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

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National Renewable Energy Laboratory

Vehicle Technologies Program Annual Merit Review
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Project ID: APE052

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Overview

Timeline

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

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)

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 **

Partners

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

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

Relevance - The PHEV/EV Thermal Challenge

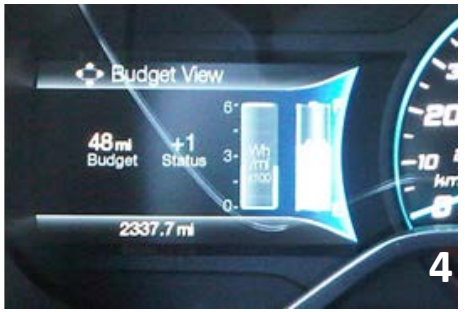
- **Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) have increased vehicle thermal management complexity**
  - Separate coolant loop for advanced power electronics and electric motors (APEEM)
  - Thermal requirements for energy storage systems (ESS)
- **Additional thermal components 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

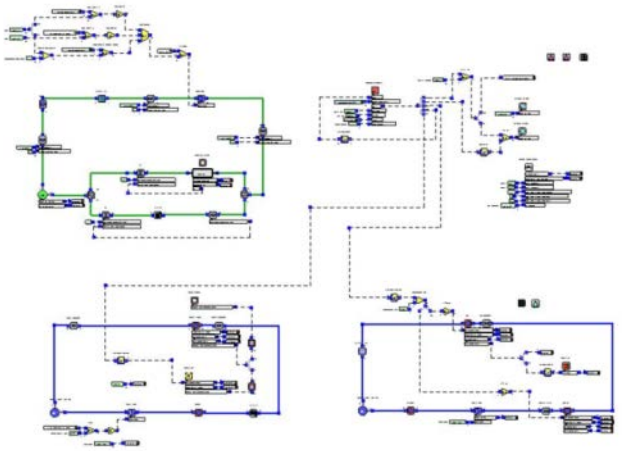
Approach/Strategy

- **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

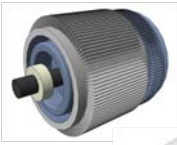
→ Electric range and fuel consumption

Energy Storage
Tien Duong
Brian Cunningham
Peter Faguy

→ Battery temperature and life

Power Electronics & Electric Motors
Susan Rogers
Steven Boyd

→ APEEM temperatures

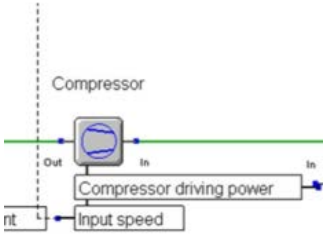


Approach - Milestones

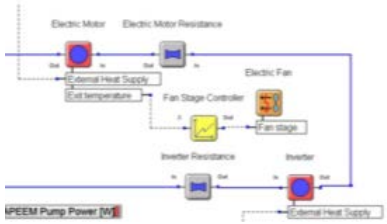
Month / Year	Description
Sept/12	Milestone • Identified advantages of combining fluid loops and strategies for bench testing Go/No-Go • Based on the successful outcome of analysis of the thermal management system concepts, build a bench test facility to evaluate combined cooling loop strategies
Sept/13	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

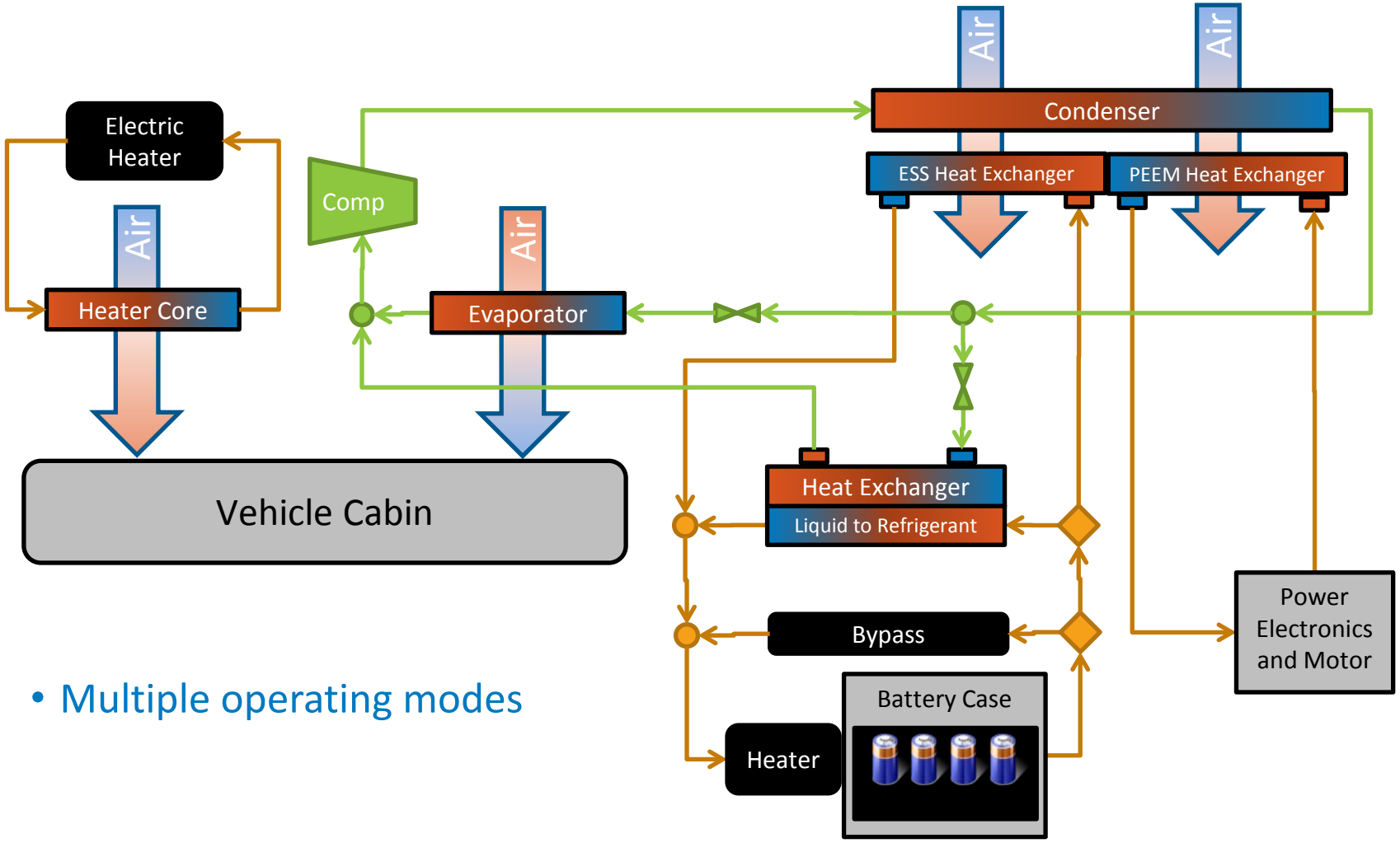
Improvements to Baseline Models (March/12 – March/13)



