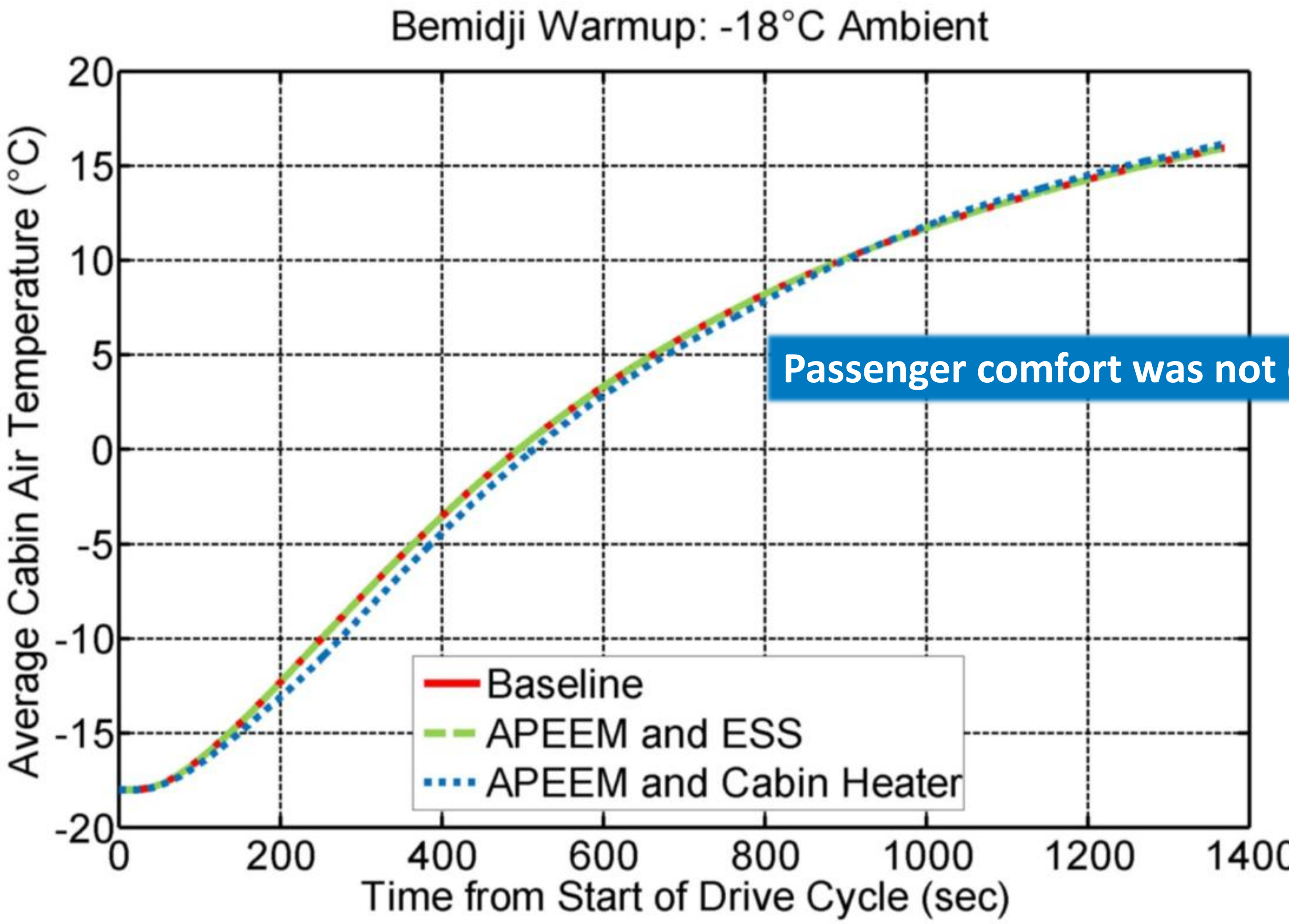
Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)



Warmup: Average Cabin Air Temperature

Cabin Air Temperatures Are the Same While Using Less Electrical Power

Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)

