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

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May 15, 2012

Project ID: VSS046

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Overview

Timeline

Project Start Date: FY11
Project End Date: FY14
Percent Complete: 35%

Budget

Total Project Funding: $ 750 K*
Funding Received in FY11: $ 375 K*
Funding for FY12: $ 375 K*

*** Shared funding between VTP programs: VSST, APEEM, ESS**

Barriers

- **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
  - "Detroit 3" OEM — CRADA is in approval process
  - Visteon Corp.
  - Magna Steyr
- Project lead: NREL

Overview – Collaboration Between Vehicle Technology Programs

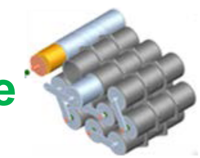
Hybrid Electric Systems
Dave Howell – Team Lead

Vehicle Systems
Lee Slezak
David Anderson

→ **Electric range and fuel consumption**

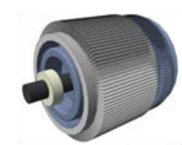
Energy Storage
Tien Duong
Brian Cunningham
Peter Faguy

→ **Battery temperature and life**



Power Electronics & Electric Motors
Susan Rogers
Steven Boyd

→ **APEEM temperatures**



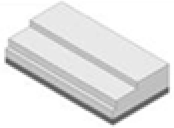


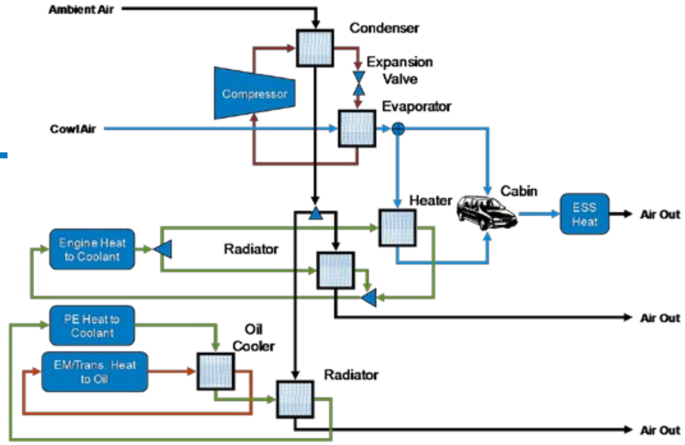
Photo Credit: John Rugh, NREL

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 APEEM
  - Thermal requirements for 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
- **Since thermal management crosses multiple groups at automobile manufacturers, cross-cutting system designs are challenging**

Photo Credit: Mike Simpson, NREL

Relevance/Objective



Objective

- Collaborate with industry partners to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains

Targets

- Improve vehicle performance and reduced cost from the synergistic benefits of combining thermal management systems
- Reduce volume and weight
- Reduce APEEM coolant loop temperature (less than 105°C) without requiring a dedicated system

Approach – Overall

- Build a 1-D thermal model (using KULI software)
  - APEEM, energy storage, engine, transmission, and passenger compartment thermal management systems
  - Identify the synergistic benefits from combining the systems
  - Perform a detailed performance assessment with production-feasible component data
- Conduct bench tests to verify performance and identify viable hardware solutions
- 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

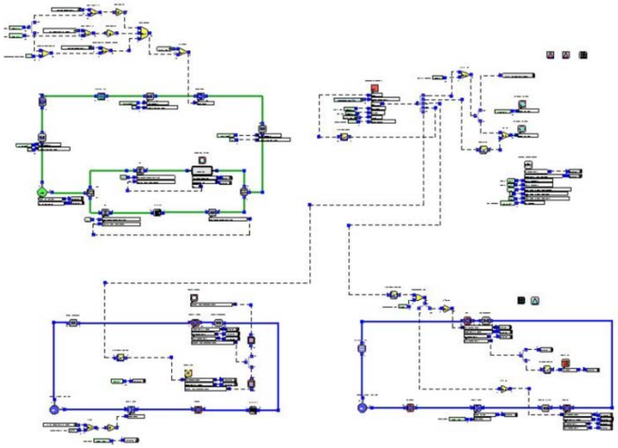
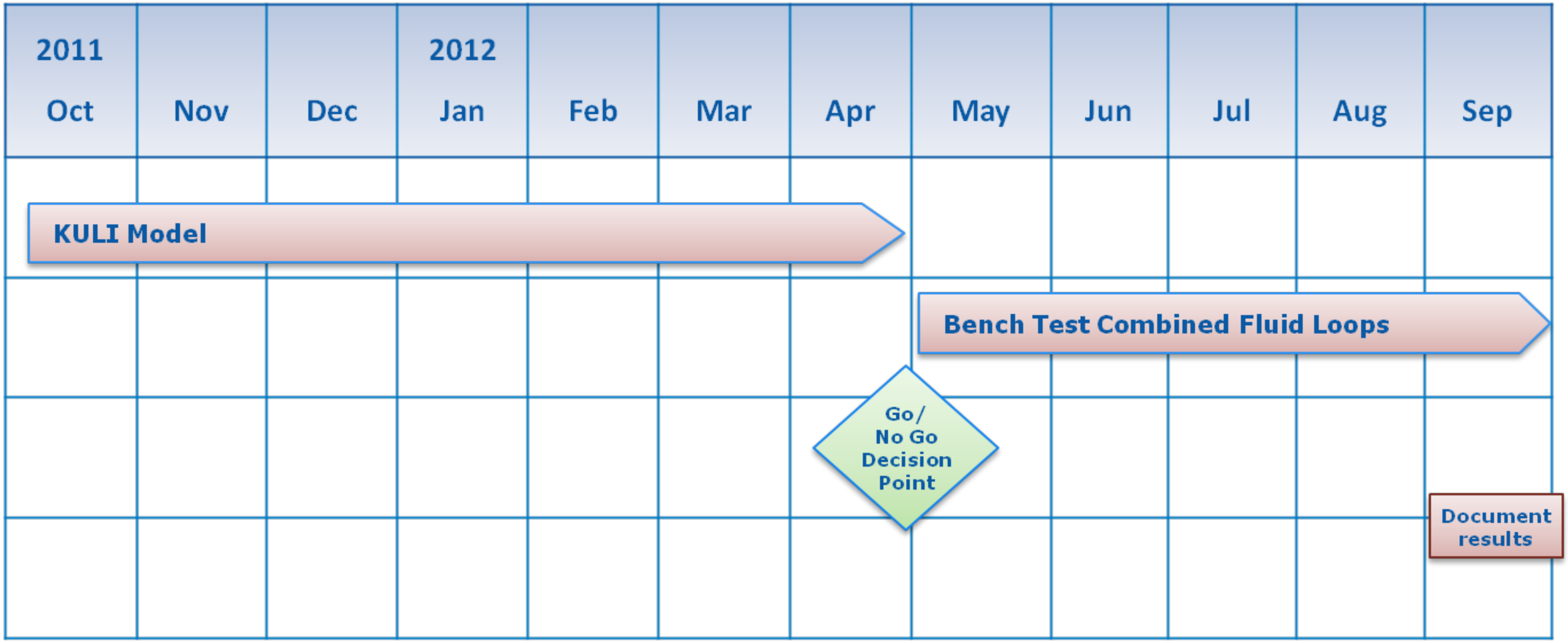


Photo Credit: Charlie King, NRELc

Approach FY12 – Go/No-Go

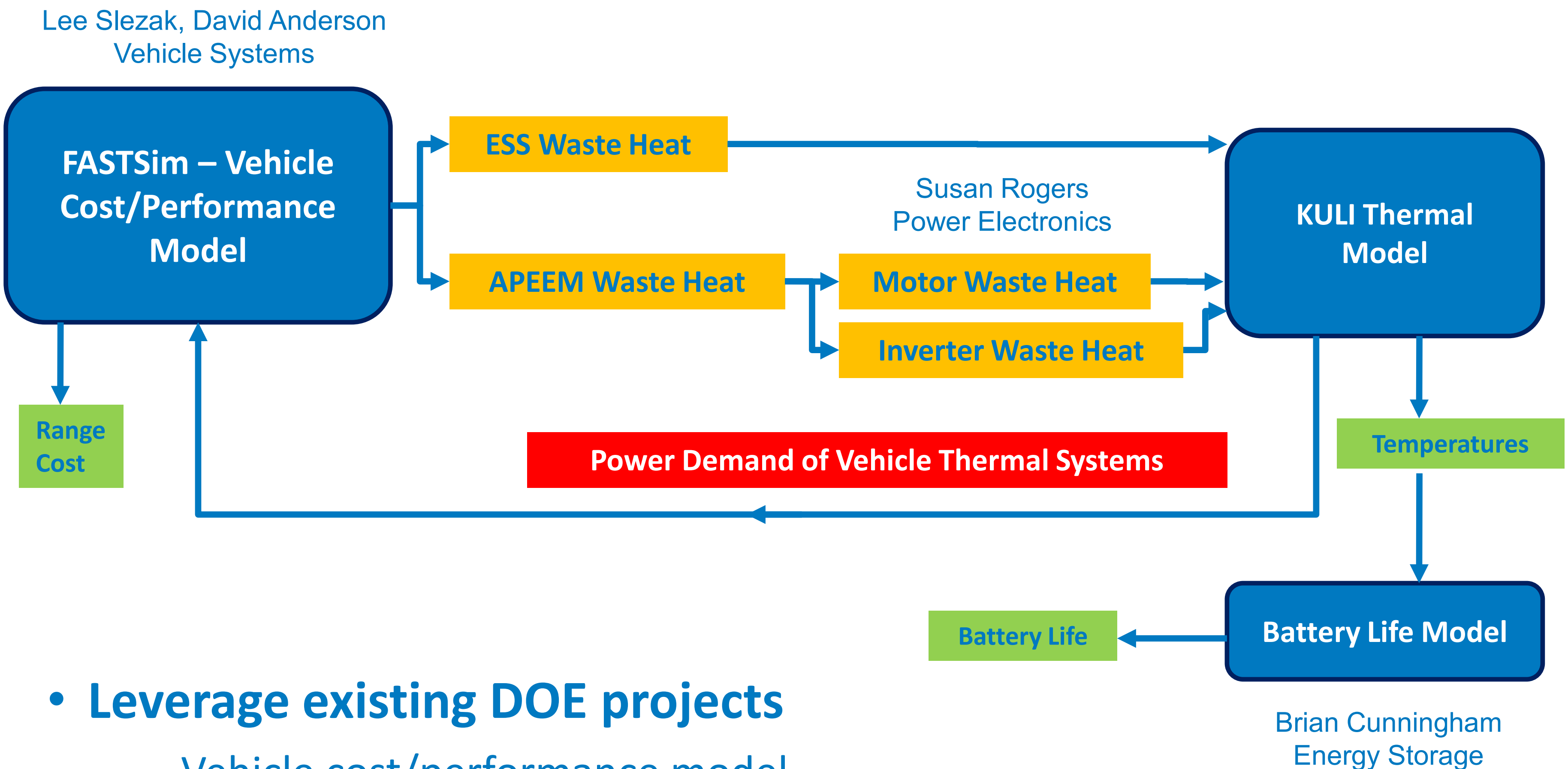


Go/No-Go Decision Point: Based on the outcome of analysis of the thermal management system concepts, assess if building a benchtop system is justified or if further analysis is needed