- **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



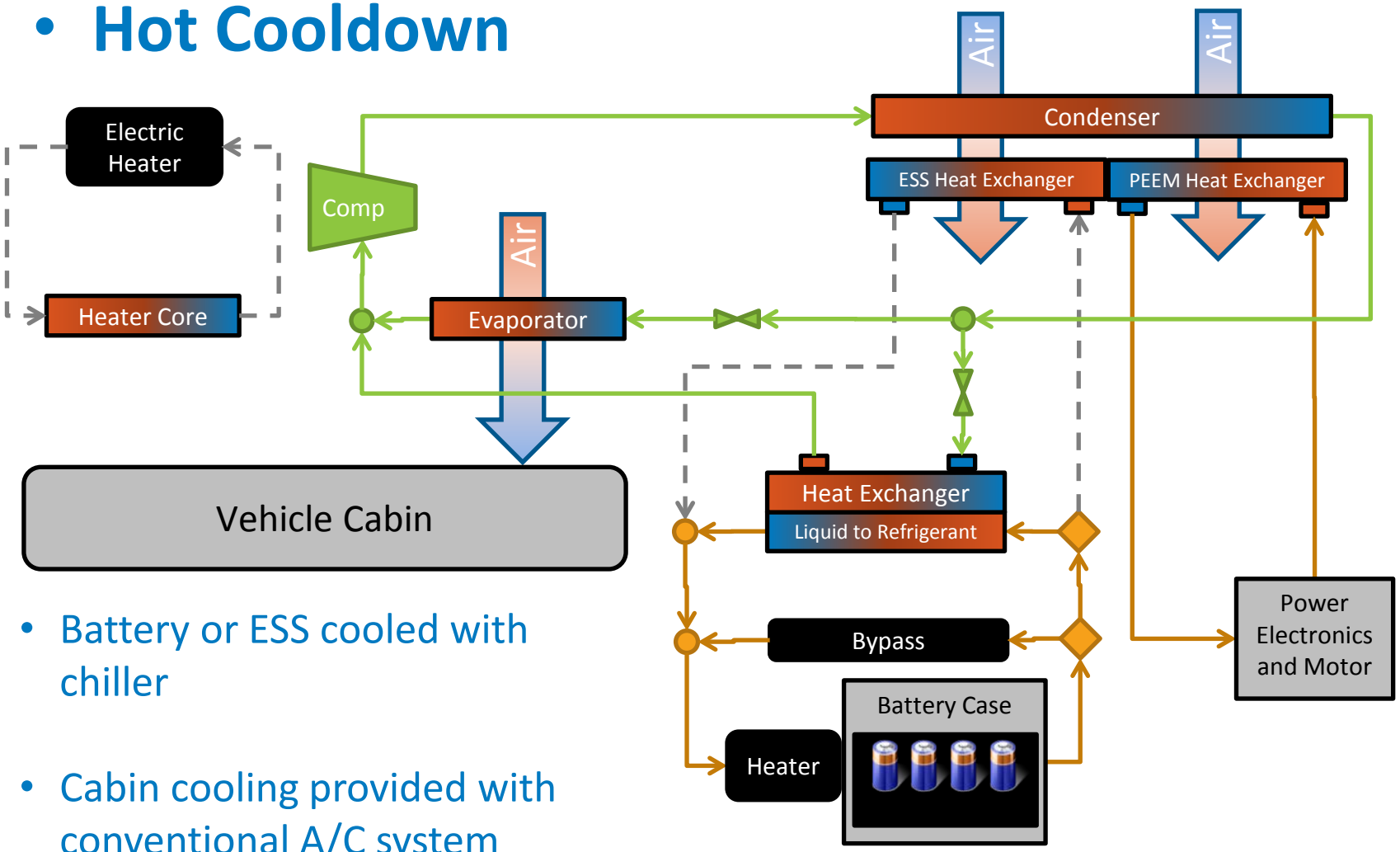
EV Baseline Thermal Management System



- Multiple operating modes

EV Baseline Thermal Management System

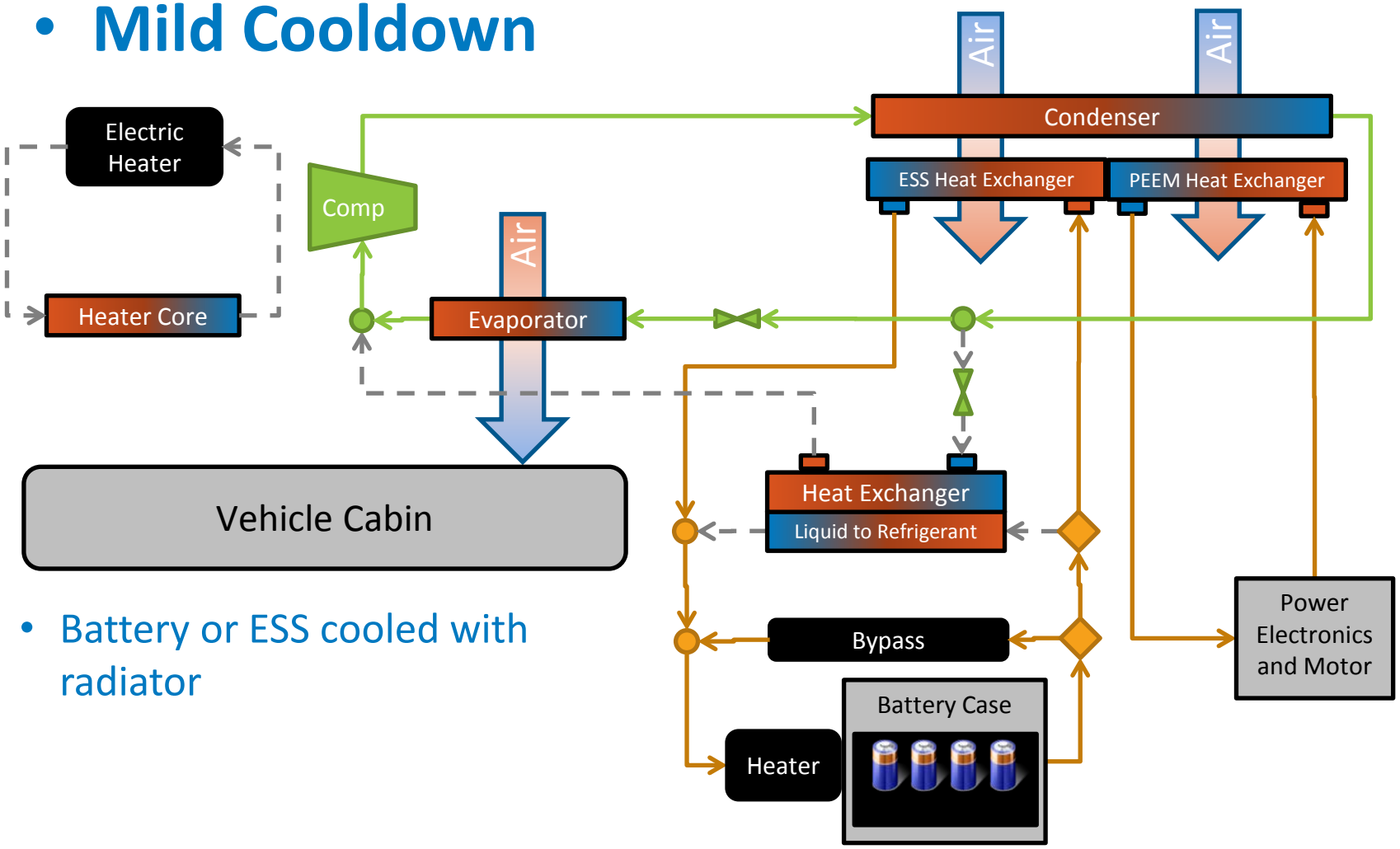
- **Hot Cooldown**



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

EV Baseline Thermal Management System

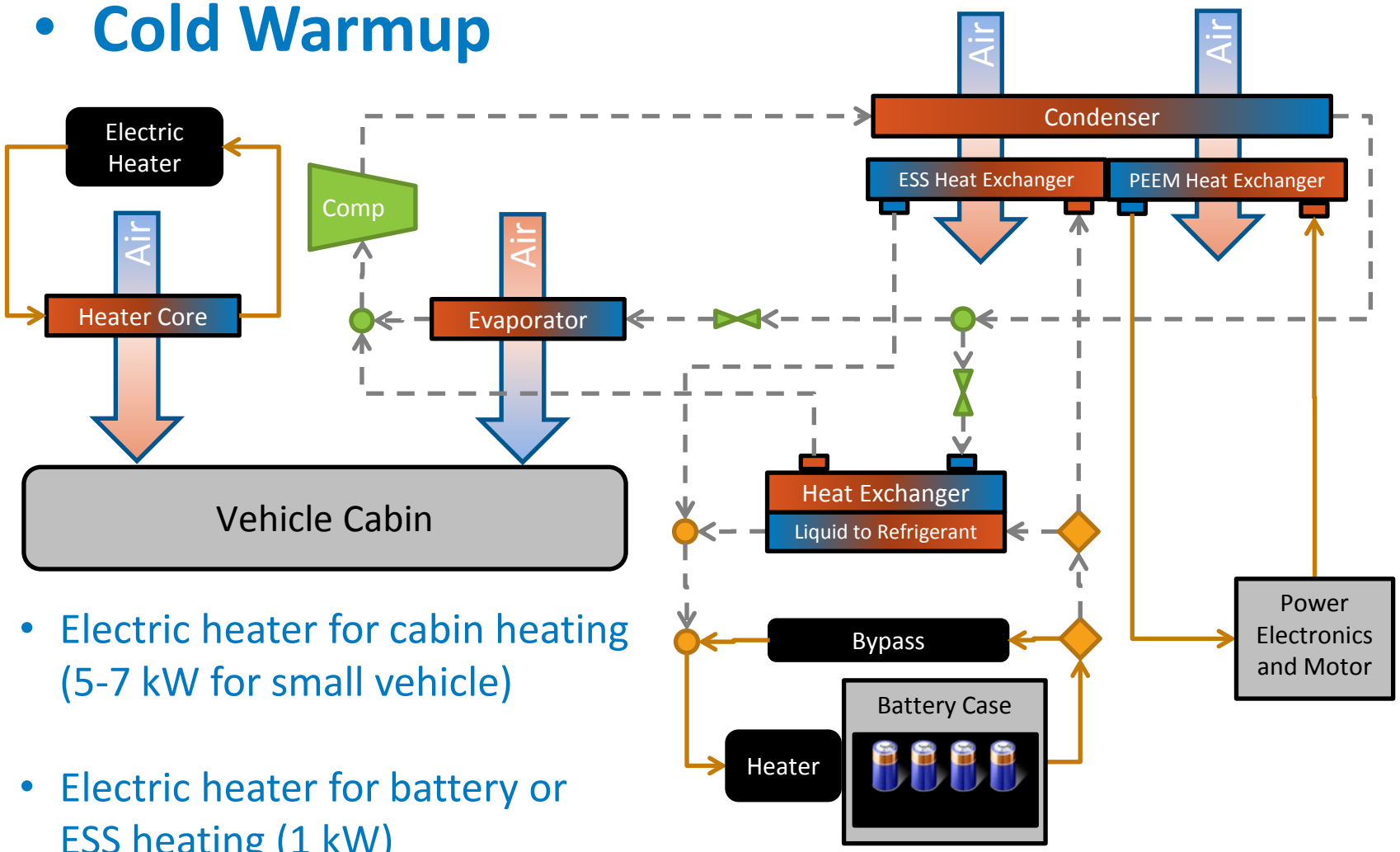
- **Mild Cooldown**



- Battery or ESS cooled with radiator

EV Baseline Thermal Management System

- **Cold Warmup**

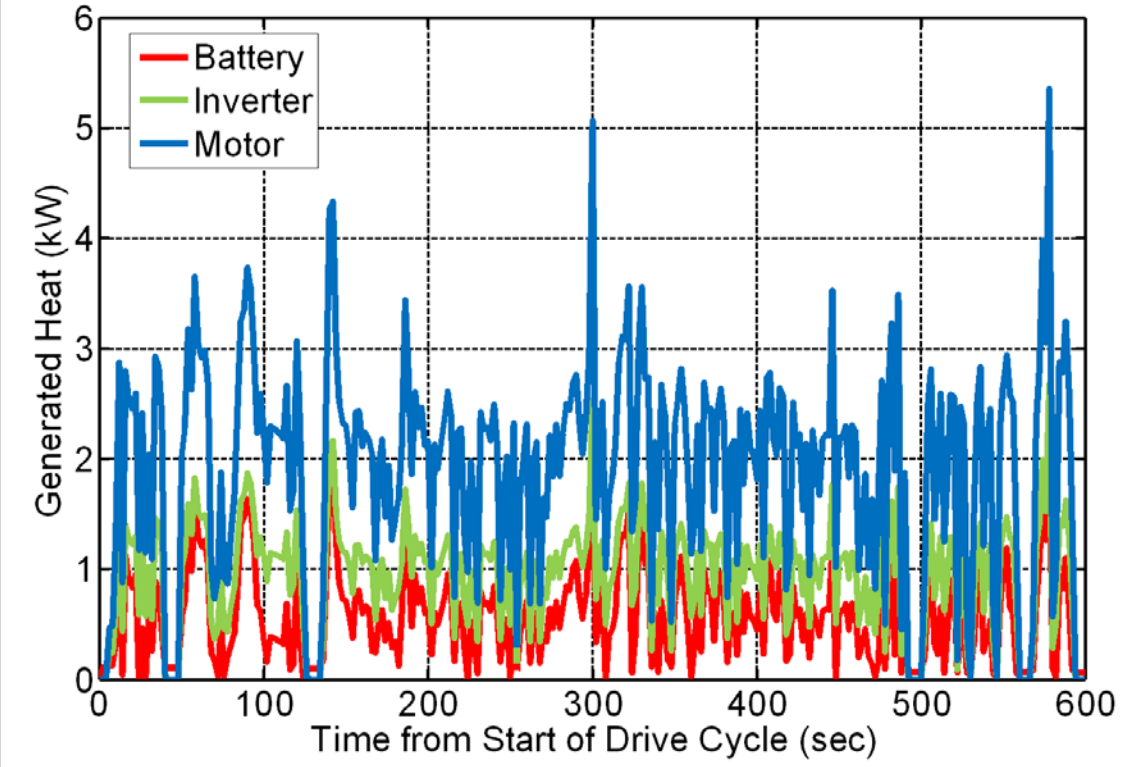


- Electric heater for cabin heating (5-7 kW for small vehicle)
- Electric heater for battery or ESS heating (1 kW)