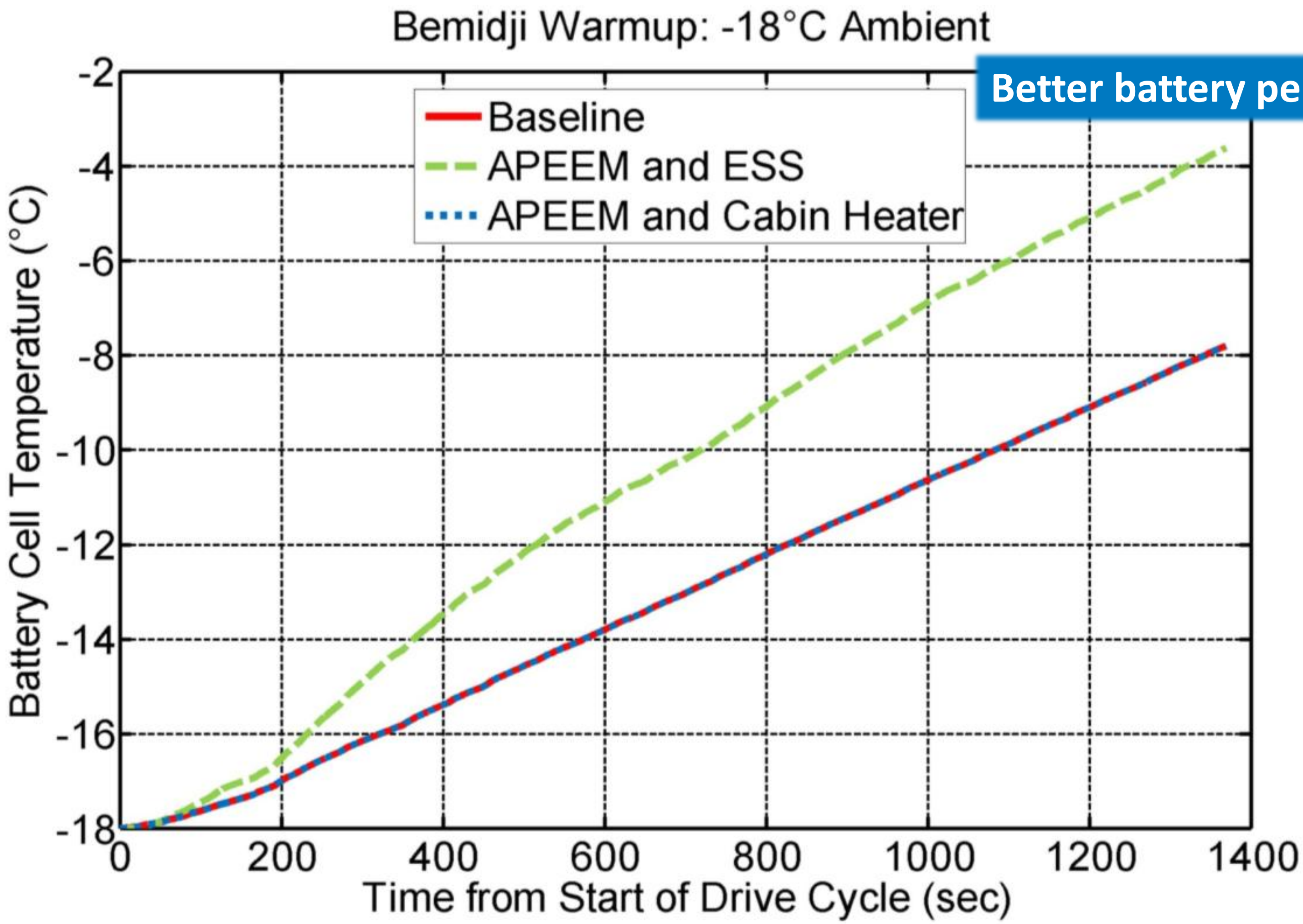


Passenger comfort was not degraded

Warmup: Battery Temperature

Battery Is Warmer with APEEM Waste Heat

Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)