Challenges / Barriers:

- Integration of requirements and coordination of the diverse groups that have thermal management activities at the automotive OEMs and DOE
- Meeting the heat load requirements of the APEEM components, battery, engine, and passenger compartment with a thermal management system that is less costly and complex

Approach – Analysis Flow Chart



- **Leverage existing DOE projects**
  - Vehicle cost/performance model
  - Lumped parameter motor thermal model
  - Battery life model

FASTSim = Future Automotive System Technology Simulator

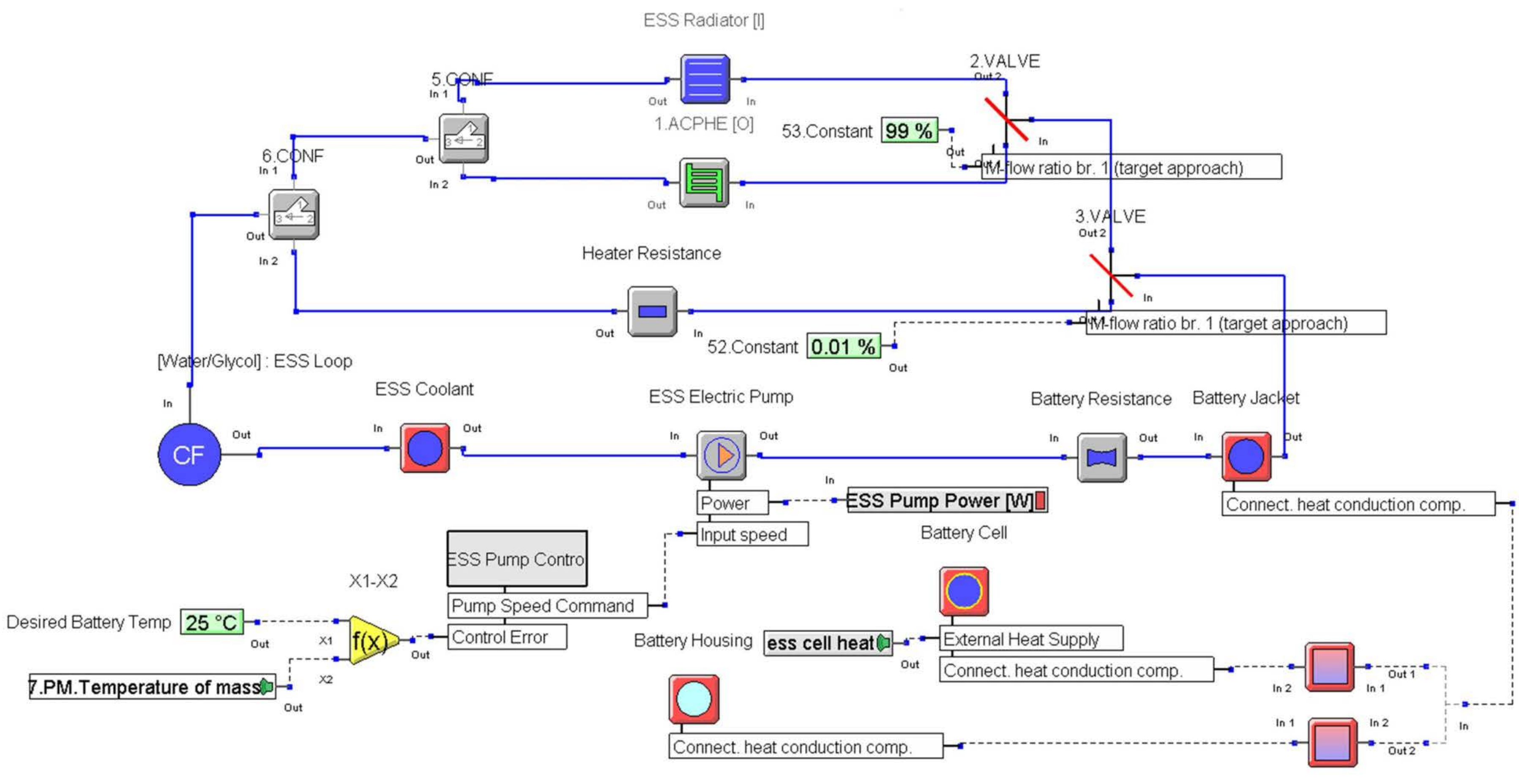
March 2011 – Solid Foundation for March 2011 - March 2012 Research

- **Thermal component and system information**
  - Visteon Corp. (Tier 1 HVAC component supplier)
  - Drawings
  - Thermal and flow component data
  - System data
- **Built components in KULI**
  - Used geometry, heat transfer, pressure drop, etc.
  - Verified component functioning as expected
- **Developed A/C, cabin thermal, and APEEM cooling loop models**
  - Connected components
  - Compared to test data

Improvements to Models

- Improved electric motor model
- Added inverter model
- Updated FASTSim model (heat generated for ESS and APEEM components)
- Improved A/C compressor control
- Adjusted heat exchanger air-side positions to more closely match current EVs
- Developed hot and cold design cases

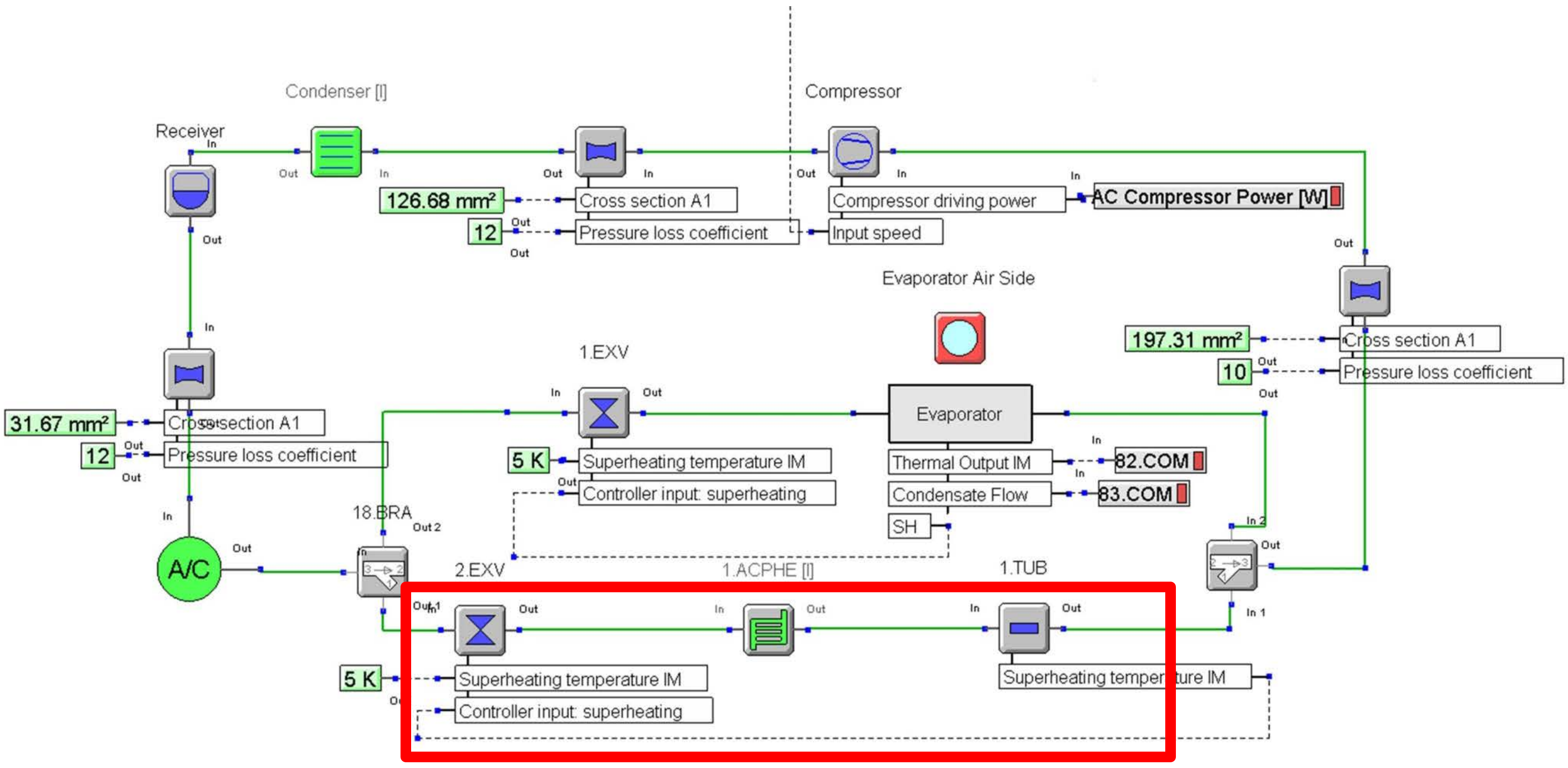
ESS Cooling Loop Model Battery Jacket Cooled by a Chiller (WEG to Refrigerant Heat Exchanger) or a Radiator