Baseline EV Thermal Management System

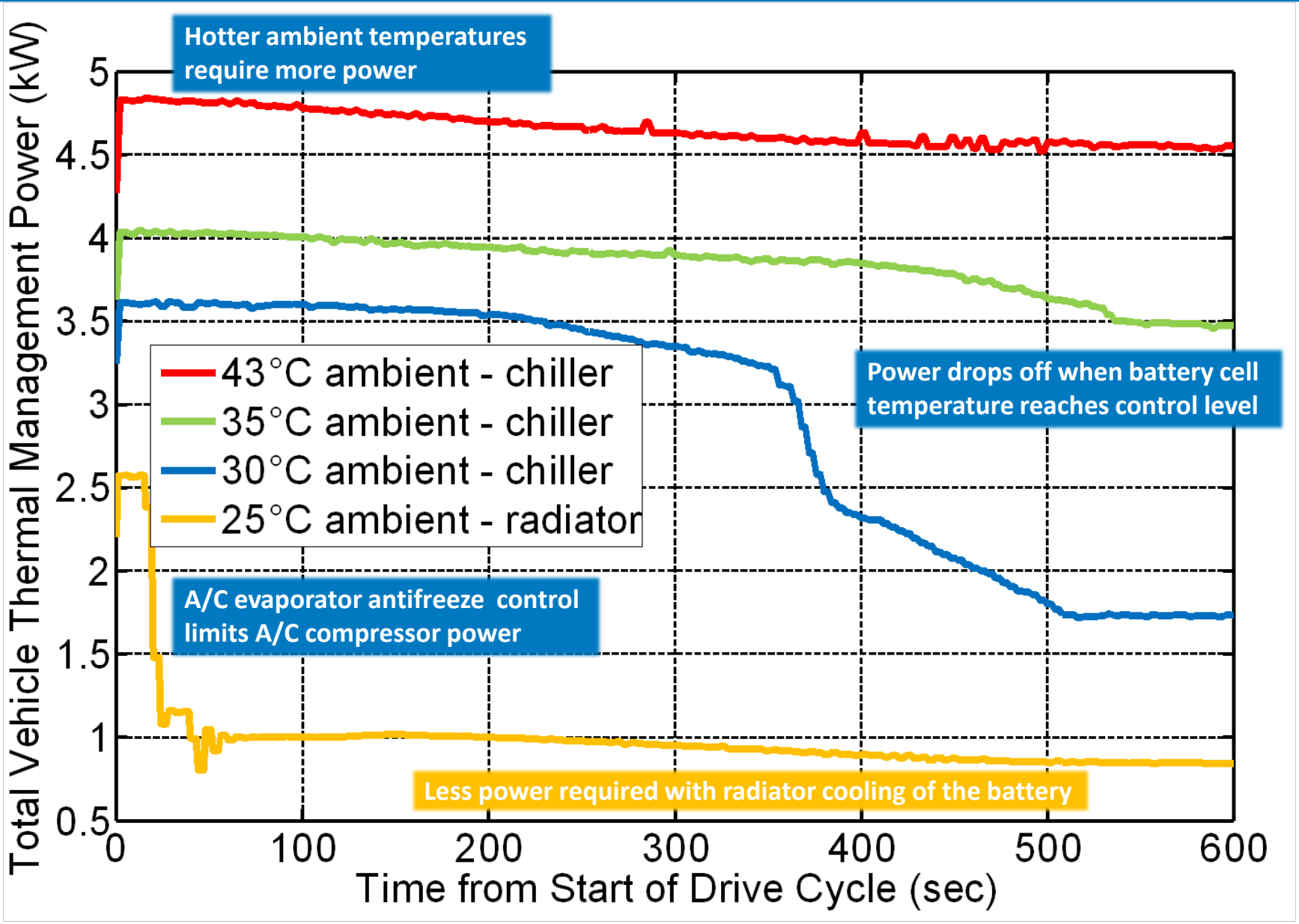
EV Test Case at Four Ambient Temperatures