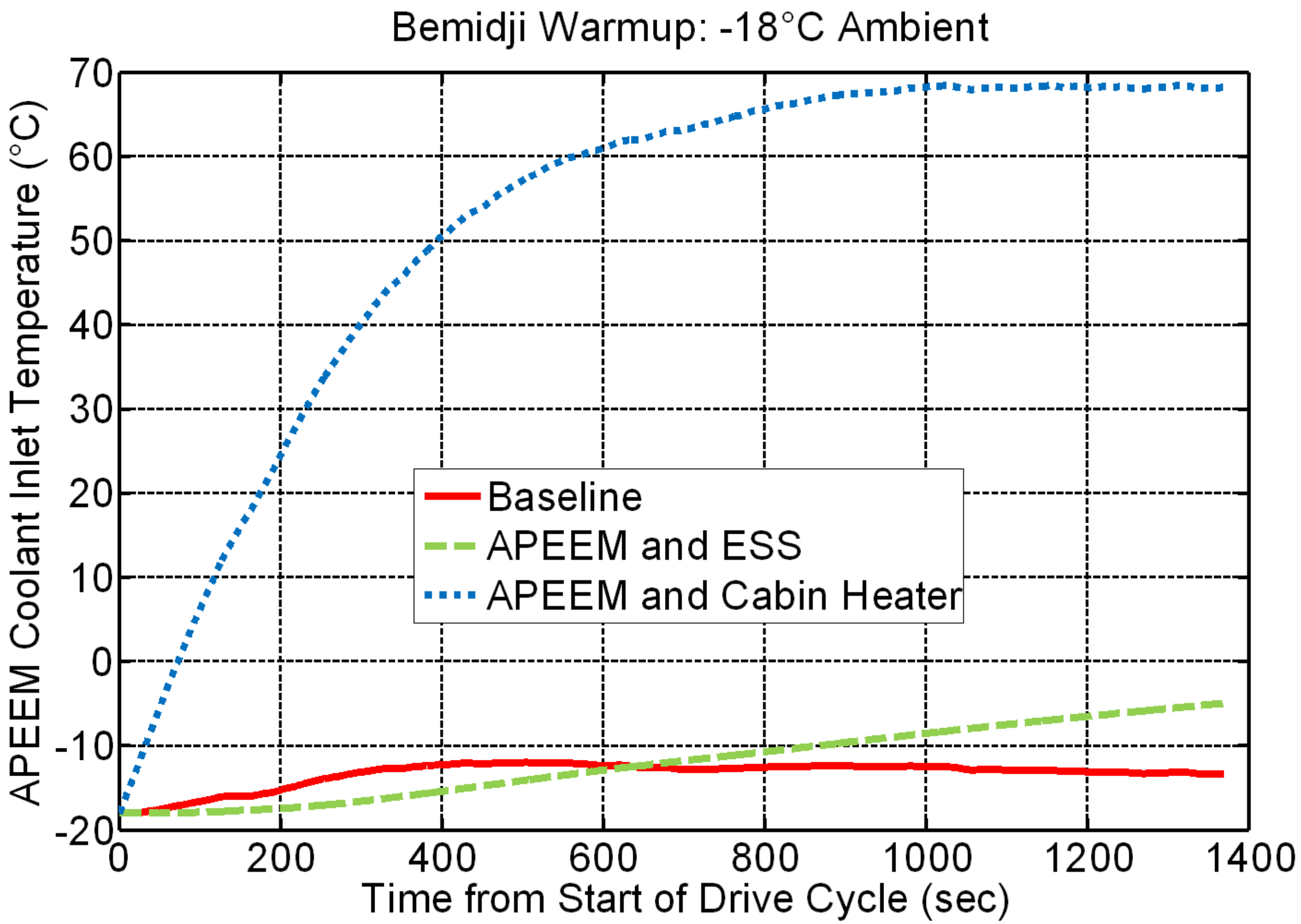


Better battery performance

Warmup: APEEM Coolant Temperature

APEEM Coolant Temperature Is Under The Limit (<70°C)*

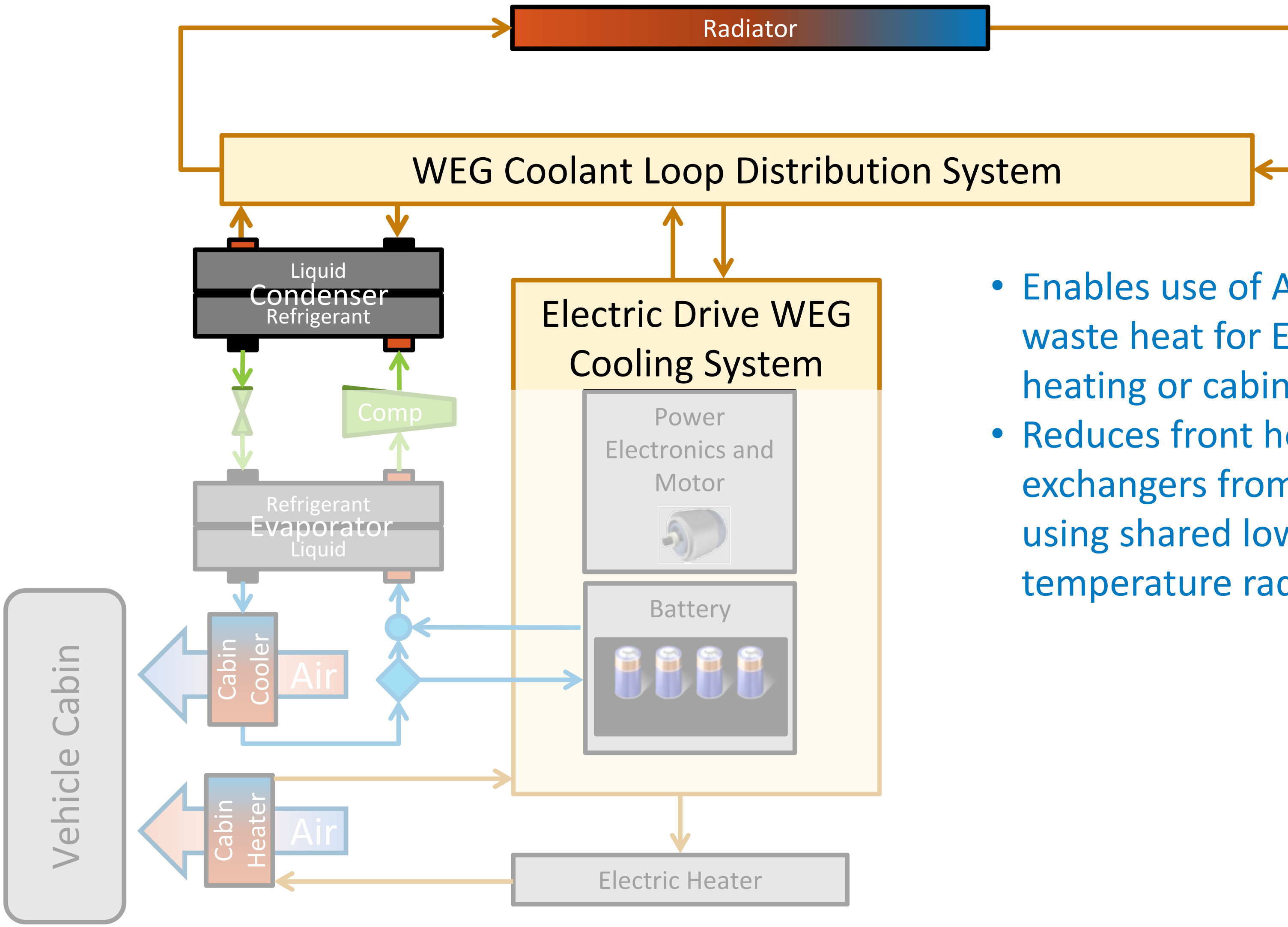
Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)



* "Electrical and Electronics Technical Team Roadmap." [Online]. Available: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_12-7-10.pdf. [Accessed: 11-Oct-2011].