WEG = water-ethylene glycol

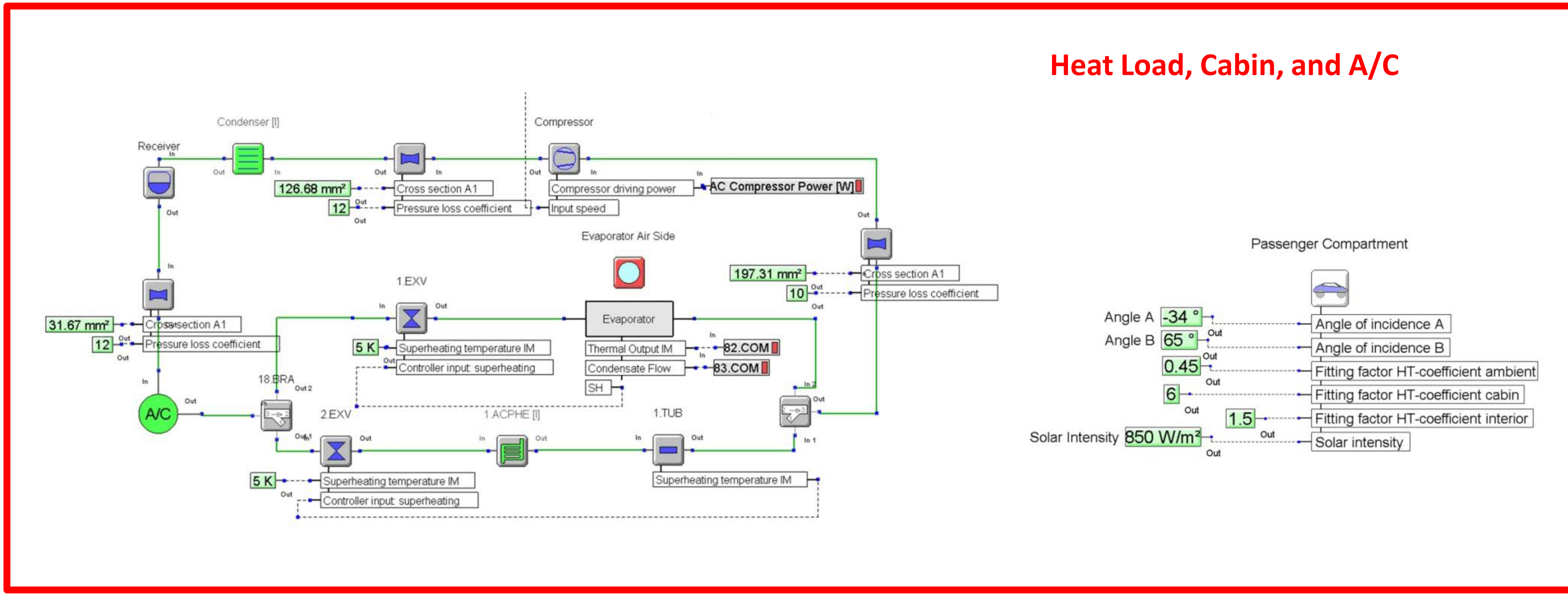
A/C System Model

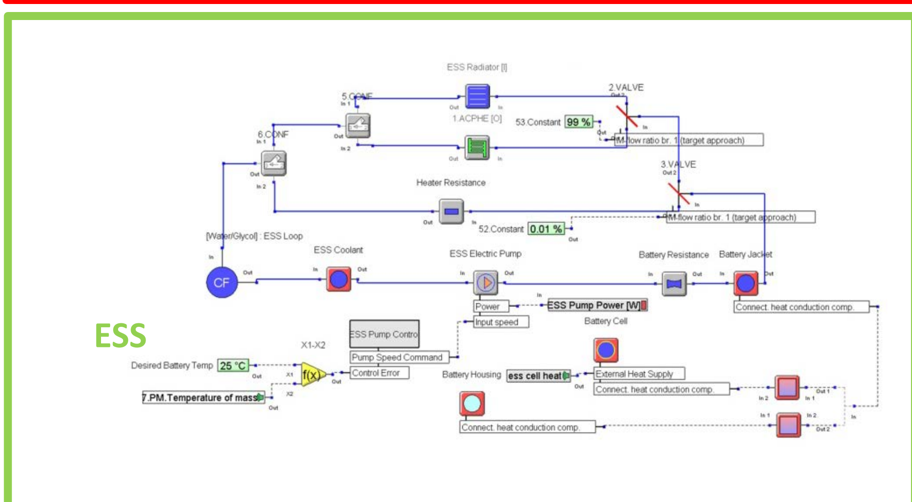
Added Chiller Branch for ESS Cooling Loop