- 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



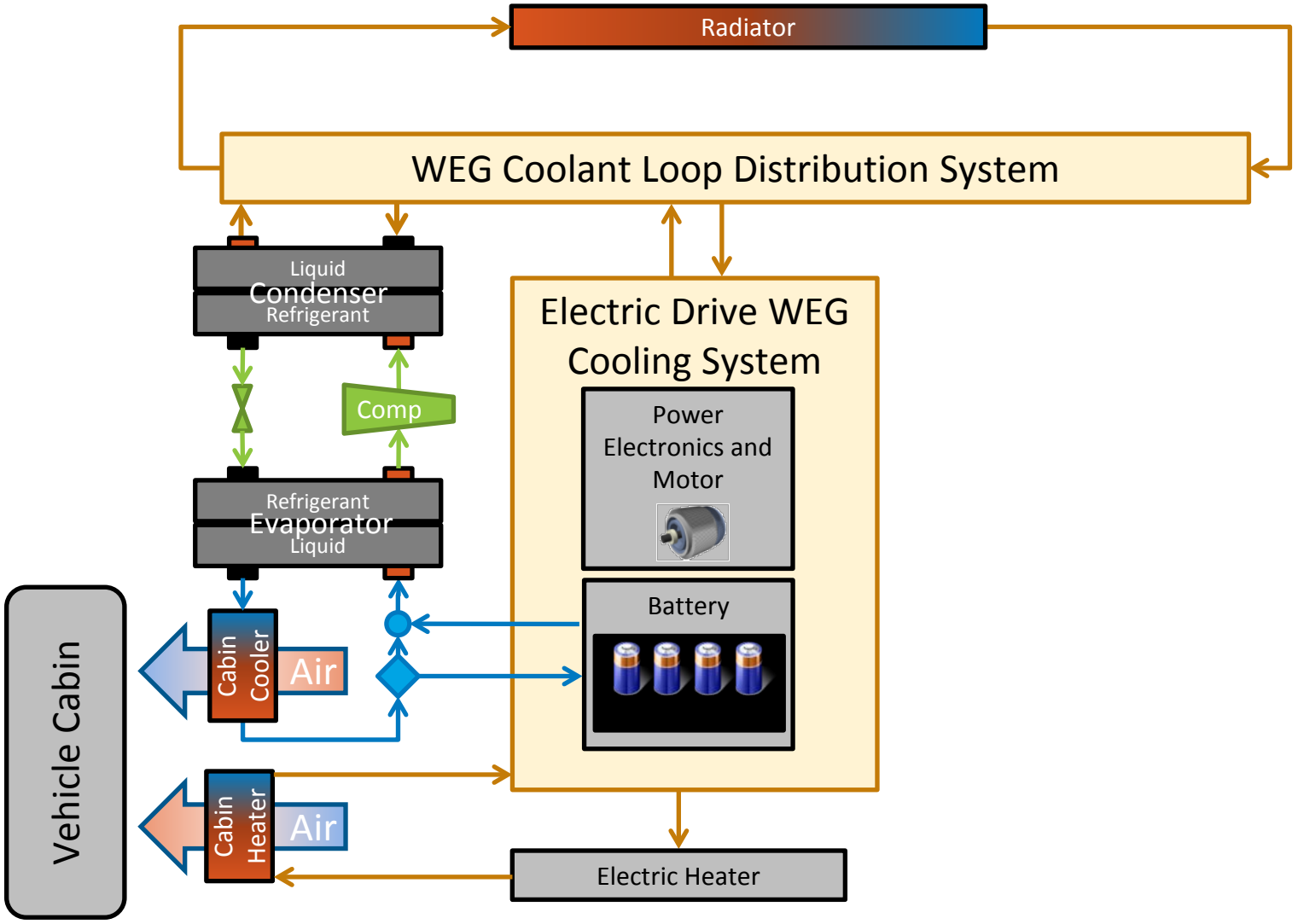
Baseline System

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



Combined System

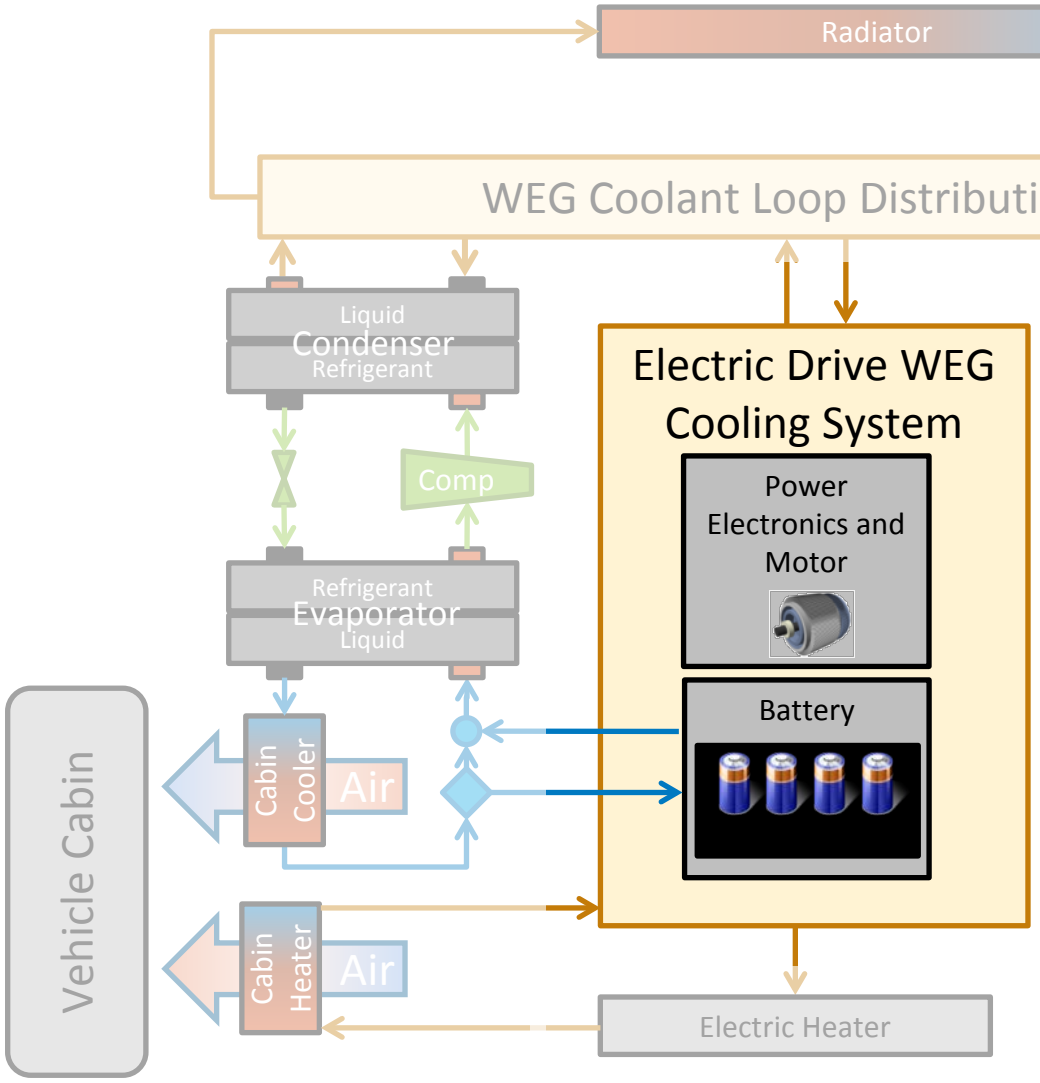
Combining APEEM and ESS Cooling Loops



WEG = Water/Ethylene Glycol

Combined System – Configuration 1

Combining APEEM and ESS Cooling Loops

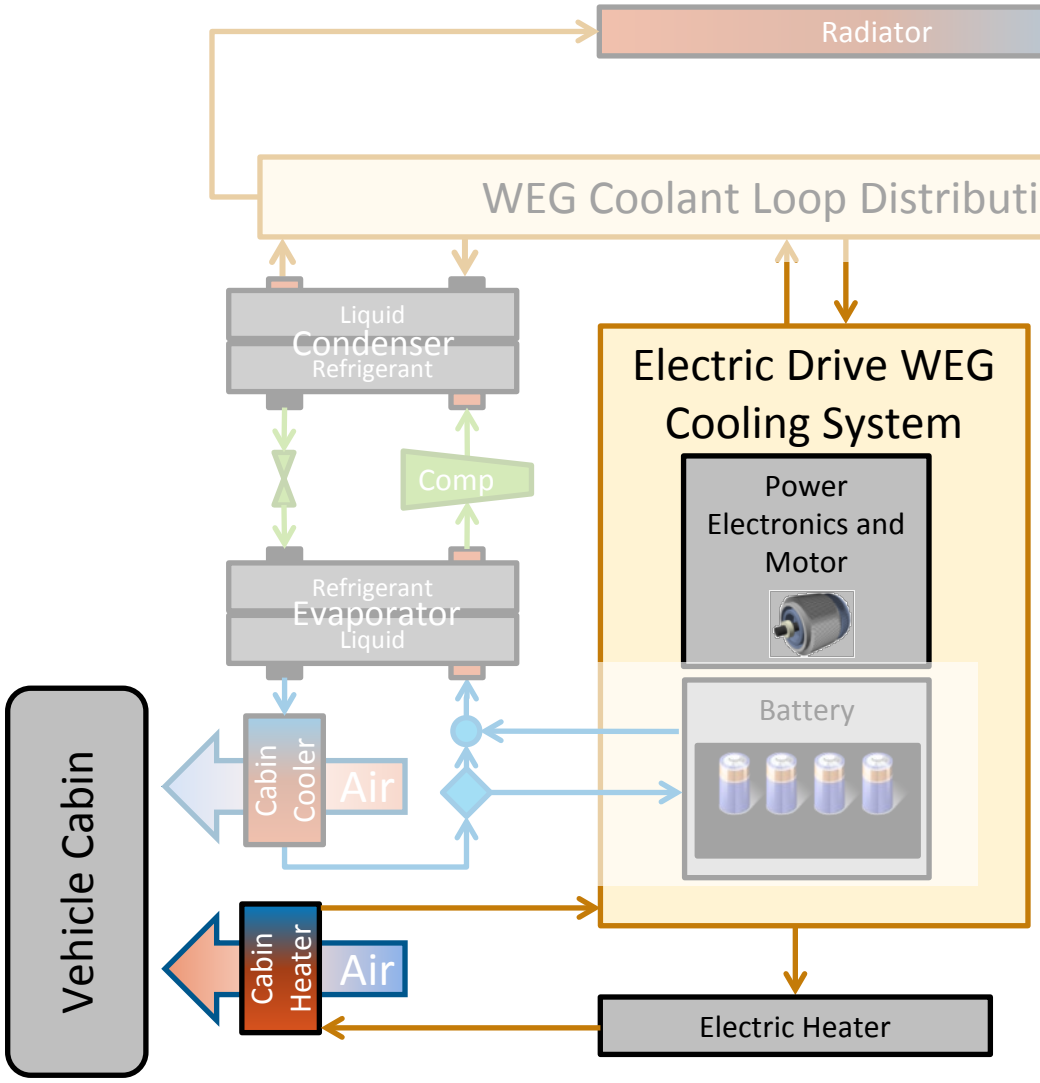


- Enables use of APEEM waste heat for ESS heating

WEG = Water/Ethylene Glycol

Combined System – Configuration 2

Combining APEEM and Cabin Heating Loops



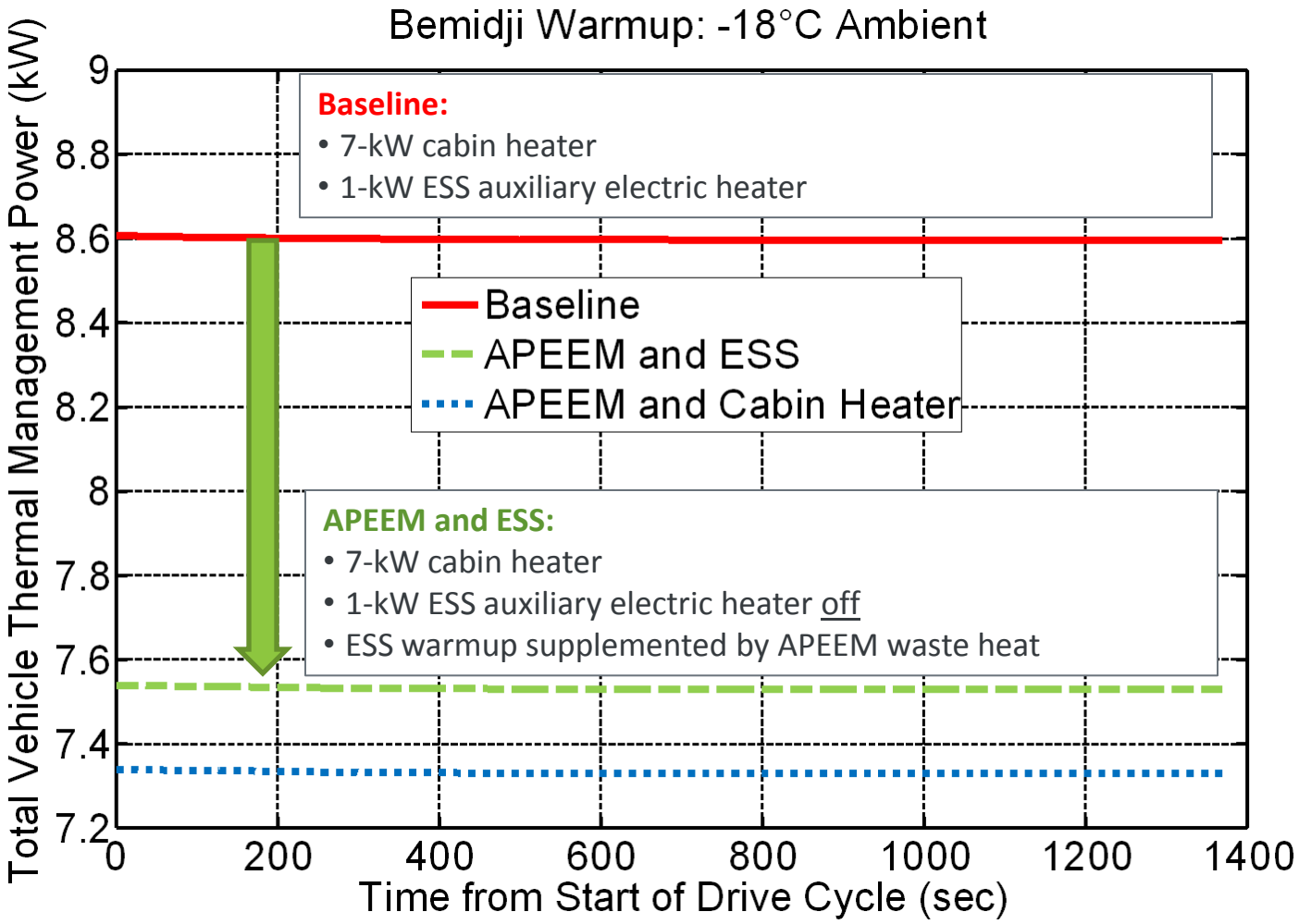
- Enables use of APEEM waste heat for ESS heating or cabin heating

WEG = Water/Ethylene Glycol

Warmup: Auxiliary Load Power

VTM Power Reduced by Using APEEM Waste Heat

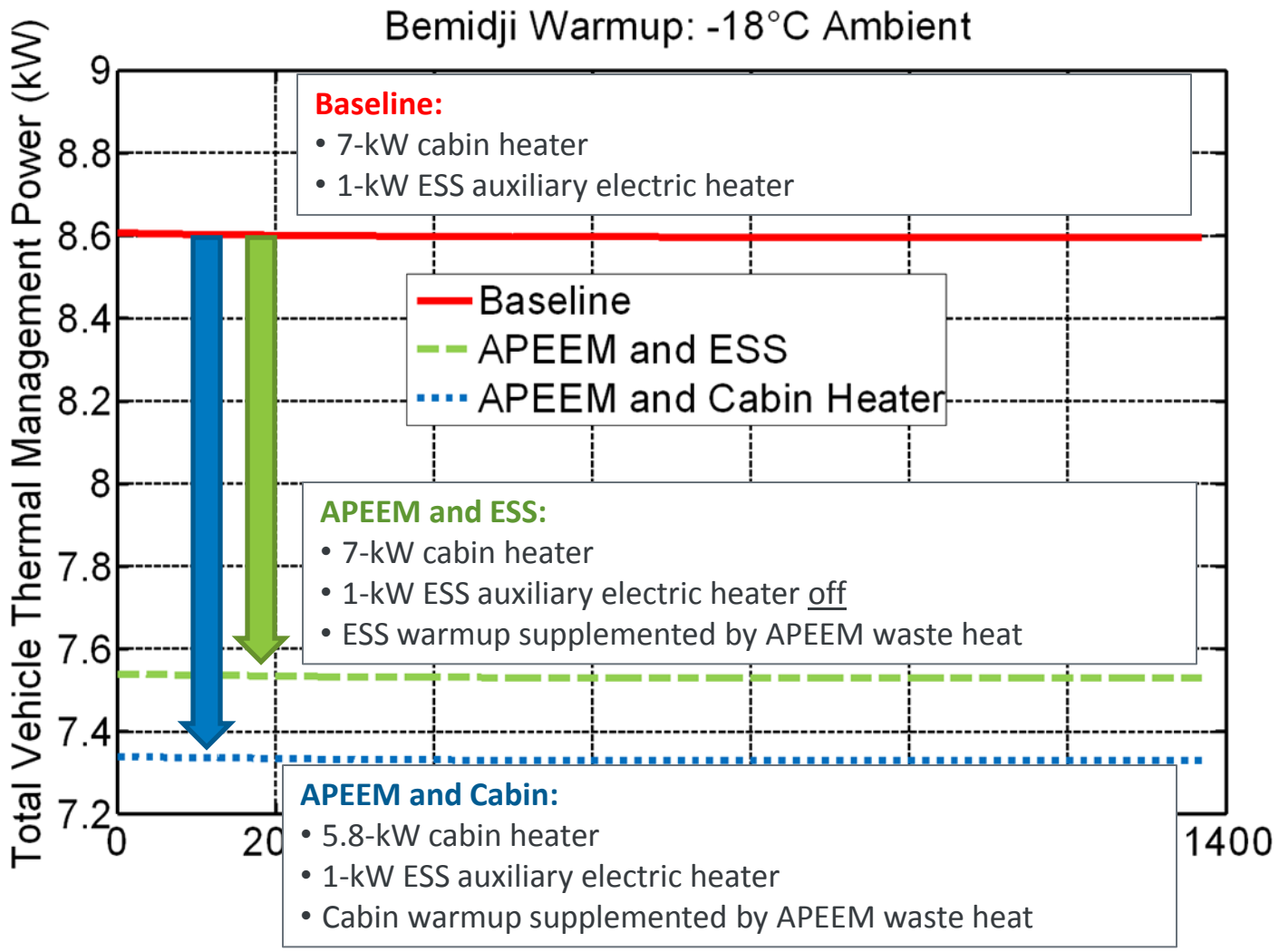
Configuration 1 (APEEM and ESS)