Combined System – Configuration 3

Liquid Cooled Condenser

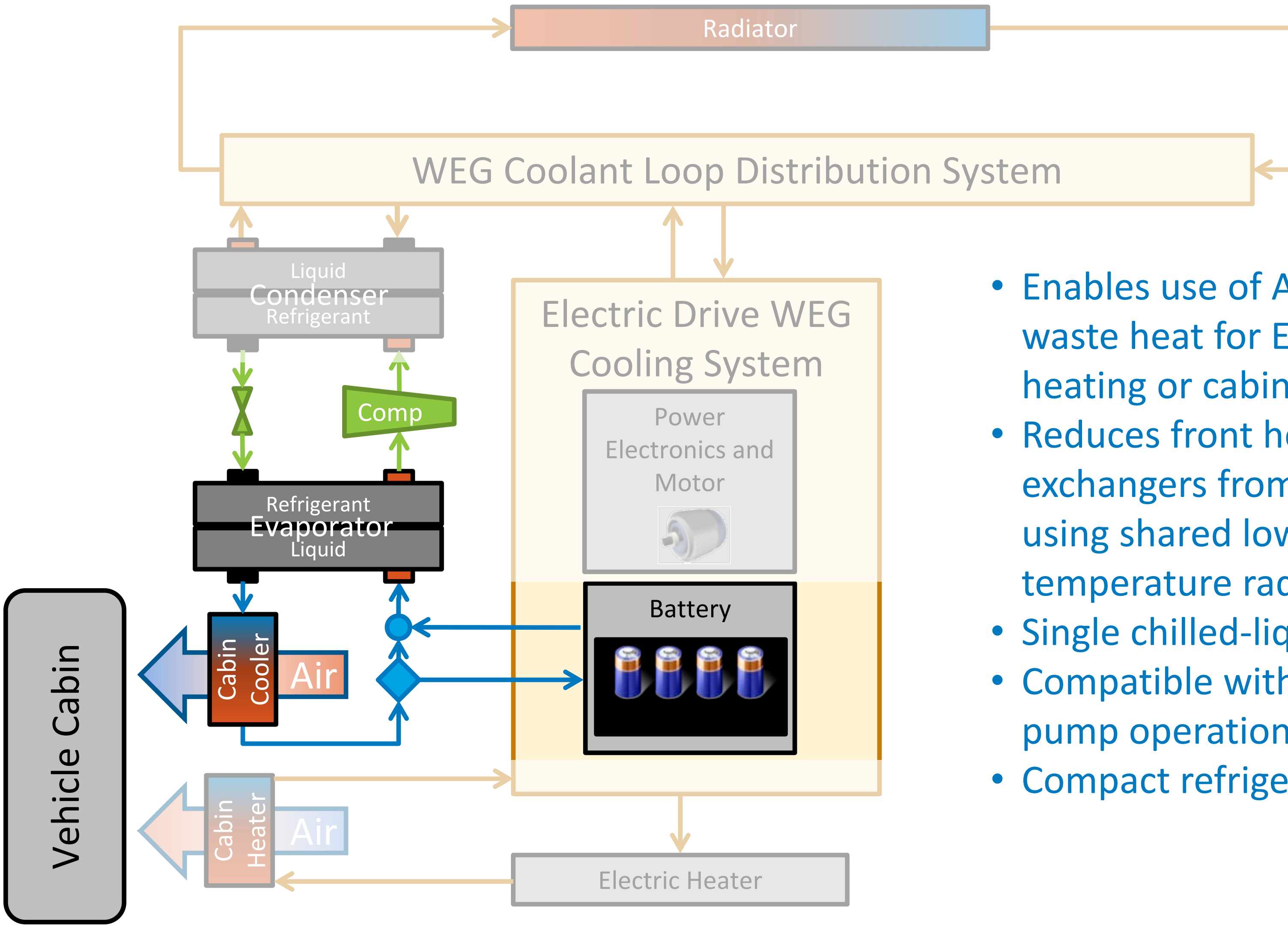


- Enables use of APEEM waste heat for ESS heating or cabin heating
- Reduces front heat exchangers from 3 to 1 using shared low-temperature radiator

WEG = Water/Ethylene Glycol

Combined System – Configuration 4

Refrigerant to Liquid Evaporator (Secondary Loop)