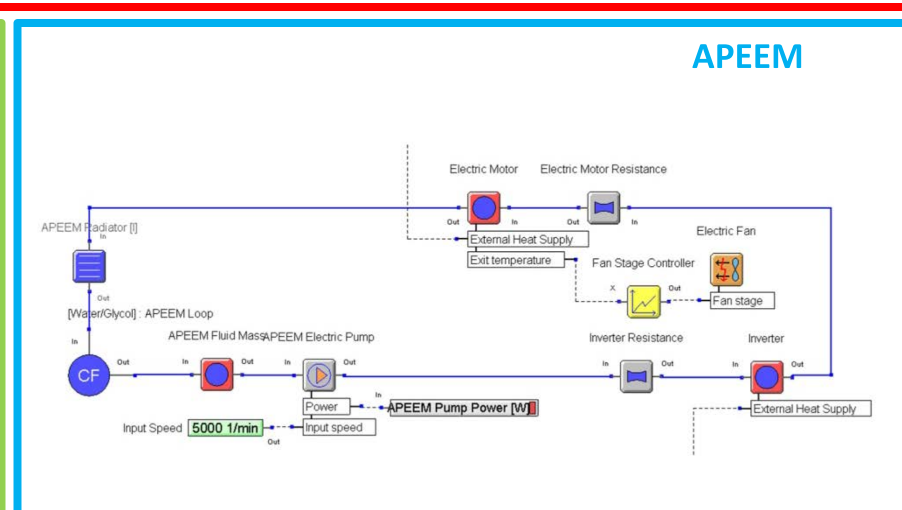


Baseline A/C, Cabin, ESS, and APEEM Cooling Loops

Liquid Circuits Combined into a Single Simulation

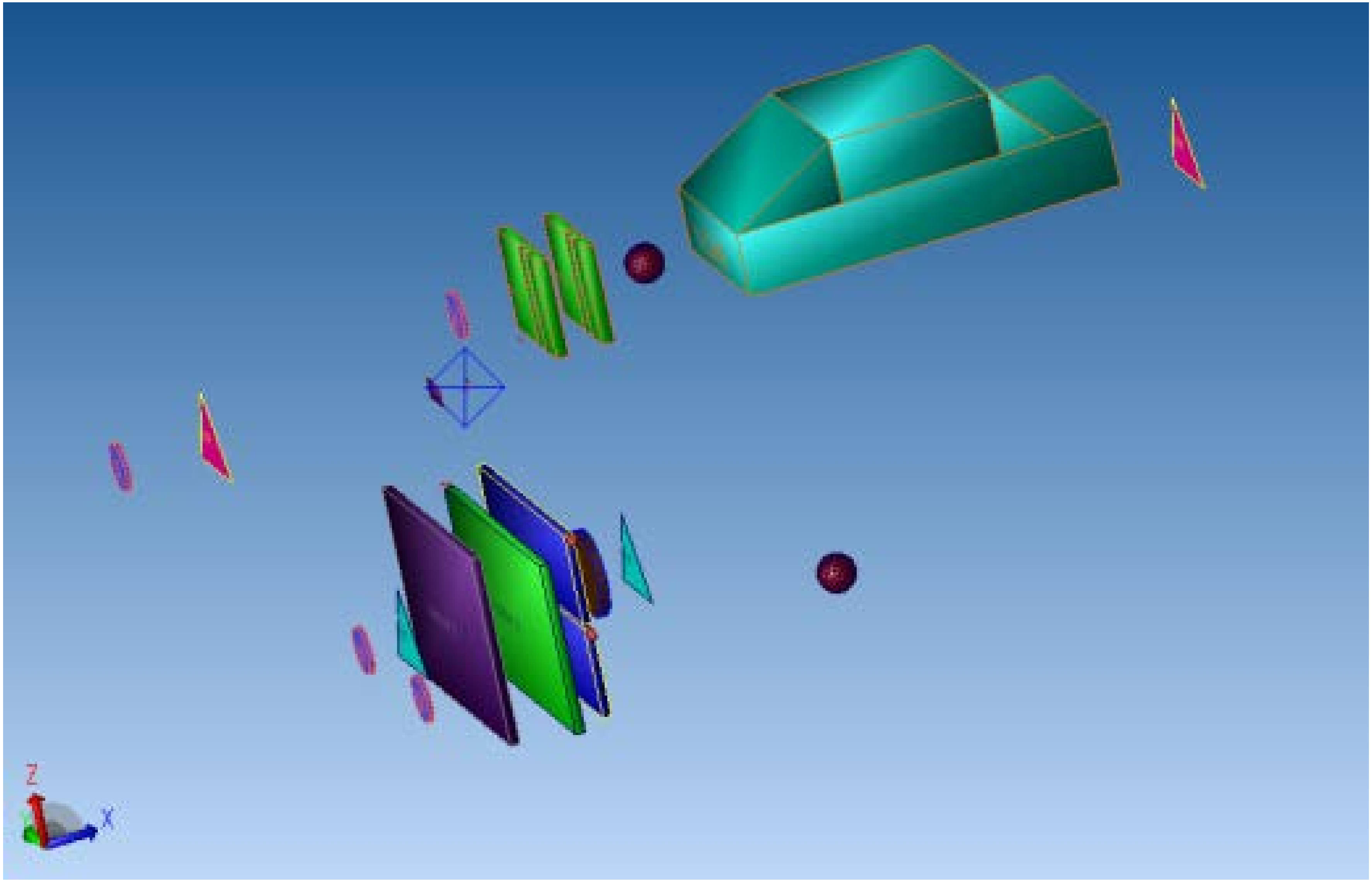






Baseline A/C, Cabin, ESS, and APEEM Cooling Loops

Air Side – Low Temperature Radiators Behind Condenser



Baseline EV Thermal Management System

EV Test Case at Four Ambient Temperatures

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

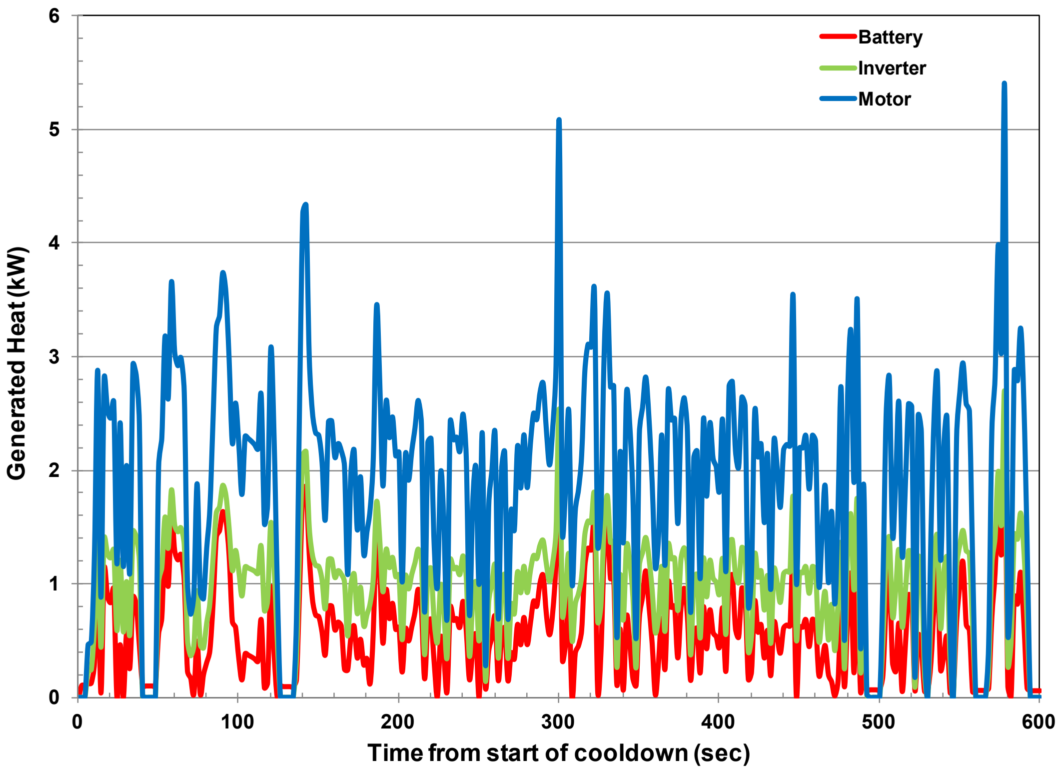


Photo Credit: John Rugh, NREL

Baseline System

At Higher Ambient Temperatures, Cabin is still Warm after 10 min.

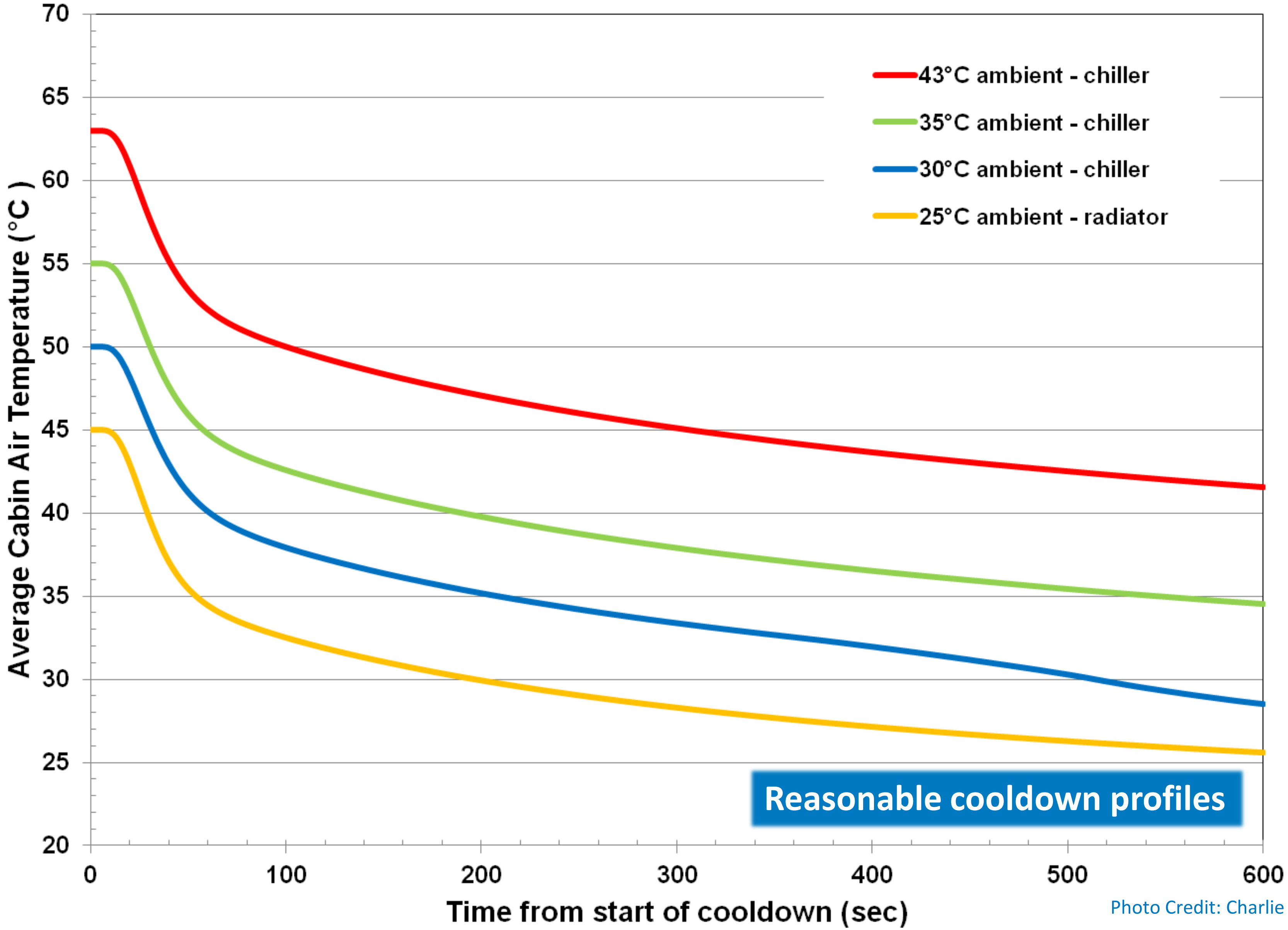
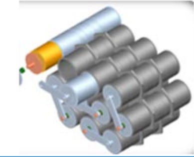
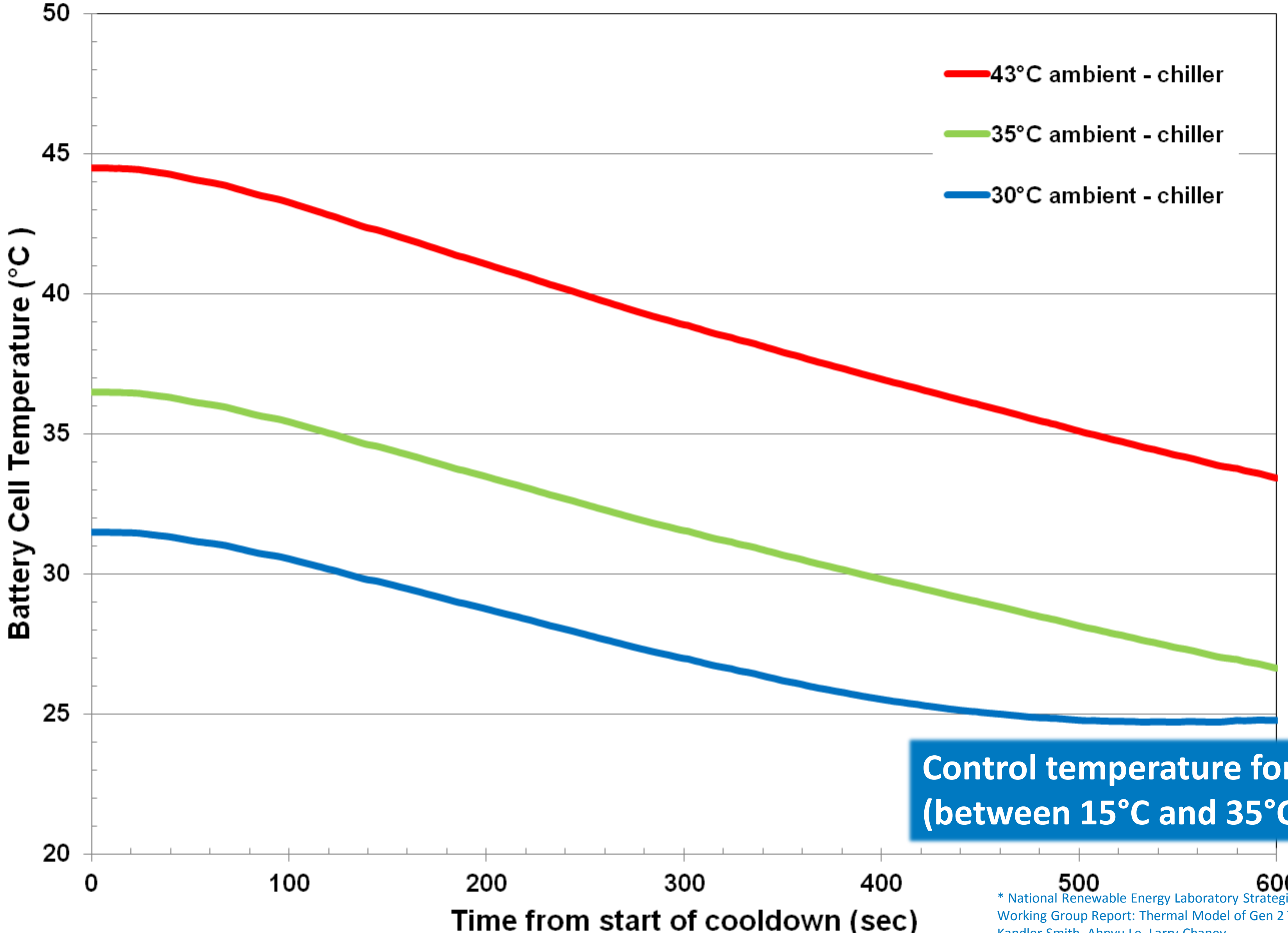