Warmup: Auxiliary Load Power

VTM Power Reduced by Using APEEM Waste Heat

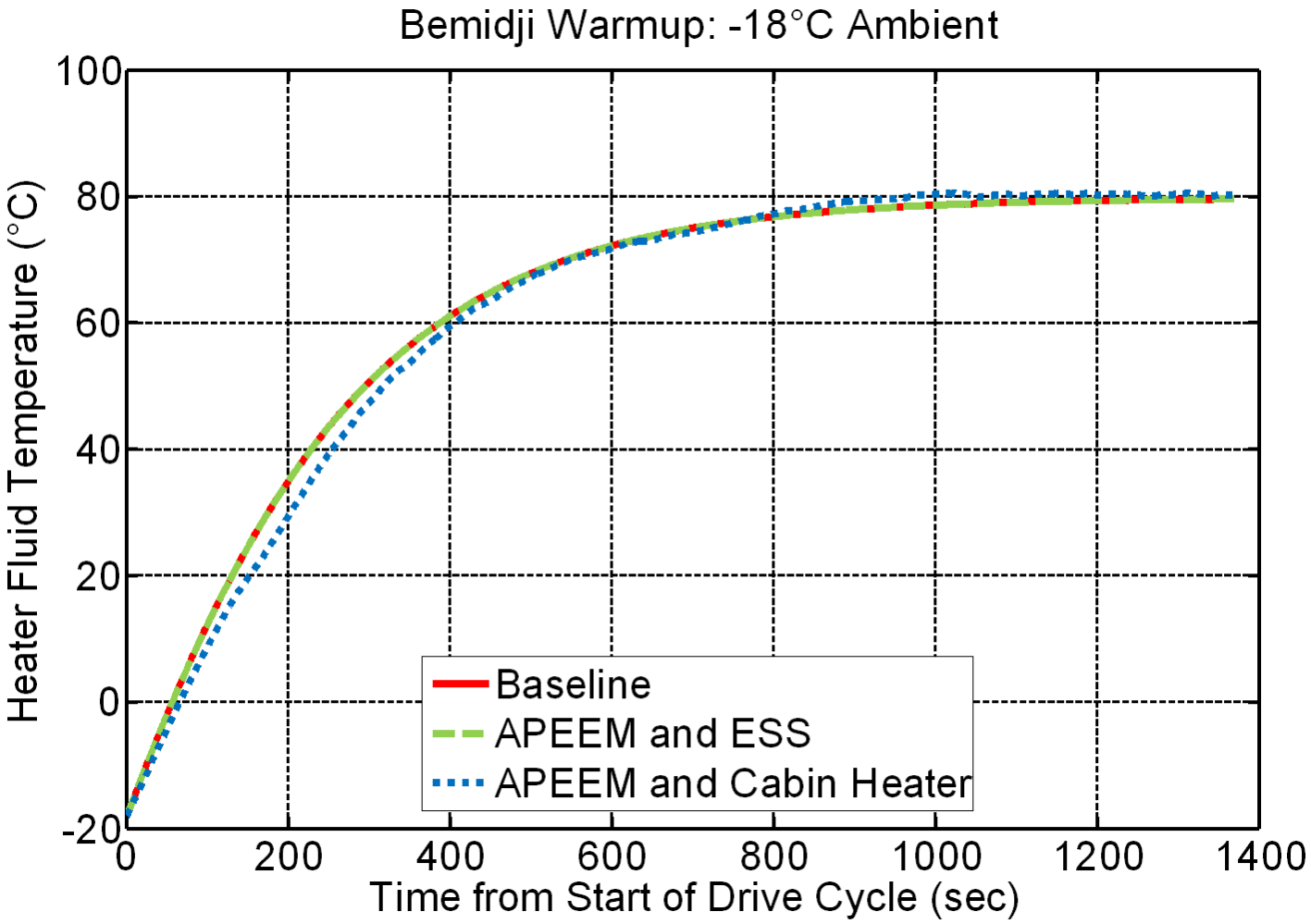
Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)



Warmup: Cabin Heater Fluid Temperature

Cabin Heater Fluid Temperatures Are Very Similar

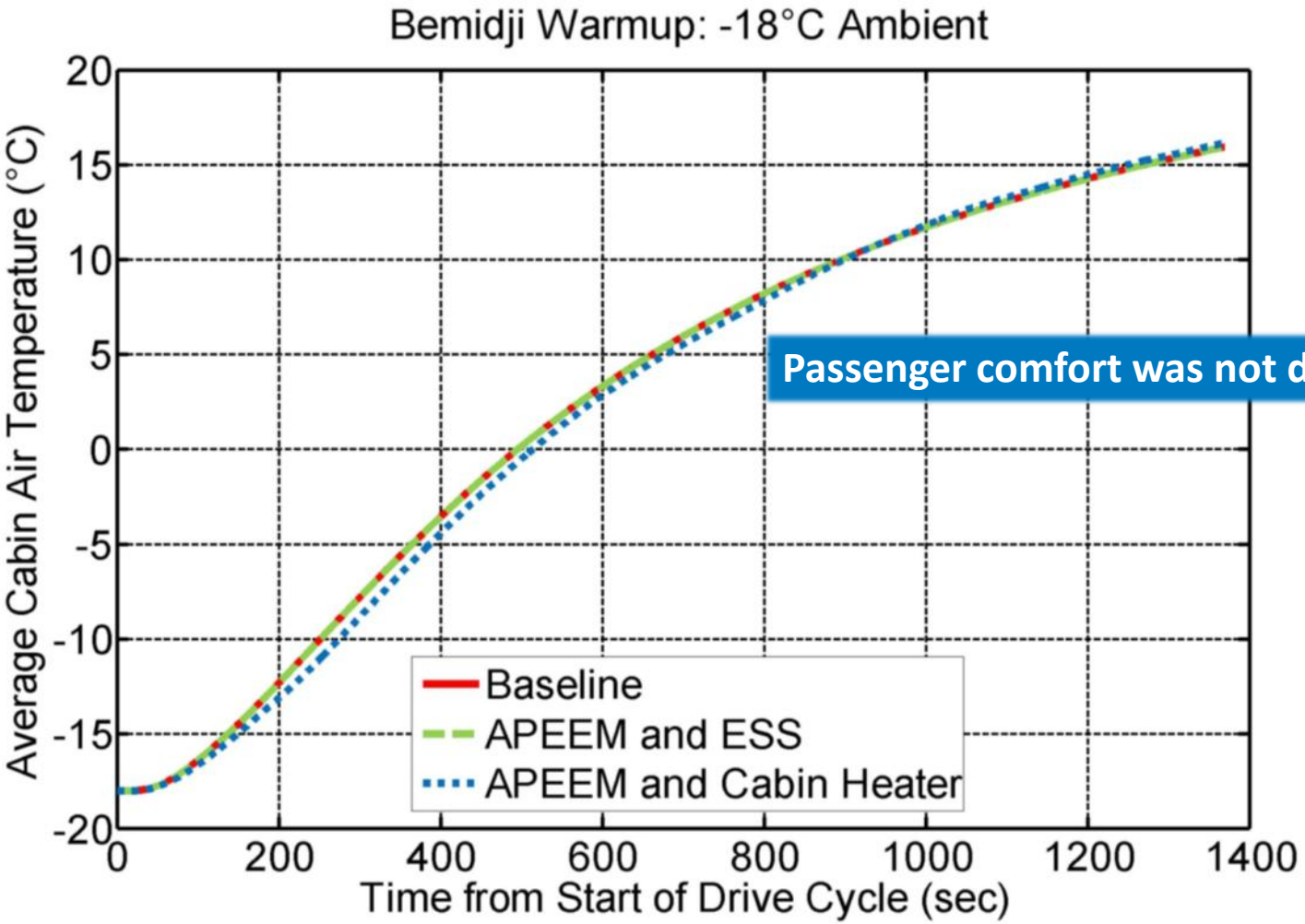
Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)



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)