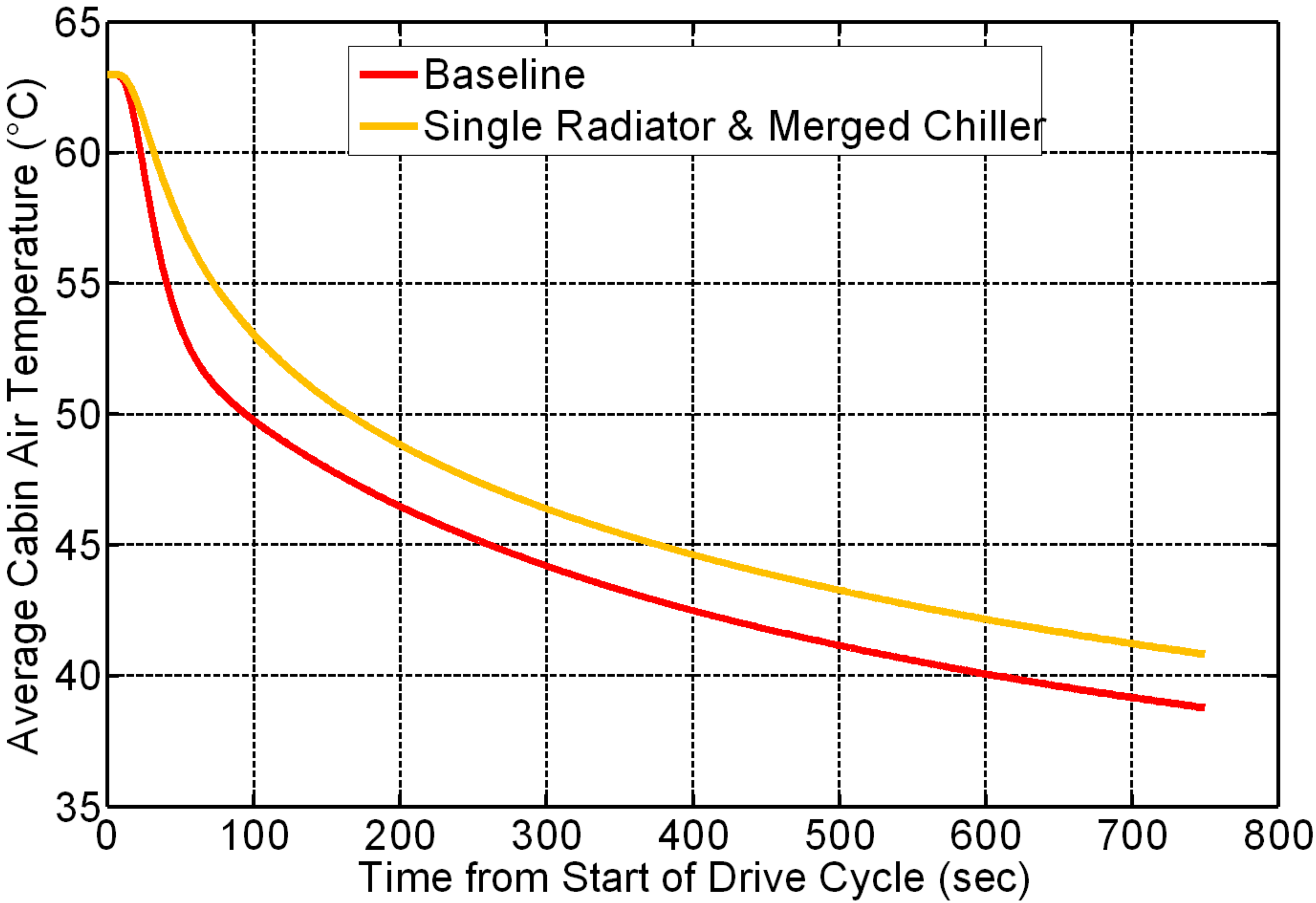
- Enables use of APEEM waste heat for ESS heating or cabin heating
- Reduces front heat exchangers from 3 to 1 using shared low-temperature radiator
- Single chilled-liquid loop
- Compatible with heat pump operation
- Compact refrigerant loop

WEG = Water/Ethylene Glycol

Cooldown: Cabin Air Temperature

Slightly Warmer Cabin Air (A/C Performance Not Significantly Impacted)