Photo Credit: Charlie King, NREL

Baseline System



Battery Cells Cool Quickly with the Chiller

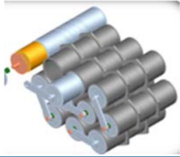


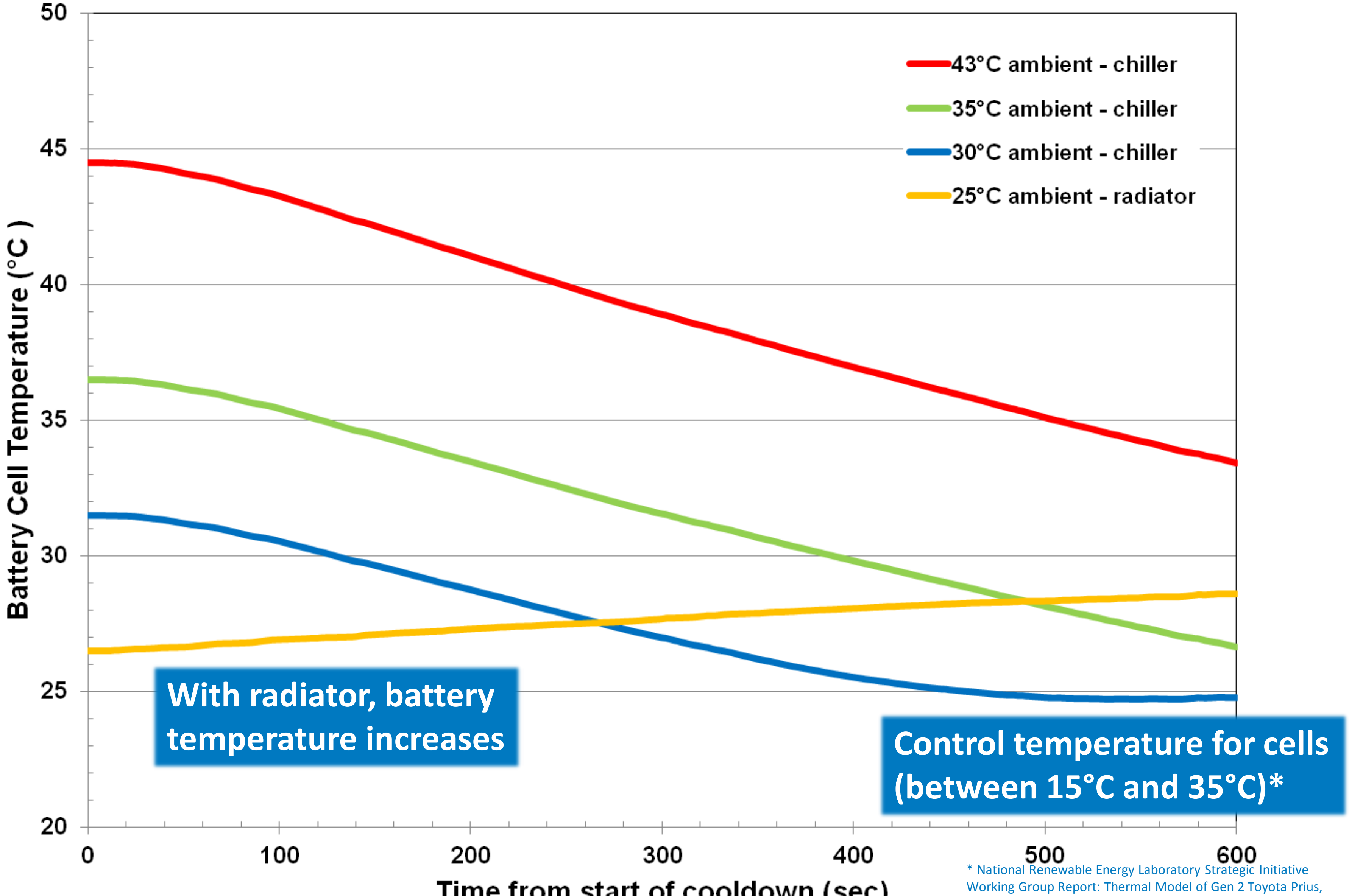
Control temperature for cells (between 15°C and 35°C)*

* National Renewable Energy Laboratory Strategic Initiative Working Group Report: Thermal Model of Gen 2 Toyota Prius, Kandler Smith, Ahnvu Le, Larry Chaney.

Baseline System

Battery Cells Cool Quickly with the Chiller

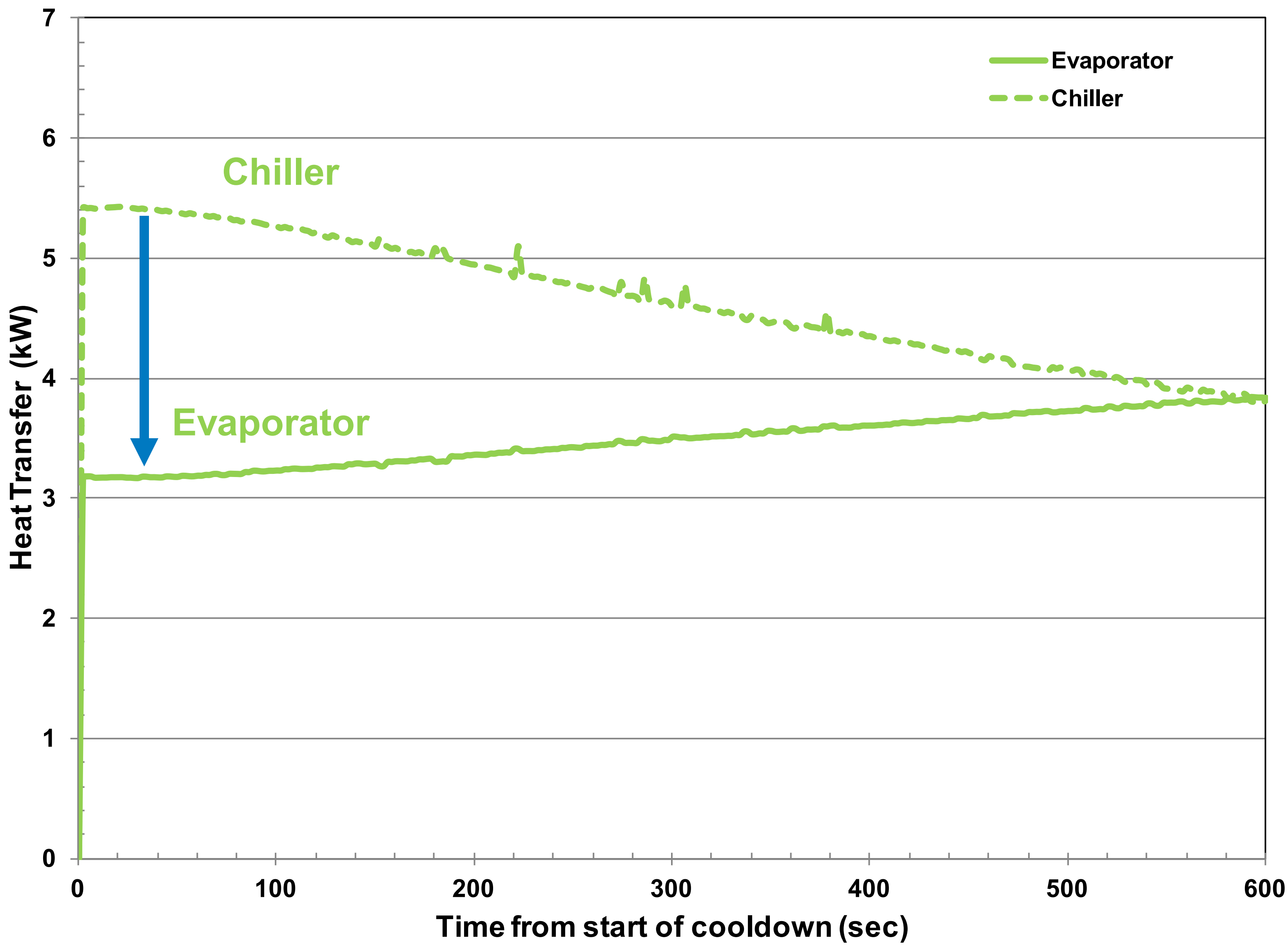




* National Renewable Energy Laboratory Strategic Initiative Working Group Report: Thermal Model of Gen 2 Toyota Prius, Kandler Smith, Ahnvu Le, Larry Chaney.