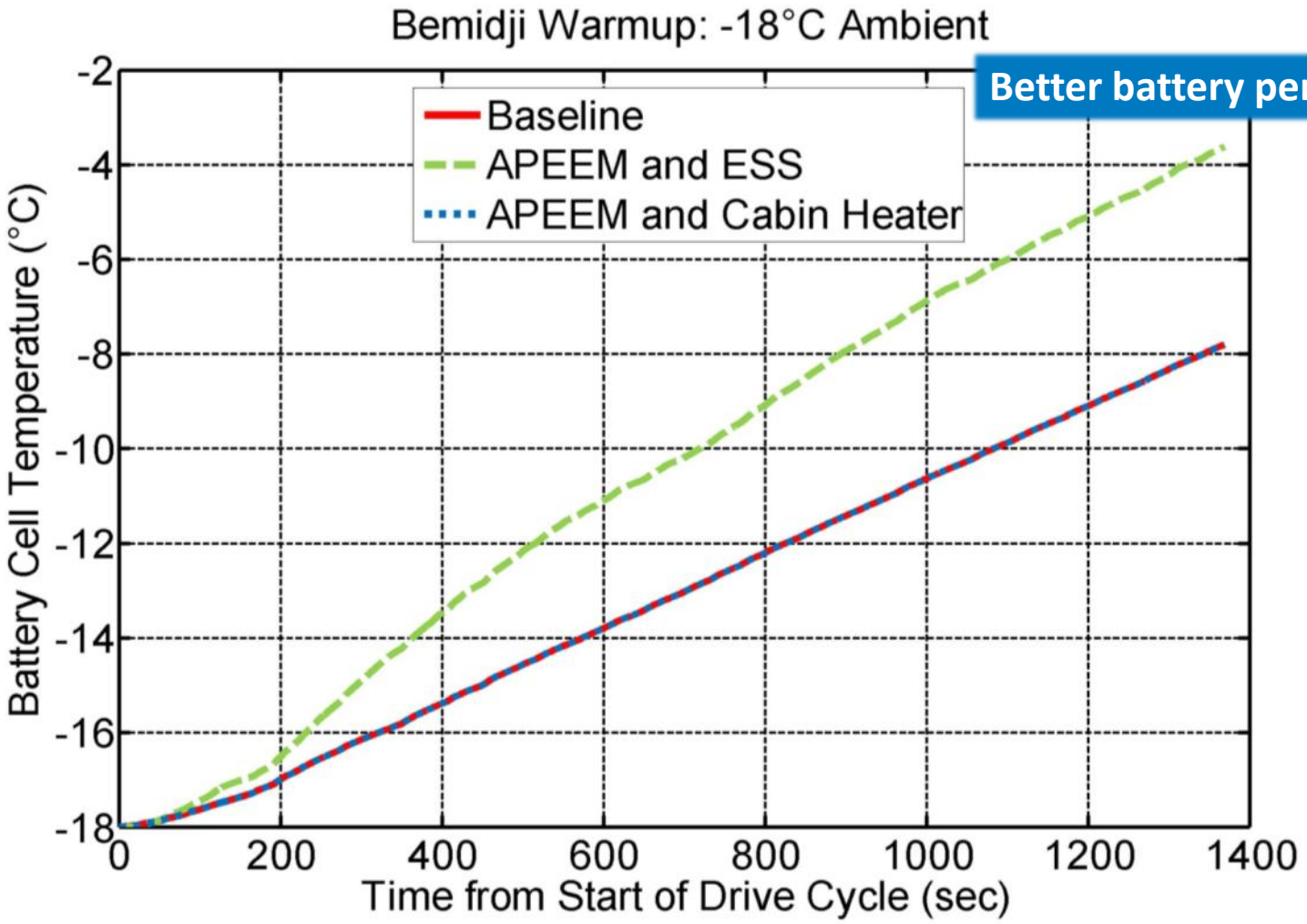


Passenger comfort was not degraded

Warmup: Battery Temperature

Battery Is Warmer with APEEM Waste Heat

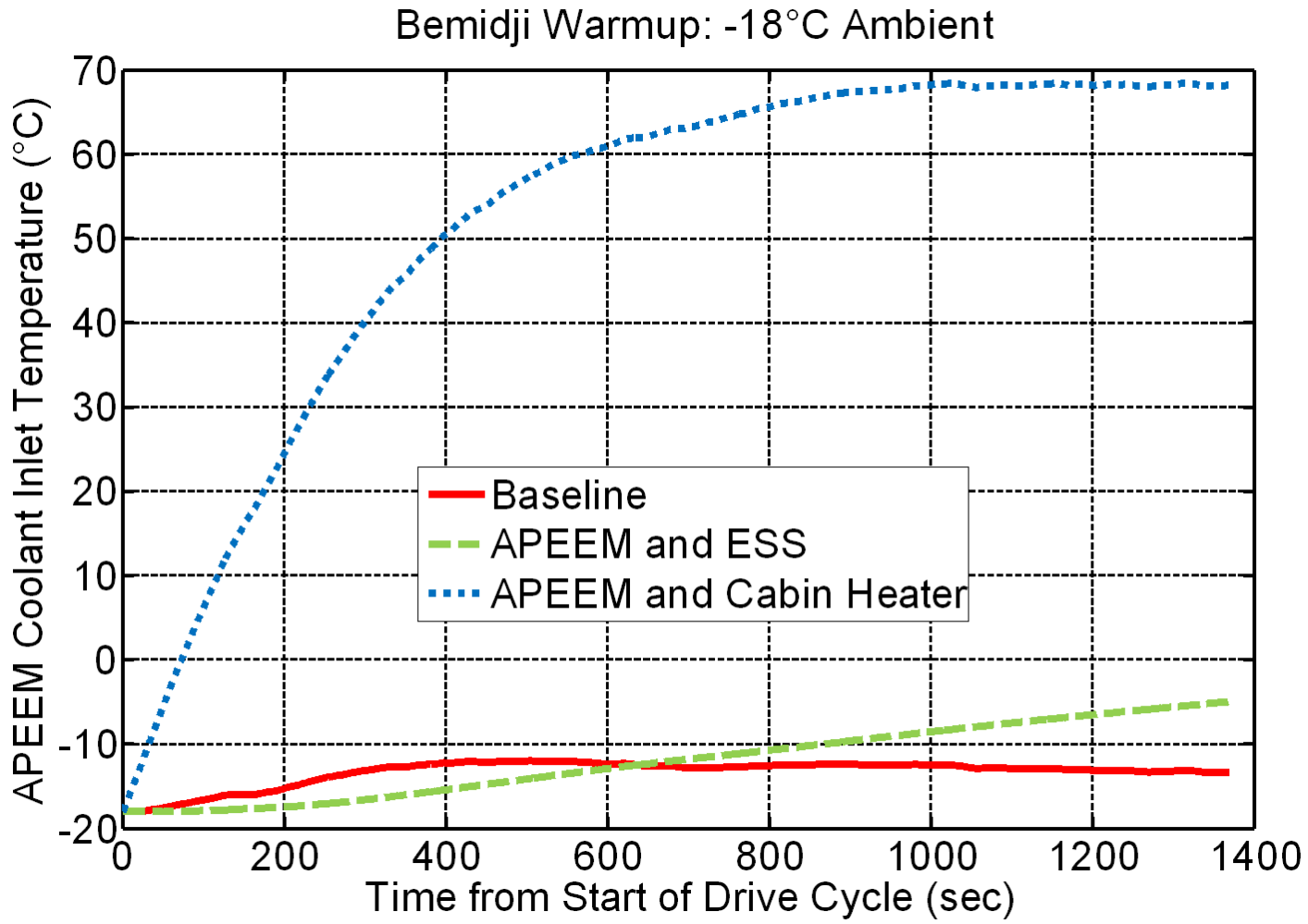
Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)



Warmup: APEEM Coolant Temperature

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

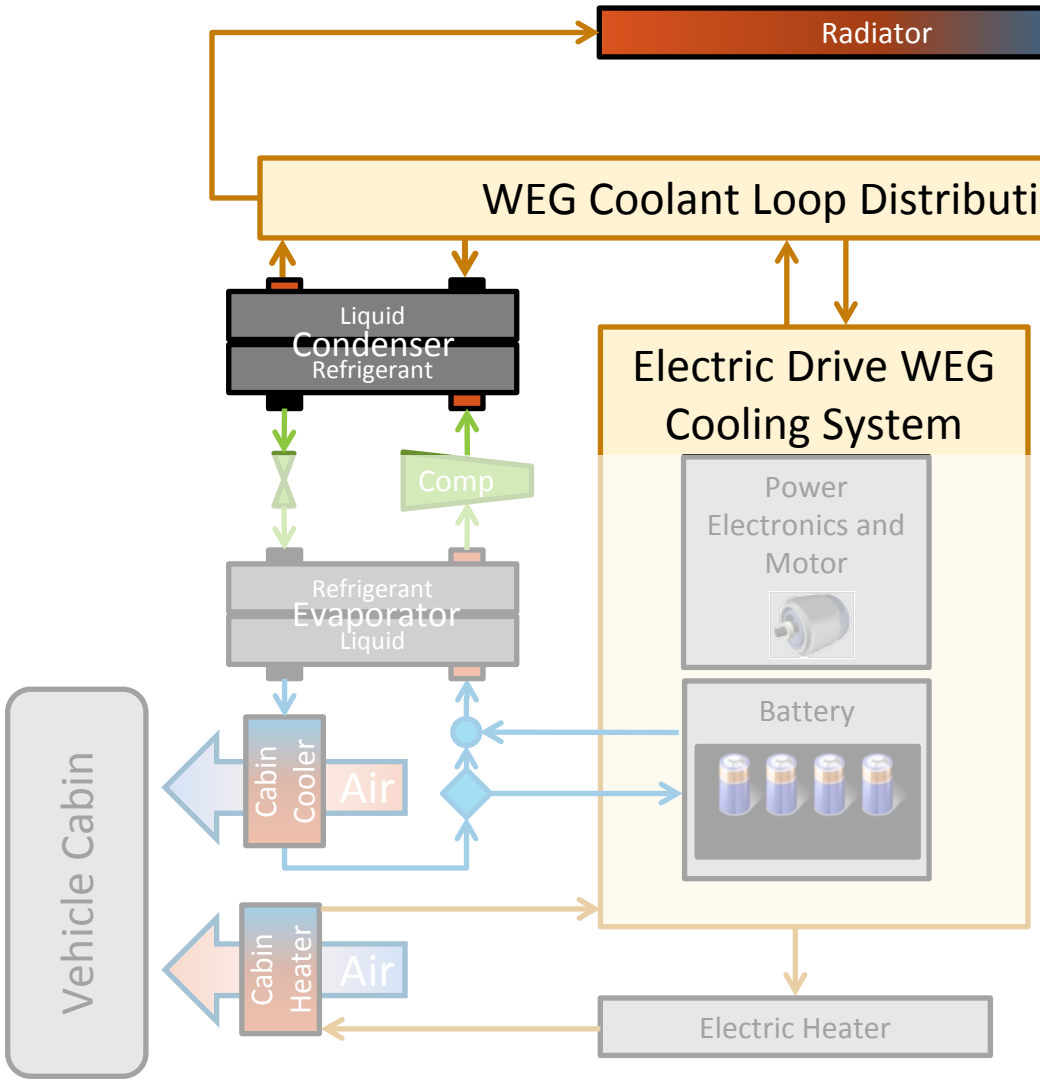
Configuration 1 (APEEM and ESS) and Configuration 2 (APEEM and Cabin Heating)



* "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

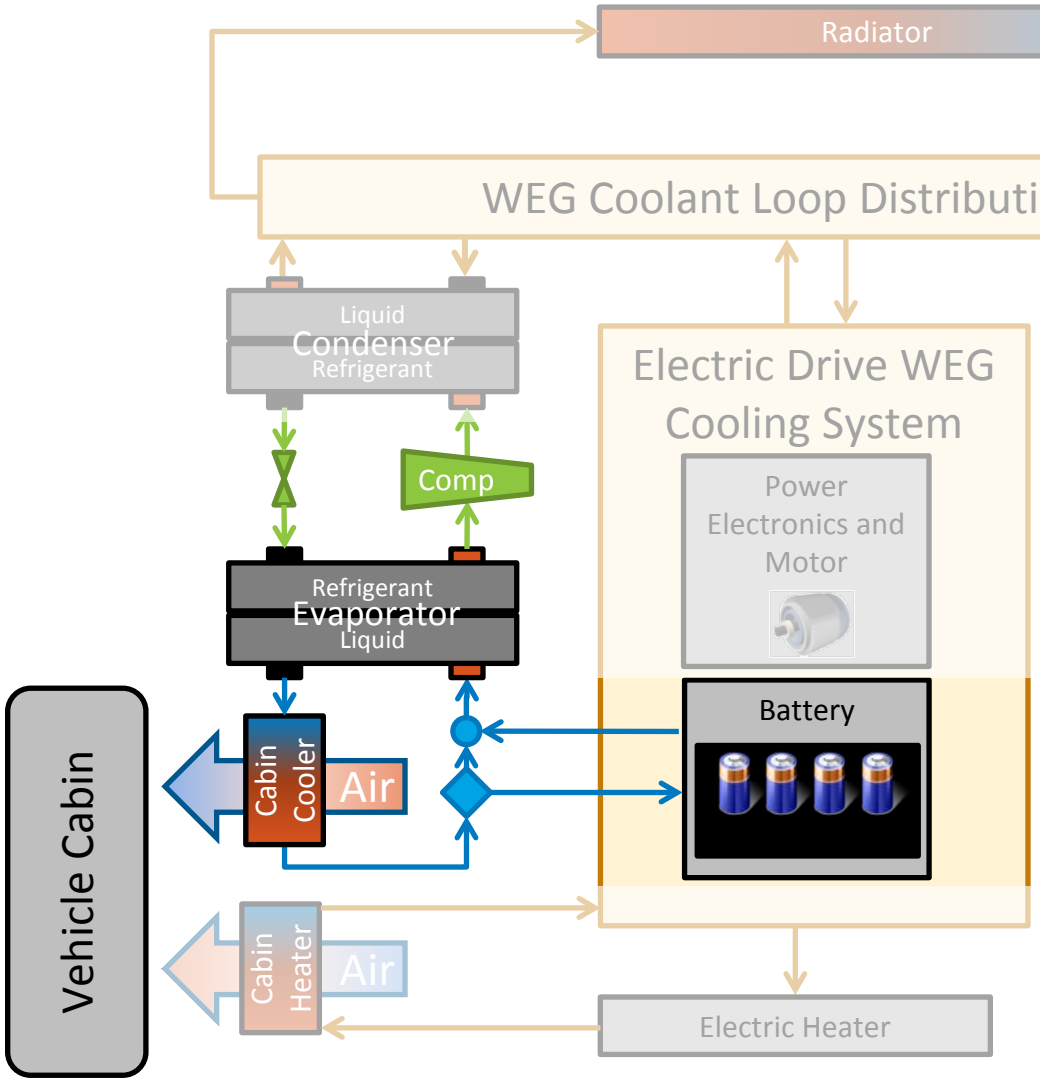


- Enables use of APEEM waste heat for ESS heating or cabin heating
- Reduces front heat exchangers from 3 to 1 using shared low-temperature radiator