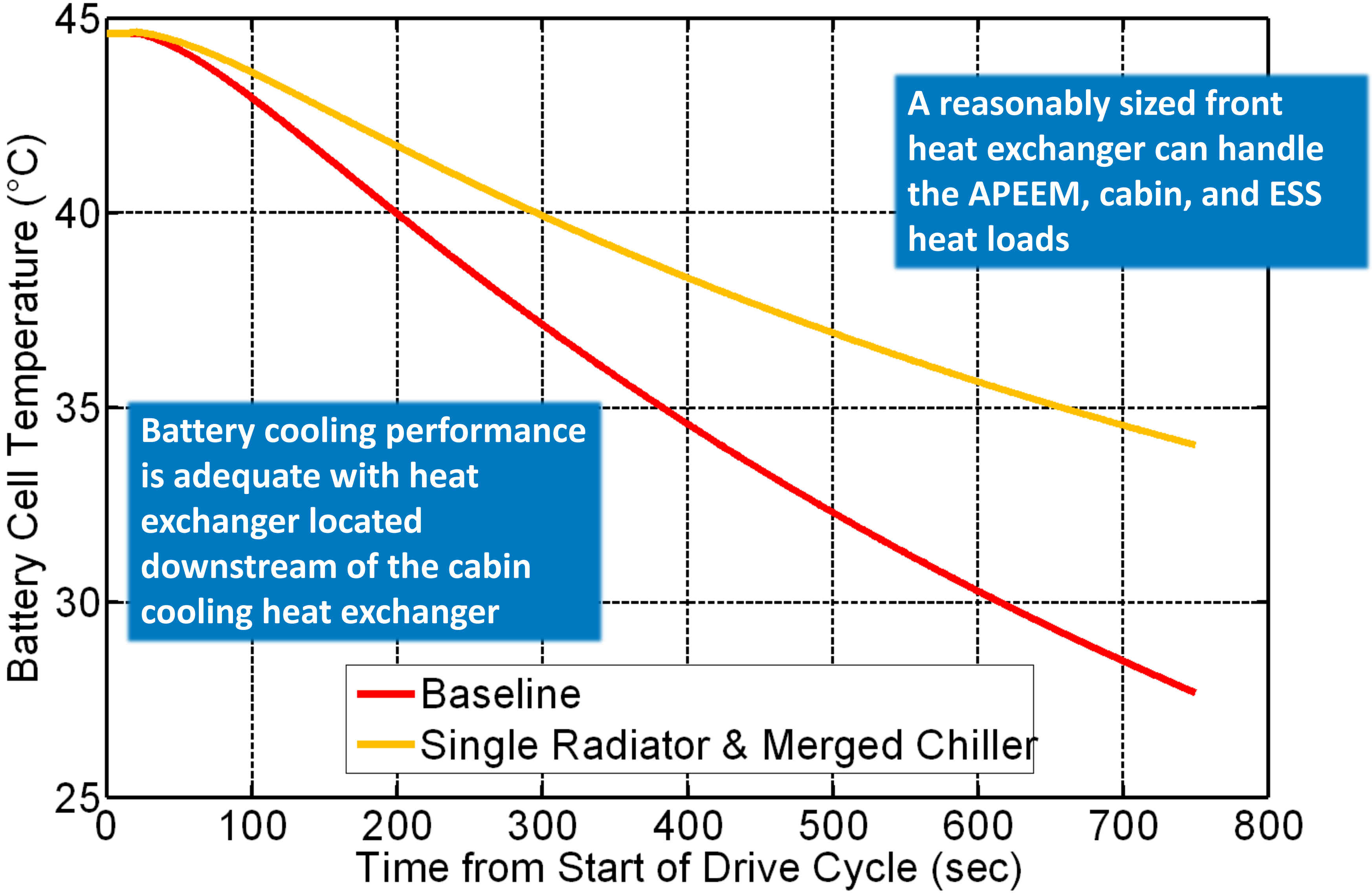
Configurations 3 & 4 (Liquid-Cooled Condenser and Refrigerant to Liquid Evaporator – Secondary Loop)



Cooldown: Battery Temperature

Slightly Warmer Battery (But Still a Reasonable Cooldown)

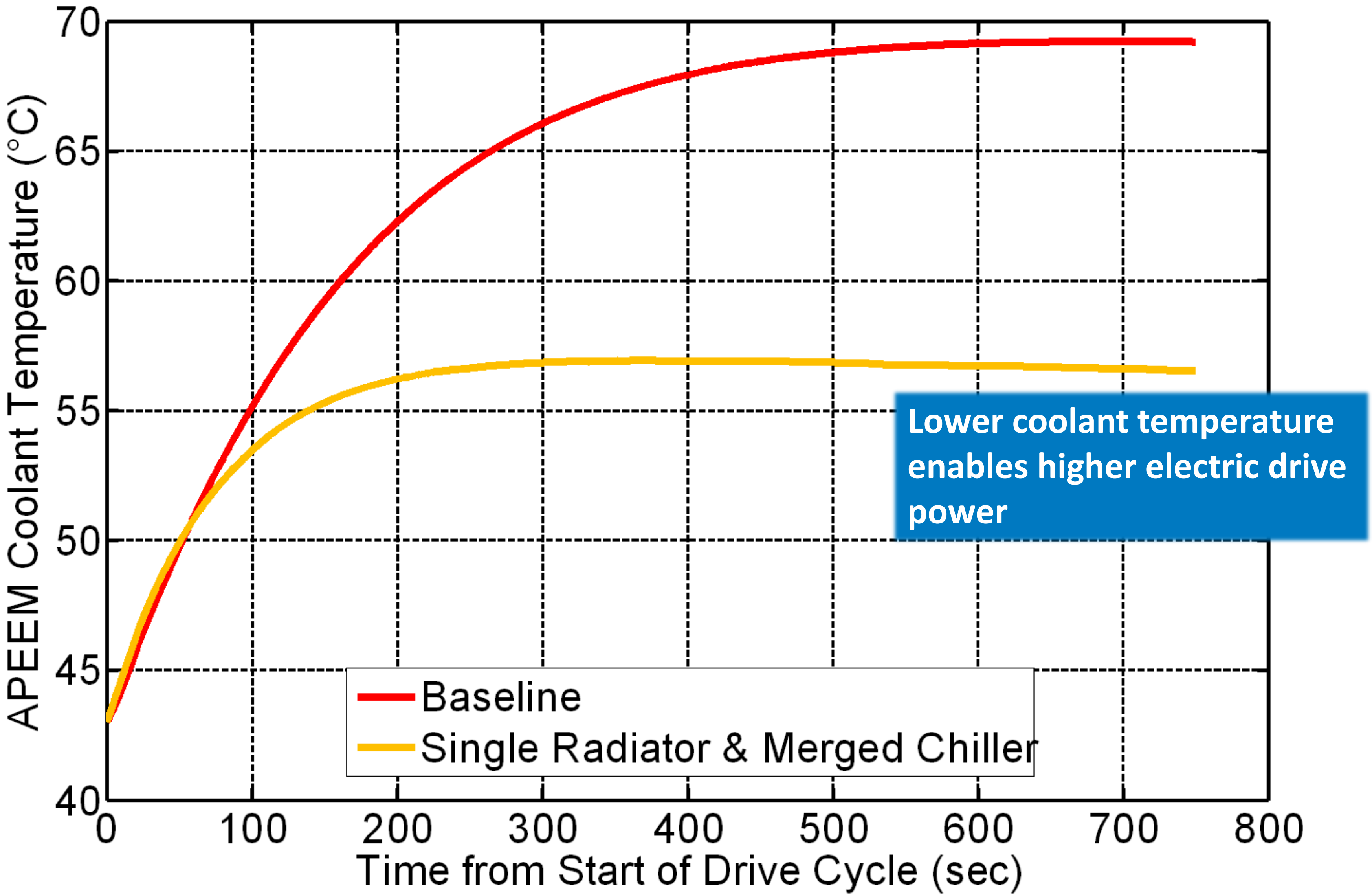
Configurations 3 & 4 (Liquid-Cooled Condenser and Refrigerant to Liquid Evaporator – Secondary Loop)