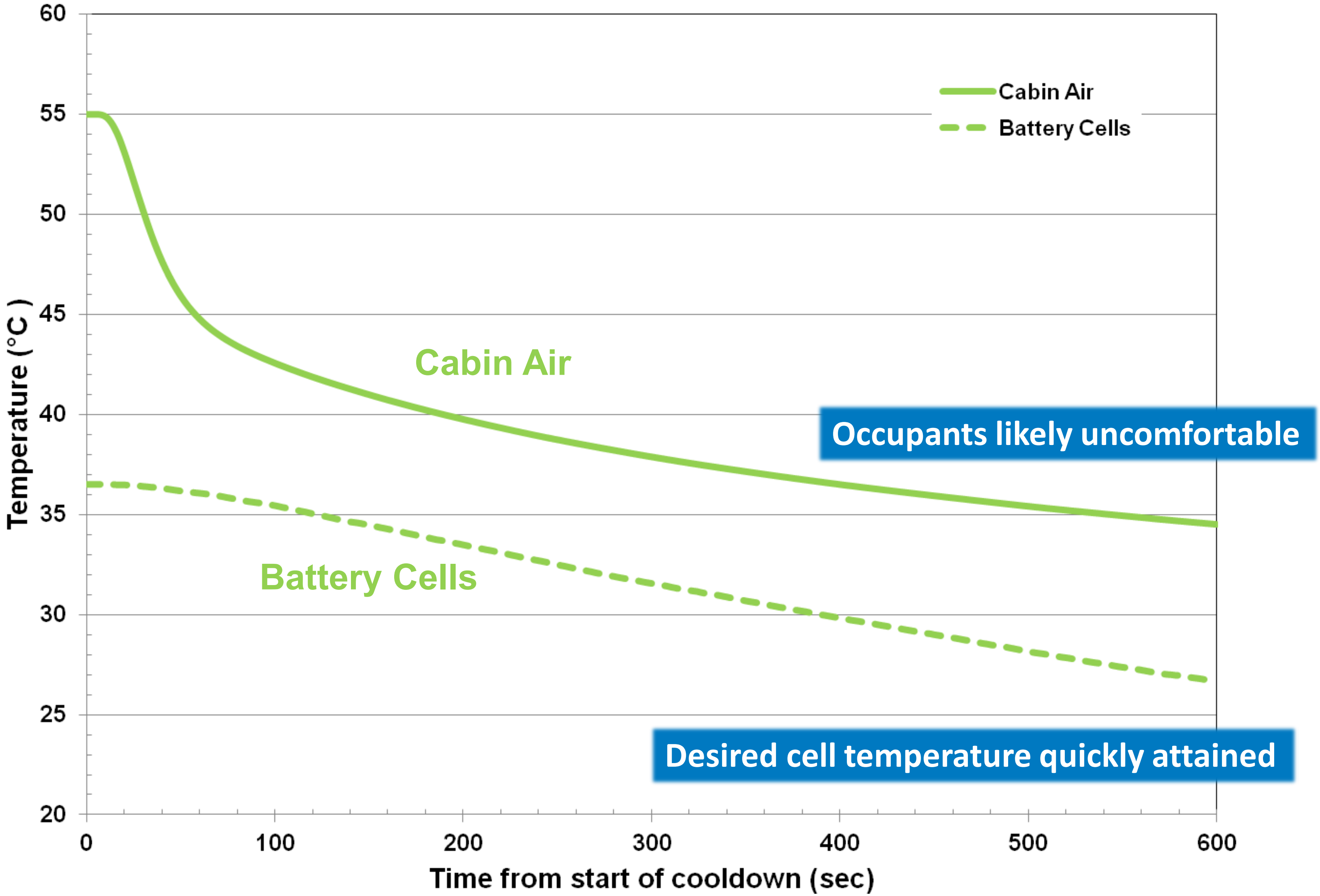
35¢C Ambient – Cabin and ESS Cooling

Initially Less Than 50% of the A/C System Capacity is Going to the Cabin



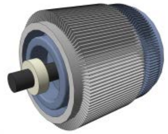
35ᵒC Ambient – Cabin and ESS Temperatures

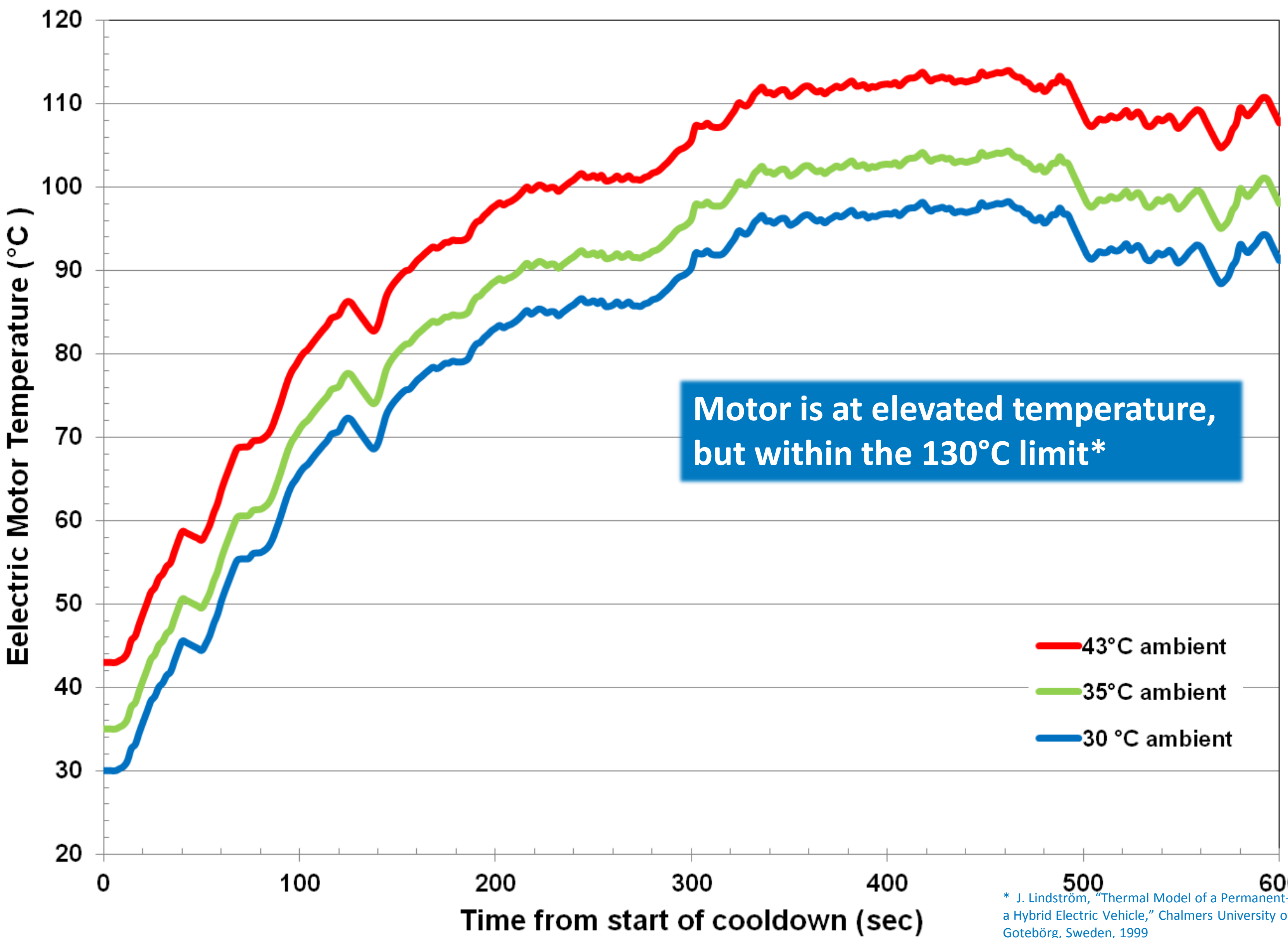
Tradeoff between Battery Cooling and Thermal Comfort



Baseline System

Electric Motor Temperatures

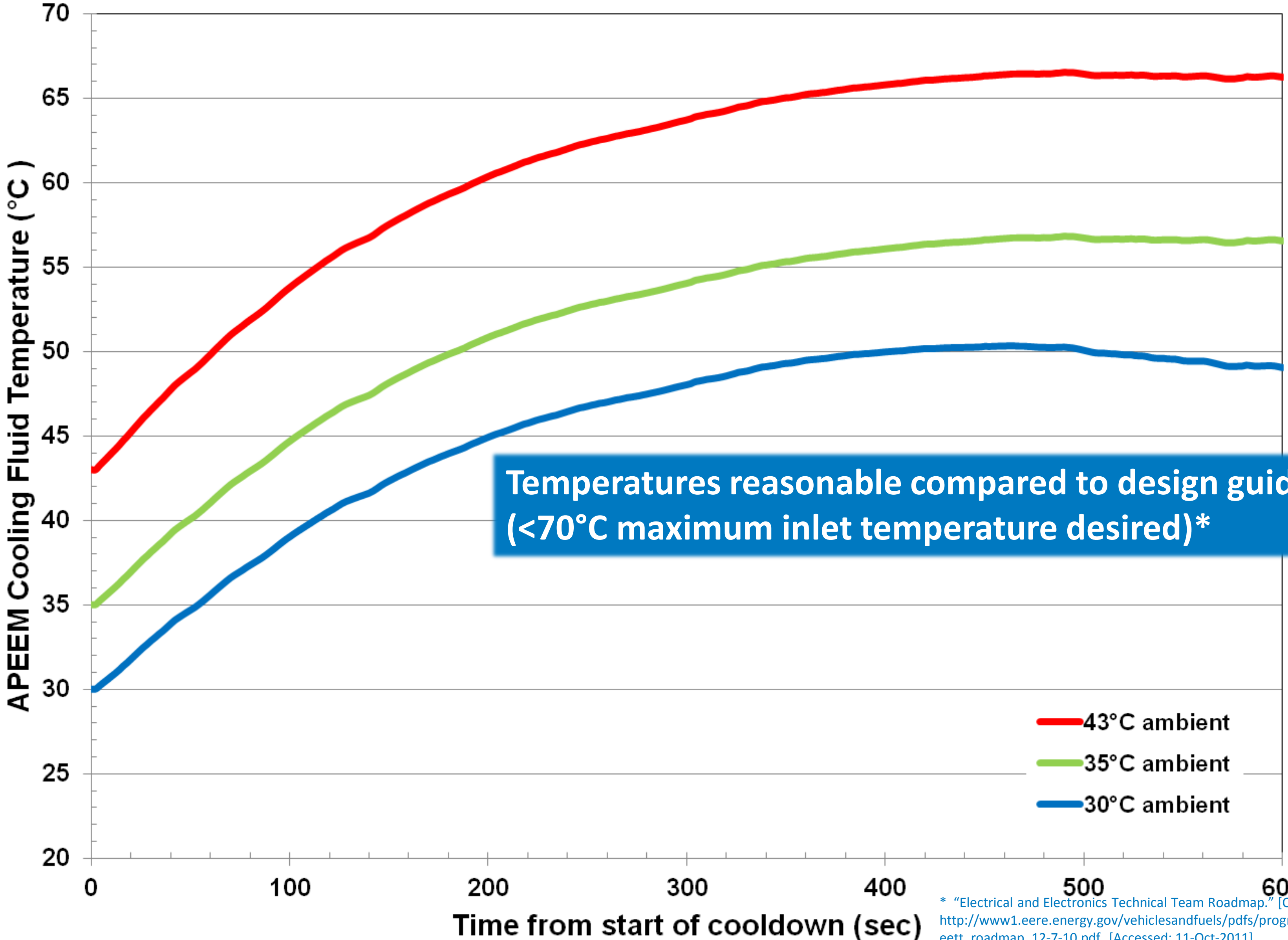




* J. Lindström, "Thermal Model of a Permanent-Magnet Motor for a Hybrid Electric Vehicle," Chalmers University of Technology, Gotebörg, Sweden, 1999

Baseline System

APEEM Fluid Temperatures – Critical to Inverter Maximum Temperature



Temperatures reasonable compared to design guideline (<70°C maximum inlet temperature desired)*

* "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].