WEG = Water/Ethylene Glycol

Combined System – Configuration 4

Refrigerant to Liquid Evaporator (Secondary Loop)



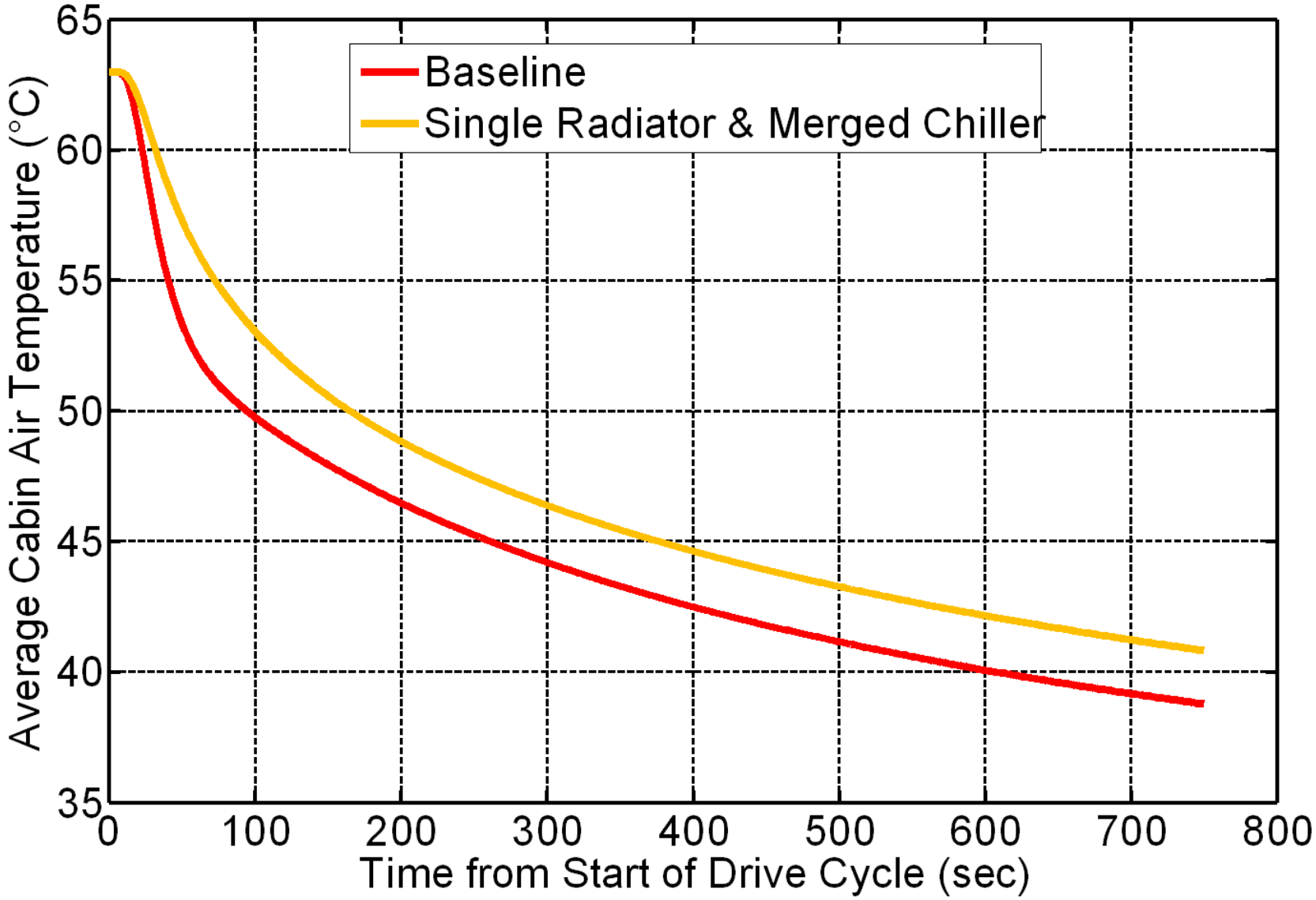
- Enables use of APEEM waste heat for ESS heating or cabin heating
- Reduces front heat exchangers from 3 to 1 using shared low-temperature radiator
- Single chilled-liquid loop
- Compatible with heat pump operation
- Compact refrigerant loop

WEG = Water/Ethylene Glycol

Cooldown: Cabin Air Temperature

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

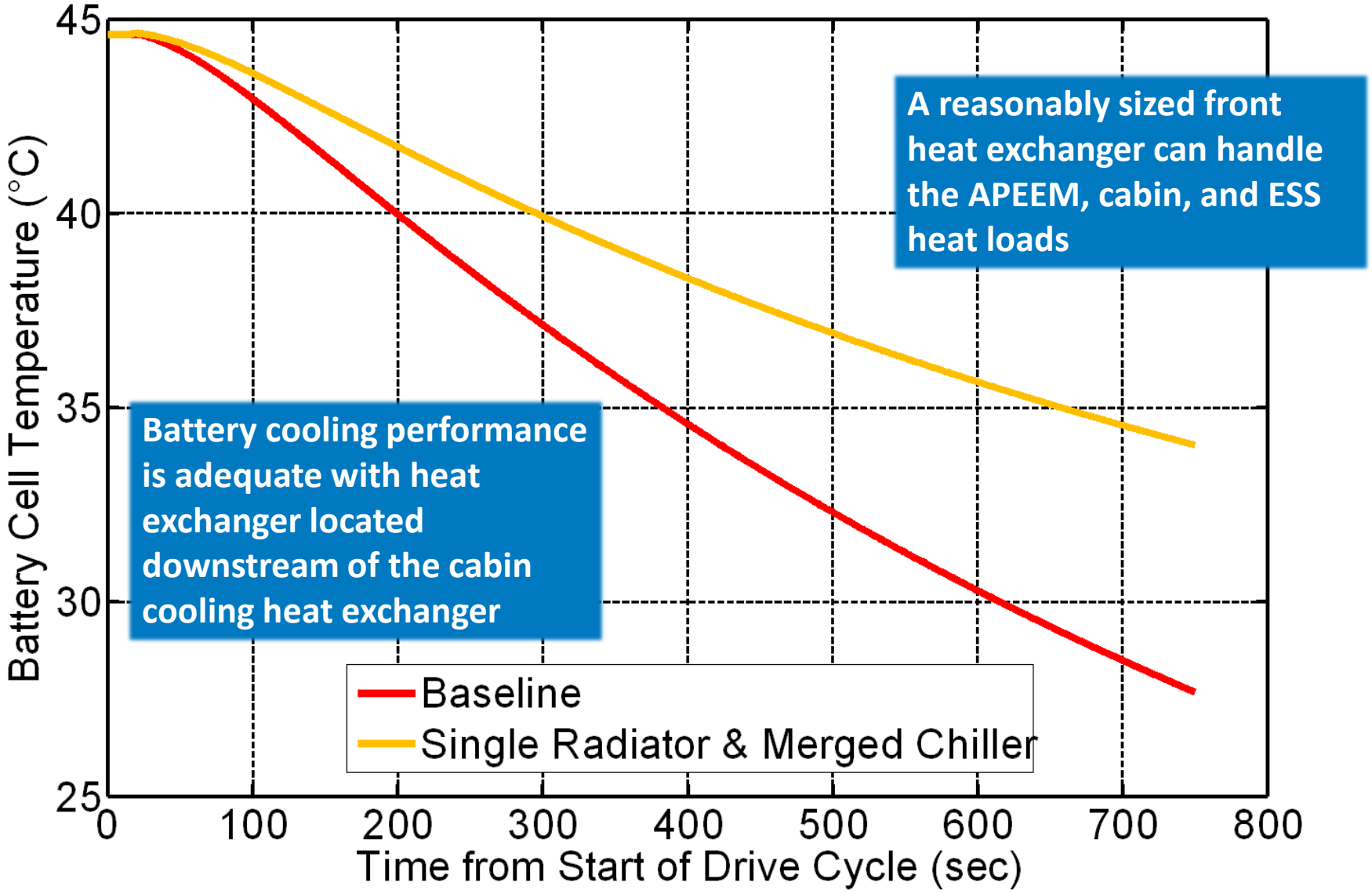
Configurations 3 & 4 (Liquid-Cooled Condenser and Refrigerant to Liquid Evaporator – Secondary Loop)



Cooldown: Battery Temperature

Slightly Warmer Battery (But Still a Reasonable Cooldown)

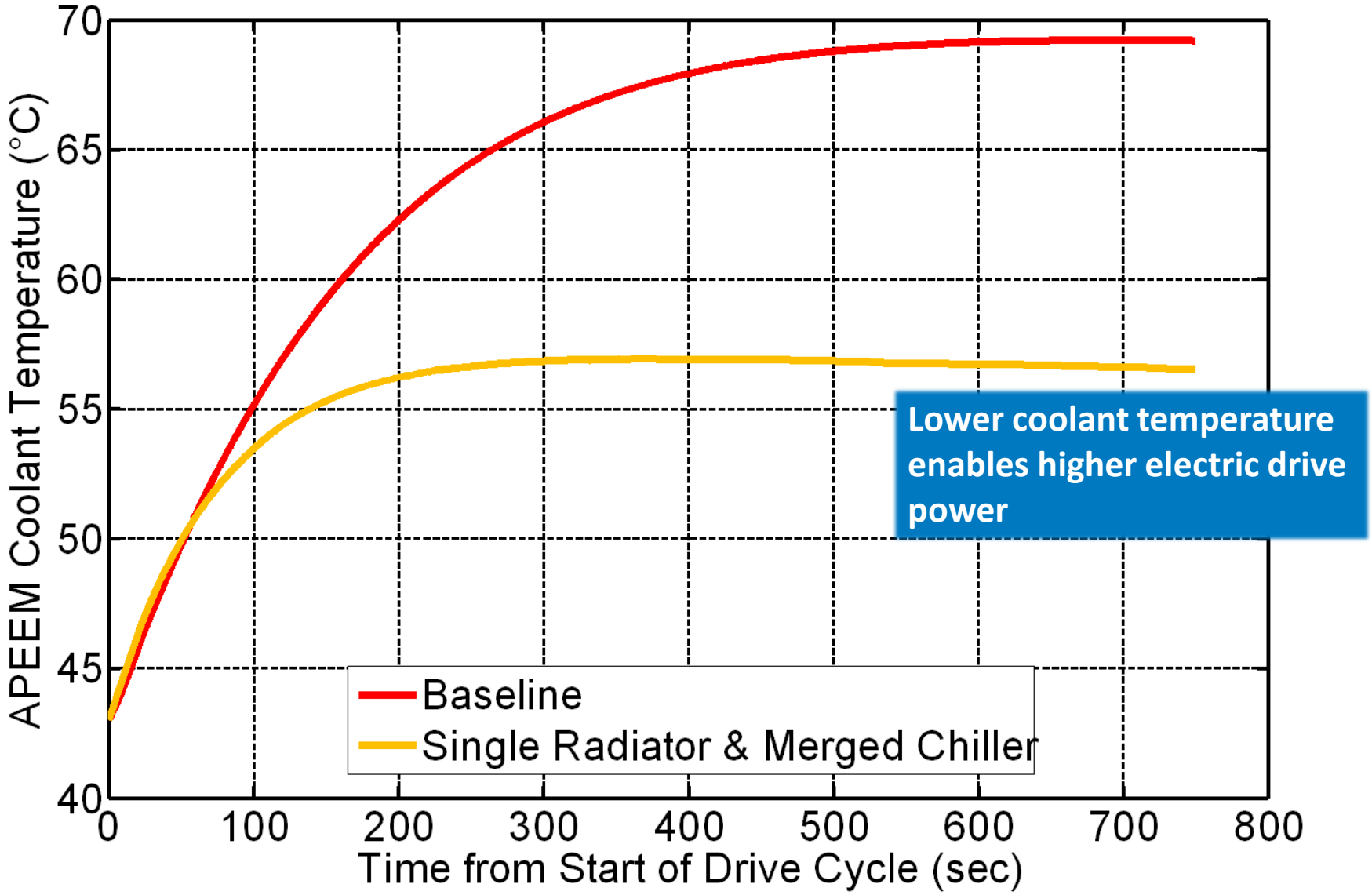
Configurations 3 & 4 (Liquid-Cooled Condenser and Refrigerant to Liquid Evaporator – Secondary Loop)