Cooldown: APEEM Coolant Temperature

Lower APEEM Coolant Because Refrigerant to Air Condenser Is Eliminated

Configurations 3 & 4 (Liquid-Cooled Condenser and Refrigerant to Liquid Evaporator – Secondary Loop)

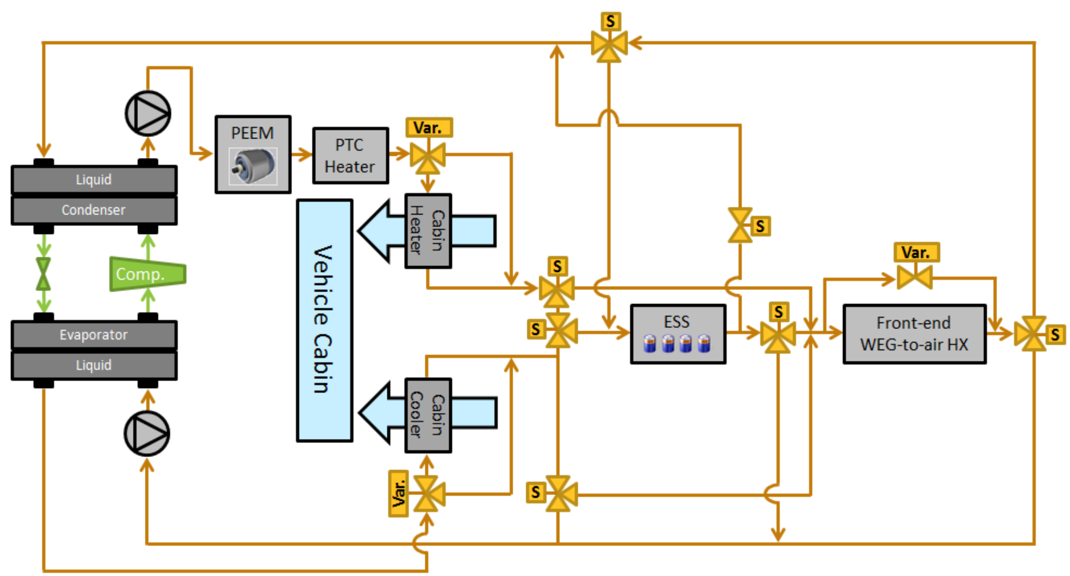


Accomplishments – Bench Test

- **Developed preliminary combined cooling loop concept for testing**
  - Maximizes operating configurations and total system energy efficiency while minimizing valves, pumps, and heat exchangers
  - Thermally conditions vehicle cabin, PE, EM, and ESS
  - Recovers PE, EM, and ESS waste heat when advantageous
  - Enables heat pump operation to reduce electrical resistance load