Baseline System

VTM Power including Compressor, Fans, Blowers, Pumps

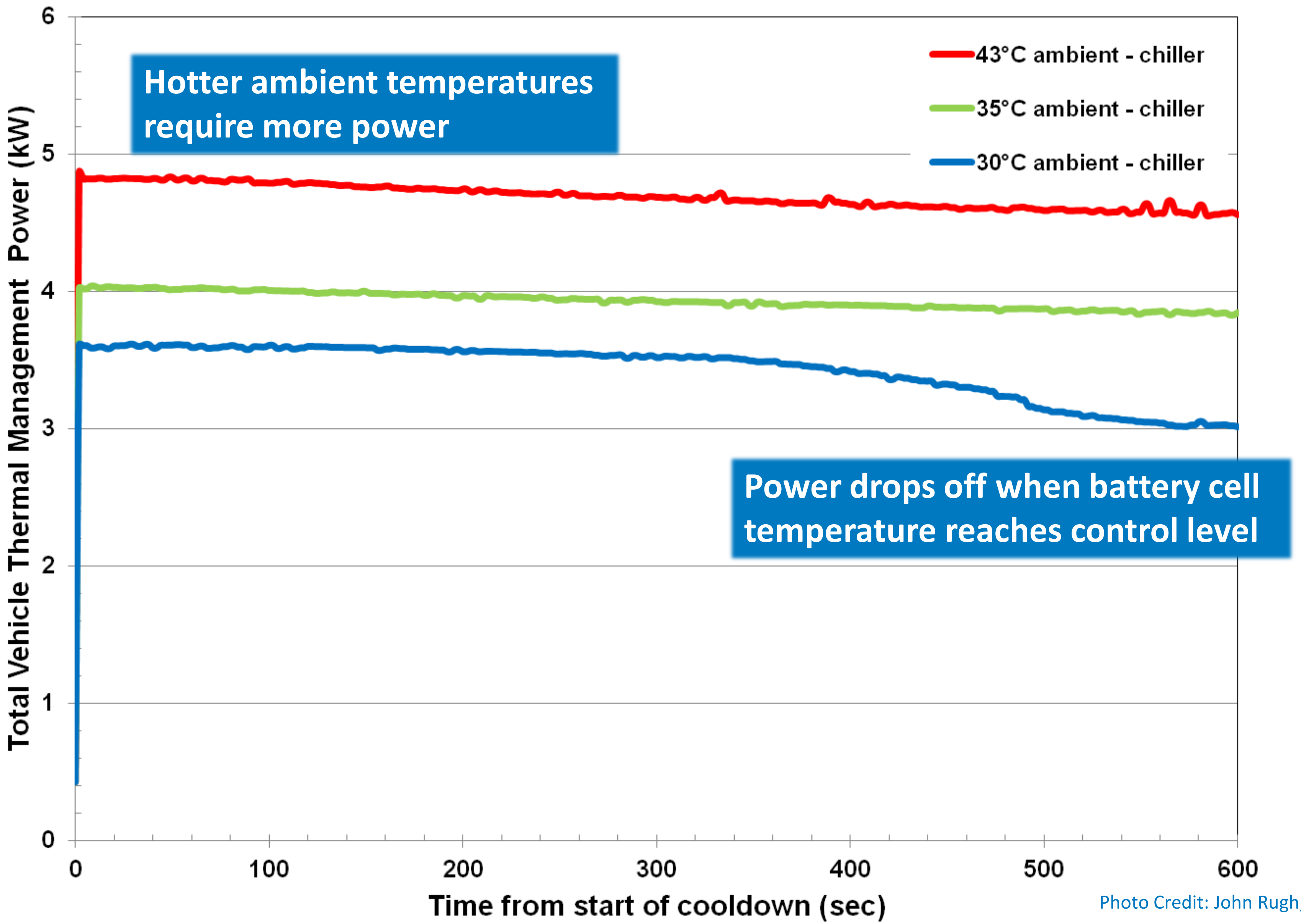


Photo Credit: John Rugh, NREL

Baseline System

VTM Power including Compressor, Fans, Blowers, Pumps

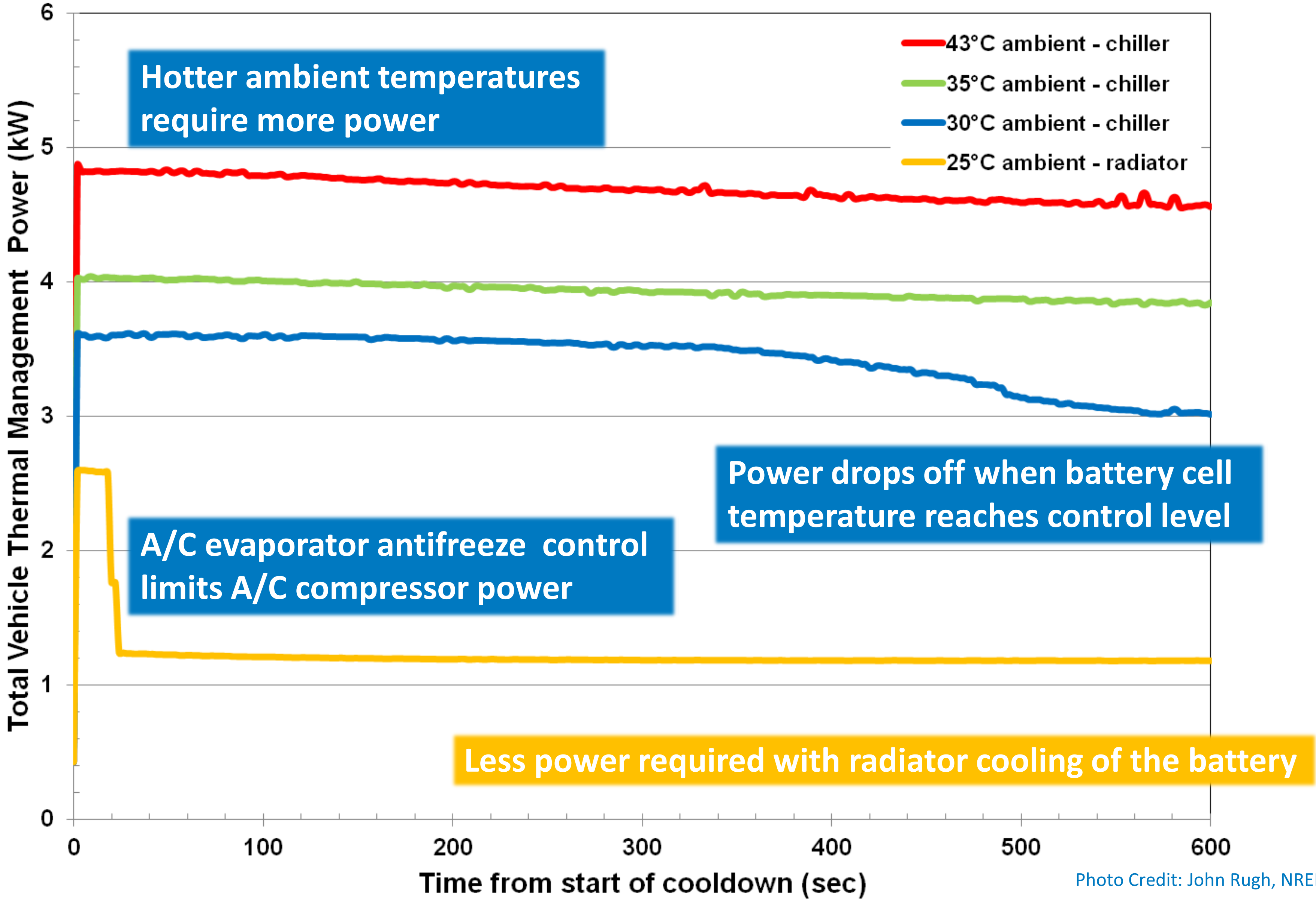
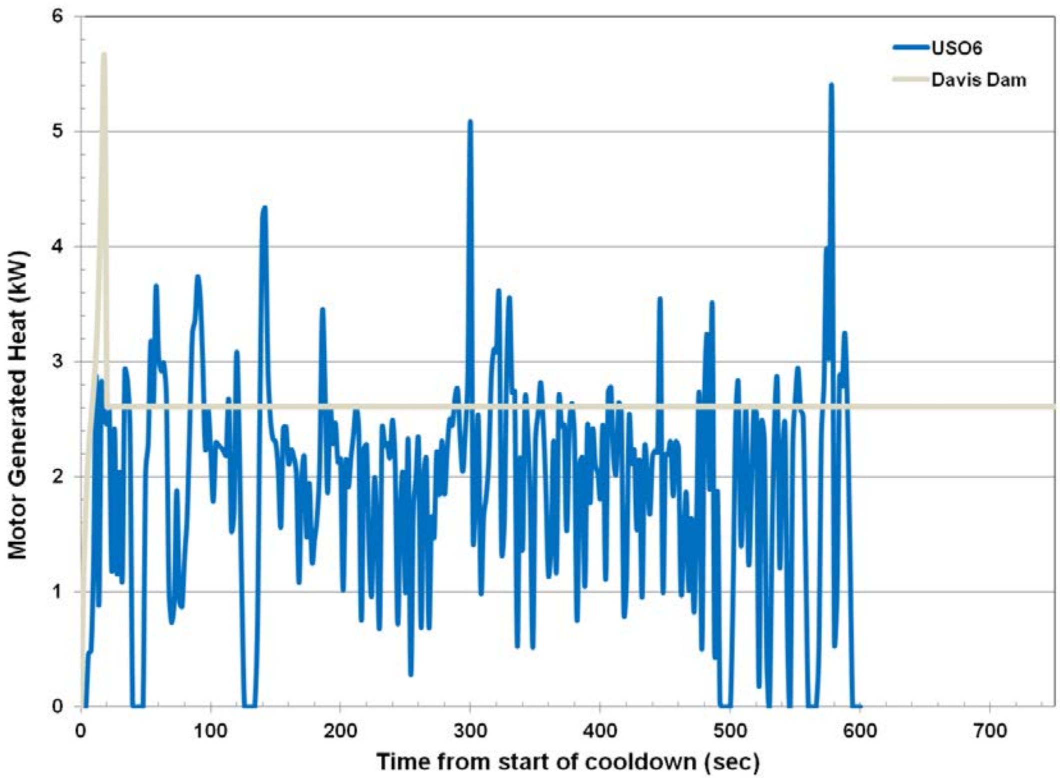