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)

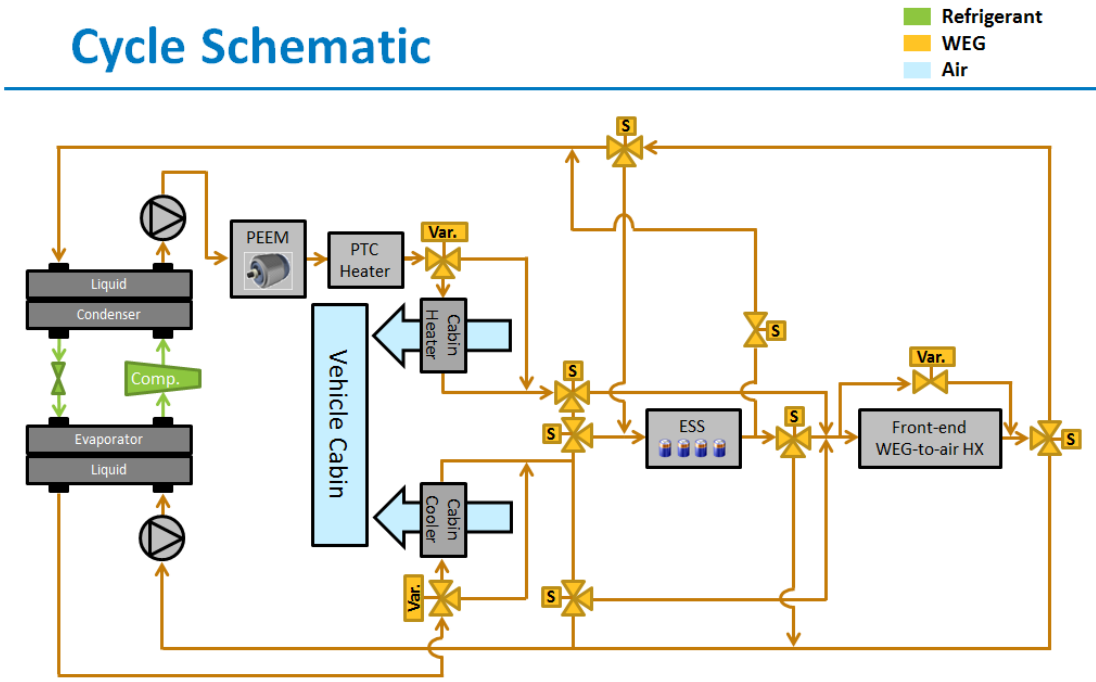


Accomplishments – Bench Test

- **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

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

Cycle Schematic

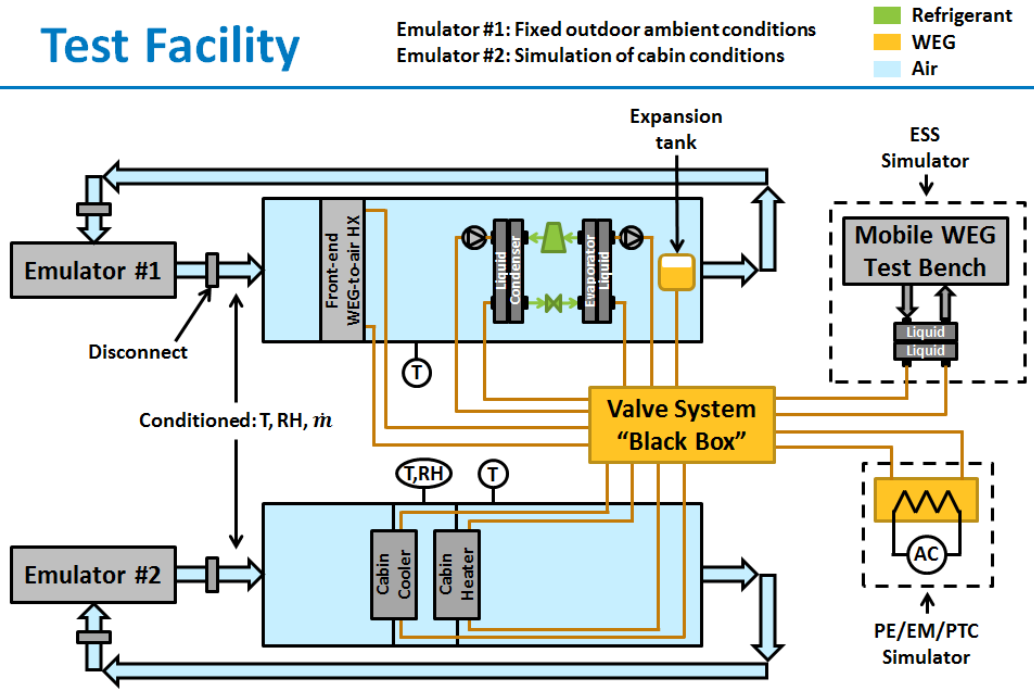


Accomplishments – Bench Test

- **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

Test Facility



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

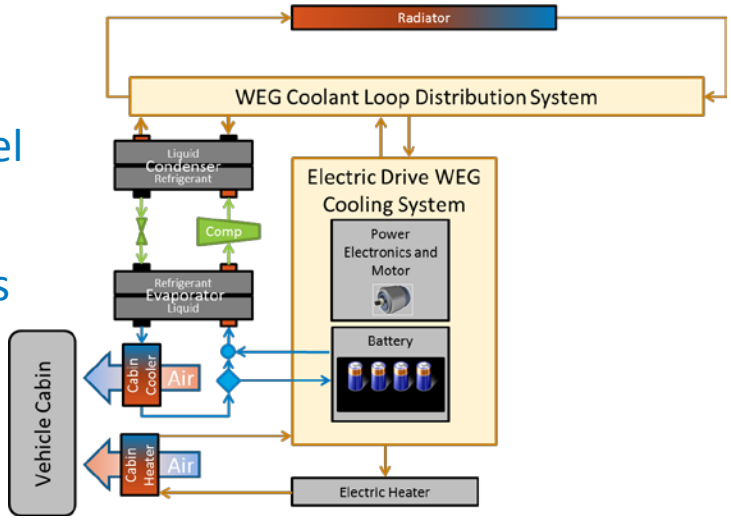
- **Remainder of FY13**
  - Finalize combined cooling loop design in conjunction with industry
    - Coordinate with Delphi and Visteon on configuration and components
  - Construct bench testing facility
  - Conduct bench testing to evaluate combined cooling loop system performance during cooling mode
  - 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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Acknowledgments:

David Anderson
Steven Boyd
Brian Cunningham
David Howell
Susan Rogers
Lee Slezak
Vehicle Technologies Office
U.S. Department of Energy

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Reviewer-Only Slides

(Note: please include this “separator” slide between those to be presented and the “Reviewer-Only” slides. These slides will be removed from the presentation file and the DVD and Web PDF files.)

FY12 AMR Reviewer Comments & Response

Feedback:	The reviewer said that continuing to refine and incorporate more data as you go forward is a must.
Response:	In FY12 and FY13, the baseline model of an EV thermal management was refined (components added, controls improved). The model was then modified to assess combined cooling loop strategies.
Feedback:	Overall, the reviewer asserted that the project seems to have a reasonable approach, but that it would be good to know whether it has been vetted and received positively by industry.
Response:	A project overview and results of the modeling was presented at the 2012 SAE Thermal Management Systems Symposium
Feedback:	Another reviewer indicated that the model seems okay but so far seems to be looking at limits and tradeoffs one at a time.
Response:	The liquid cooled condenser and refrigerant-to-liquid evaporator were assessed in a single simulation. In all combined concept cases, the critical parameters were assessed (cabin, ESS, motor, and APEEM fluid temperatures as well as total VTM power.)
Feedback:	While the presentation provides a reference for a thermal model of a permanent magnet motor, the reviewer did not have a chance to read it, and said that it was not clear what level of detail is included in the electric motor model. According to the reviewer, it is critical to limit the peak temperature of the motor, and using a lumped model representation may not provide adequate resolution to capture the peak temperature.
Response:	While the motor thermal model is a 3-node representation, careful review of literature and selection of the lumped-node parameters provided confidence that the motor temperatures were representative.
Feedback:	A different reviewer pointed out the project needs more direct contributions and involvement from major subsystem suppliers and an OEM.
Response:	We have added Delphi and Ford as partners.

Publications

Rugh, J. P. and Bennion, K.; (2012) "Electric Vehicle Thermal Modeling to Assess Combined Cooling Loop Concepts ," Proceedings of the SAE Thermal Management Systems Symposium, October 31-November 1, 2012, Scottsdale, AZ.

Rugh, J. P., (2012) "Integrated Vehicle Thermal Management – Combining Fluid Loops in Electric Drive Vehicles," FY2012 Advanced Power Electronics and Electric Motors Annual Report.

Critical Assumptions and Issues

- **Assumption: Maintaining cabin and battery cooling performance with a series configuration**
  - Analysis results indicate the battery can be cooled in a reasonable time while maintaining cabin comfort. This will be verified with tests.
- **Assumption: Year-round benefits of a combined cooling loop configuration will outweigh the secondary loop disadvantages experienced in hot environments**
  - Delphi research showed the performance of a similar system. They reported the reduction in heating power offset the increase in cooling power. Performance of the proposed system will be verified through testing.
- **Assumption: In a bench setting, simulation of the APEEM, ESS, and cabin performance is equivalent to an actual vehicle in a real environment**
  - Testing will verify numerical models accurately represent the APEEM components, ESS, and cabin.
- **Issue: Potential for excessive control complexity**
  - The system must operate in all environments. With multiple valves , temperature requirements, and fluid loops, the control logic will likely be complex. Research will investigate ways to reduce complexity.