Cycle Schematic

Refrigerant
WEG
Air

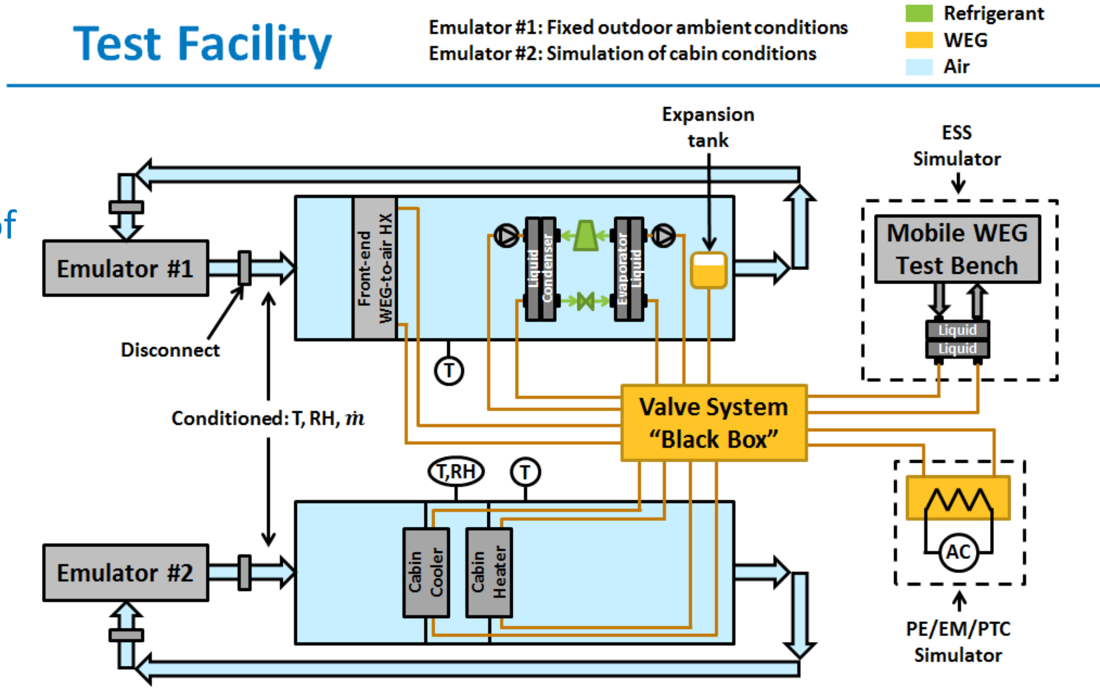


- **Significance**
  - Unique vehicle thermal system configuration that focuses on maximizing vehicle range, occupant comfort, and component lifetime

Accomplishments – Bench Test

- **Inventoried current testing capabilities to determine what can be achieved**
  – Maximized use of existing equipment and infrastructure
- **Designed preliminary bench test facility**
  – Simulation of vehicle cabin response via a mathematical model, which controls inlet air conditions to cabin heat exchangers
  – Replication of PE, EM, and ESS responses via mathematical models, which control component outlet coolant temperatures

- **Significance**
  – Initiated bench-testing phase of task while minimizing test facility upgrade cost



Collaboration and Coordination with Other Institutions

- **Delphi**
- **Halla Visteon Climate Control**
  - Data
  - Engineering support
- **Magna Powertrain – Engineering Center Steyr**
  - KULI software
  - Engineering support
- **Ford**
  - Electric Focus (loaned to NREL for the Electric Drive Vehicle Climate Control Load Reduction Task)
- **VTO Tasks**
  - Advanced Power Electronics and Electric Motors
  - Vehicle Systems
  - Energy Storage

Proposed Future Work

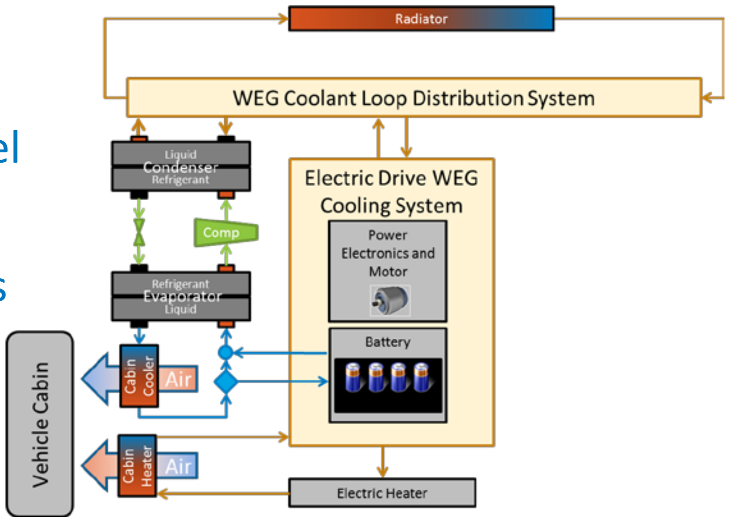
- **Remainder of FY13**
  - Finalize combined cooling loop design in conjunction with industry
    - Coordinate with Delphi and Visteon on configuration and components
  - Construct bench testing facility
  - Conduct bench testing to evaluate combined cooling loop system performance during cooling mode
  - Validate previously built KULI models of combined cooling loop
- **FY14**
  - Utilize existing bench testing facility and experimental system to conduct heating mode testing
  - Work with industry partners to design a vehicle-level test that can demonstrate vehicle system level performance when using a combined cooling loop system
  - Install experimental system and measurement equipment in a test EDV
  - Experimentally evaluate EDV performance to demonstrate the effect that the combined cooling loop has on electric vehicle range

Summary

- **DOE Mission Support**
  - Combining cooling systems in EDVs may reduce costs and improve performance, which would accelerate consumer acceptance, increase EDV usage, and reduce petroleum consumption.
- **Overall Approach**
  - Build a thermal 1-D model (using KULI software)
    - APEEM, energy storage, engine, transmission, and passenger compartment thermal management systems
    - Identify the synergistic benefits from combining the systems
  - Select the most promising combined thermal management system concepts and perform a detailed performance assessment and bench top tests
  - Collaborate with automotive manufacturers and suppliers on a vehicle-level project
  - Solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains

Summary (cont.)

- **Technical Accomplishments**
  - Completed baseline EV thermal systems model
  - Investigated combined cooling loop strategies
  - Identified advantages of combining fluid loops
  - Identified strategies for bench testing



- **Collaborations**
  - Collaborating closely with Delphi, Halla Visteon Climate Control, Magna Powertrain - Engineering Center Steyr, and Ford
  - Leveraging previous DOE research
    - Battery life/thermal model
    - Vehicle cost/performance model
    - Lumped parameter motor thermal model
  - Co-funding by three VTO tasks demonstrates cross-cutting

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Team Members:

Kevin Bennion
Daniel Leighton
Jeff Tomerlin

For more information, contact:

Principal Investigator
John Rugh
john.rugh@nrel.gov
Phone: (303)-275-4413

APEEM Task Leader:

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov
Phone: (303)-275-4062

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