Photo Credit: John Rugh, NREL

Baseline EV Thermal Management System

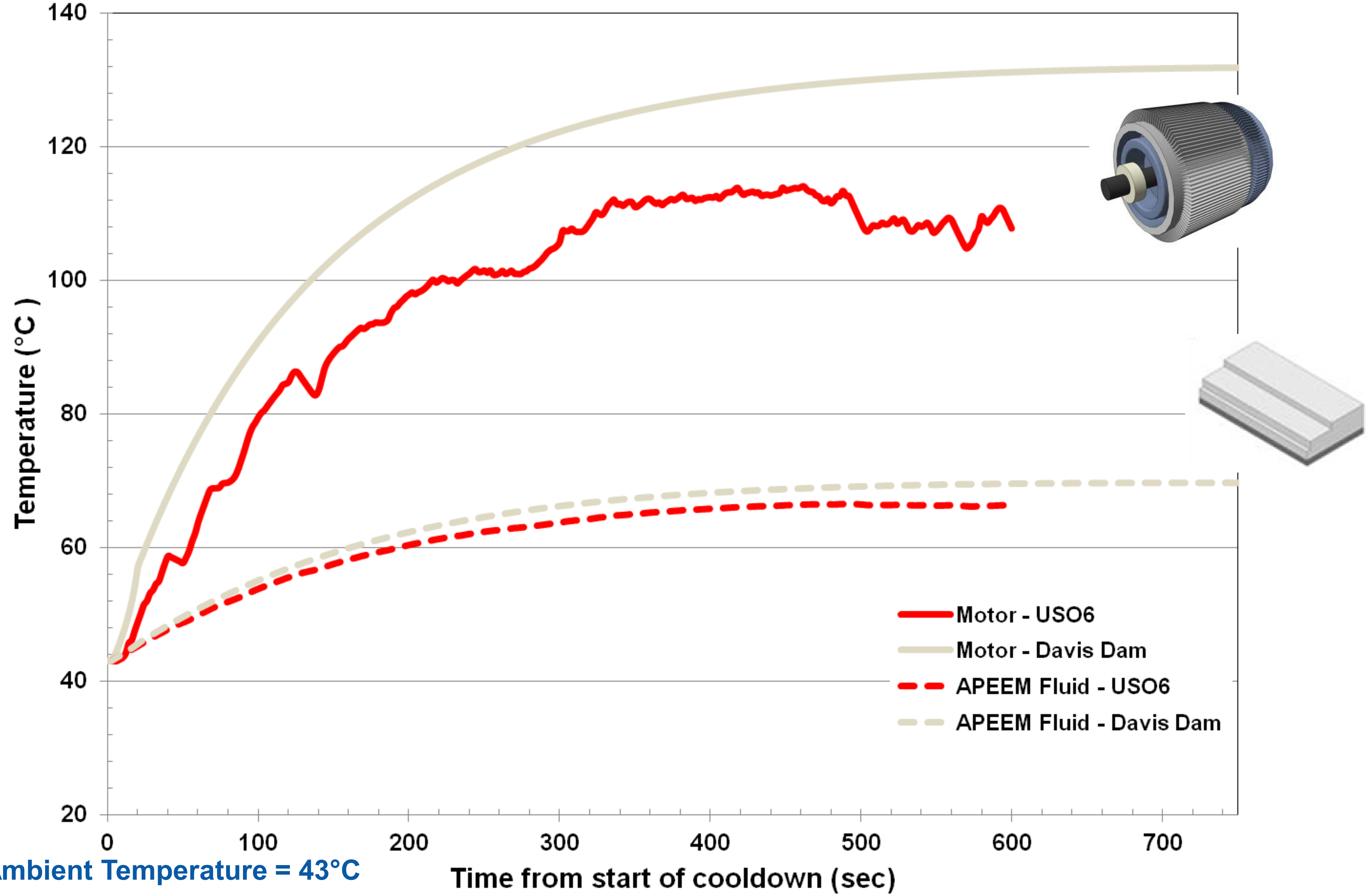
EV at Davis Dam – Exploring the Hot Design Limits

- **Davis Dam drive cycle**
  - Acceleration, then constant 55 mph up a constant 5% grade
- **24 kWh EV**
- **Environment**
  - 43°C
  - 25% relative humidity
  - 850 W/m^2
- **Cooldown simulation from a hot soak**
- **ESS – cooling loop with chiller**
- **Waste heat load from FASTSim simulations**



Baseline System - Davis Dam

In extreme conditions, APEEM components within thermal limits



Ambient Temperature = 43°C

Baseline EV Thermal Management System

EV at Bemidji – Exploring the Cold Design Limits

- **Bemidji drive cycle**
  - UDDS
- **24 kWh EV**
- **Environment**
  - -18°C
  - 25% relative humidity
  - No solar load
- **Warm-up simulation from a cold soak**
- **Waste heat load from FASTSim simulations**

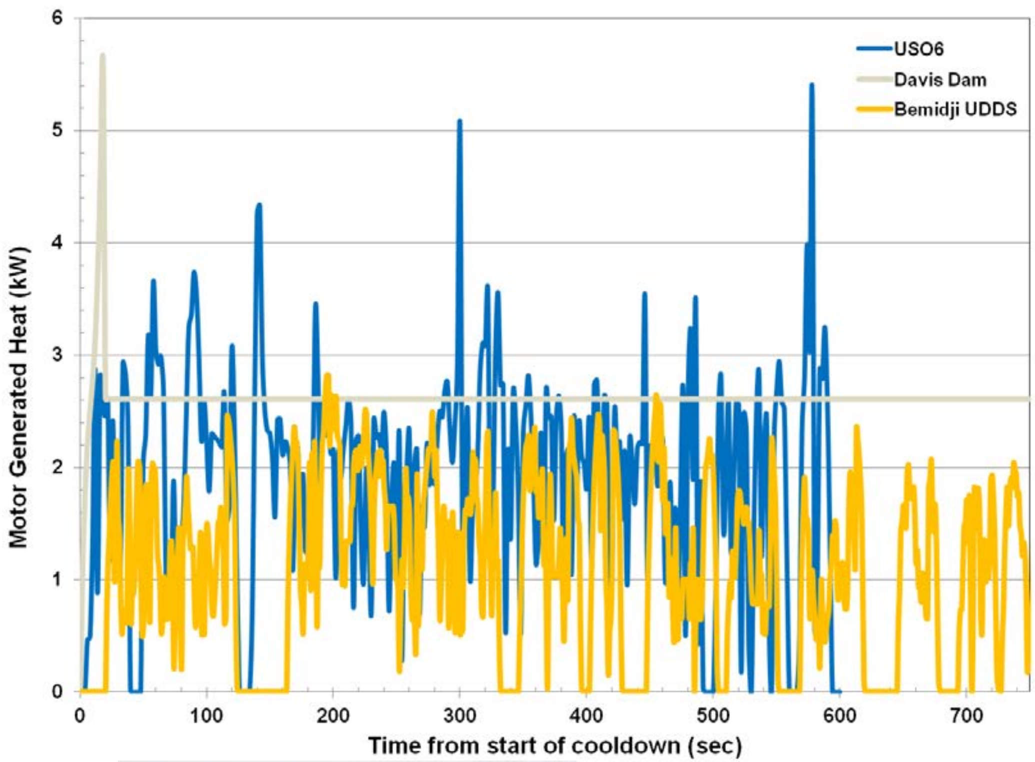


Photo Credit: Mike Simpson, NREL

Collaboration

- **Visteon Corp.**
  - Data
  - Engineering support
- **“Detroit 3” OEM – CRADA is in approval process**
- **Magna Steyr**
  - KULI software
  - Engineering support
- **VTP Tasks**
  - Vehicle Systems
  - Energy Storage
  - Advanced Power Electronics and Electric Motors

Future Work

- **Using the KULI model, analyze concepts for combining cooling loops**
  - Assess benefits
    - Maximum temperatures
    - Battery life
    - Cost
    - Range
  - Add new components
  - Improve model as required
- **Based on the analysis results, select, build, and evaluate prototype systems in a lab bench test to demonstrate the benefits of an integrated thermal management system**
- **Lead a vehicle-level project to test and validate combined cooling loop strategies**

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
  - Solve vehicle-level heat transfer problems, which will enable acceptance of vehicles with electric powertrains

Summary (cont.)

- **Technical Accomplishments**
  - Developed a modeling process to assess synergistic benefits of combining cooling loops
  - Improved A/C, cabin, APEEM cooling loop KULI models and built ESS cooling loop KULI models
  - Assembled the KULI models into a baseline simulation of a Nissan Leaf-sized EV
    - Produced reasonable component and fluid temperatures
  - Assessment of combined cooling loop concepts underway
- **Collaborations**
  - Collaborating closely with OEM, Visteon Corp. and Magna Steyr
  - Leveraging previous DOE research
    - Battery life model
    - Vehicle cost/performance model
    - Lumped parameter motor thermal model
  - Co-funding by three VTP tasks demonstrates cross-cutting

Acknowledgements, Contacts, and Team Members

Special thanks to:

David Anderson
Steven Boyd
Brian Cunningham
David Howell
Susan Rogers
Lee Slezak
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