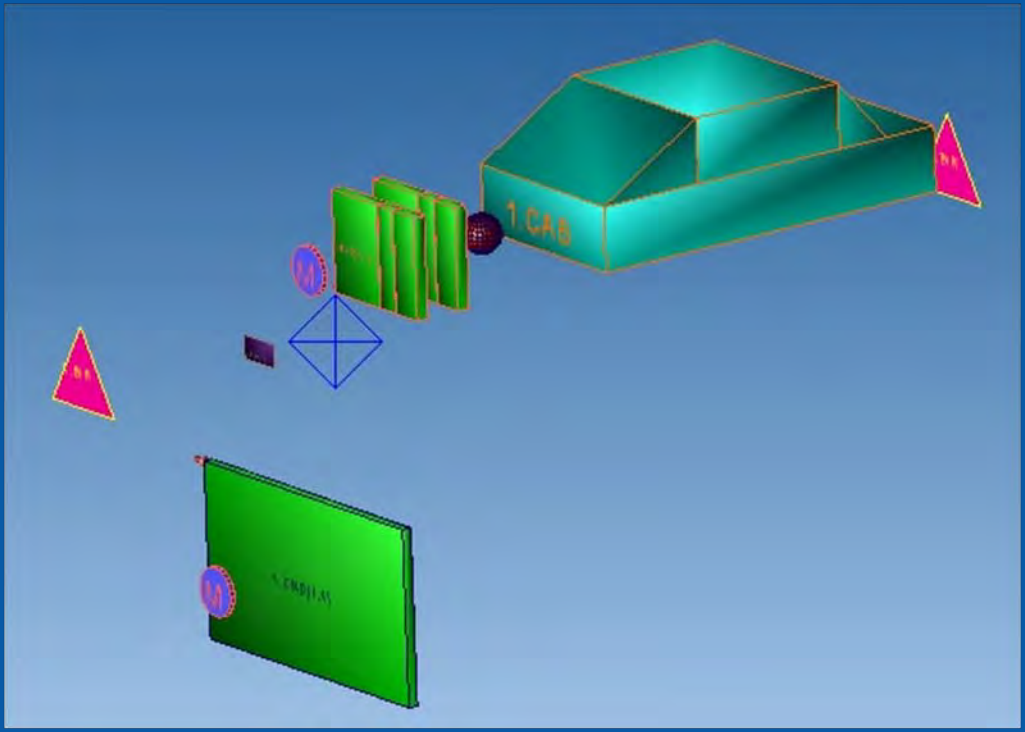
Integrated Vehicle Thermal Management – Combining Fluid Loops in Electric Drive Vehicles



U.S. Department of Energy
Annual Merit Review

National Renewable Energy Laboratory

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Project ID: VSS046
APE038

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Overview – Integrated Vehicle Thermal Management (IVTM)

Timeline

- Project start date: FY11
- Project end date: FY13
- Percent complete: 10%

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)*

Budget

- Total project funding
  - DOE share: $375k
  - Contractor share: $0
- FY11 Funding: $375k

Partners

- Interactions
  - Visteon
  - EE Tech Team
- Project lead: NREL

IVTM – FY11 Funding Overview, $375k

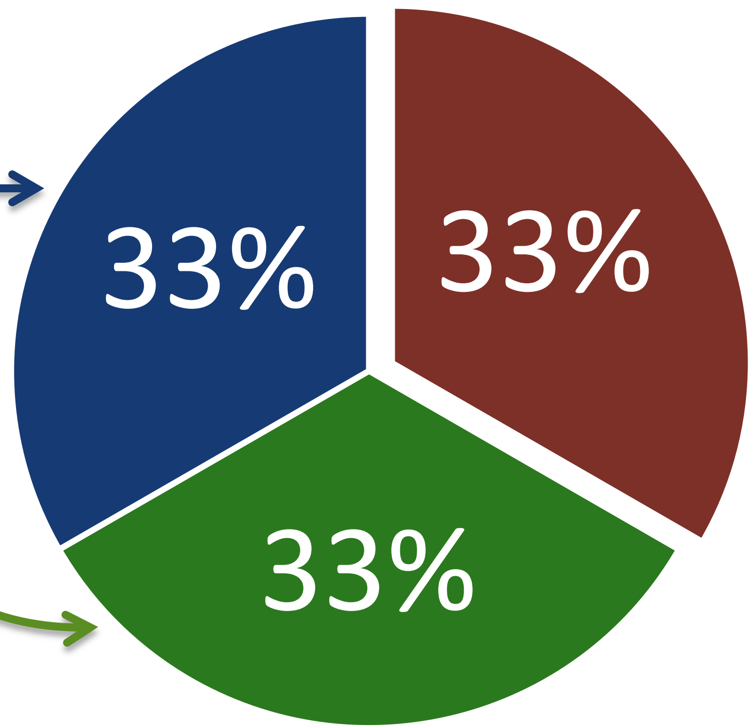
Hybrid Electric Systems
Dave Howell – Team Lead

Vehicle Systems
Lee Slezak
David Anderson

Energy Storage
Steve Goguen
Tien Duong
Brian Cunningham
Peter Faguy

Power Electronics & Electric Motors
Susan Rogers
Stephen Boyd

Collaboration Between 3 Vehicle Technology Activities

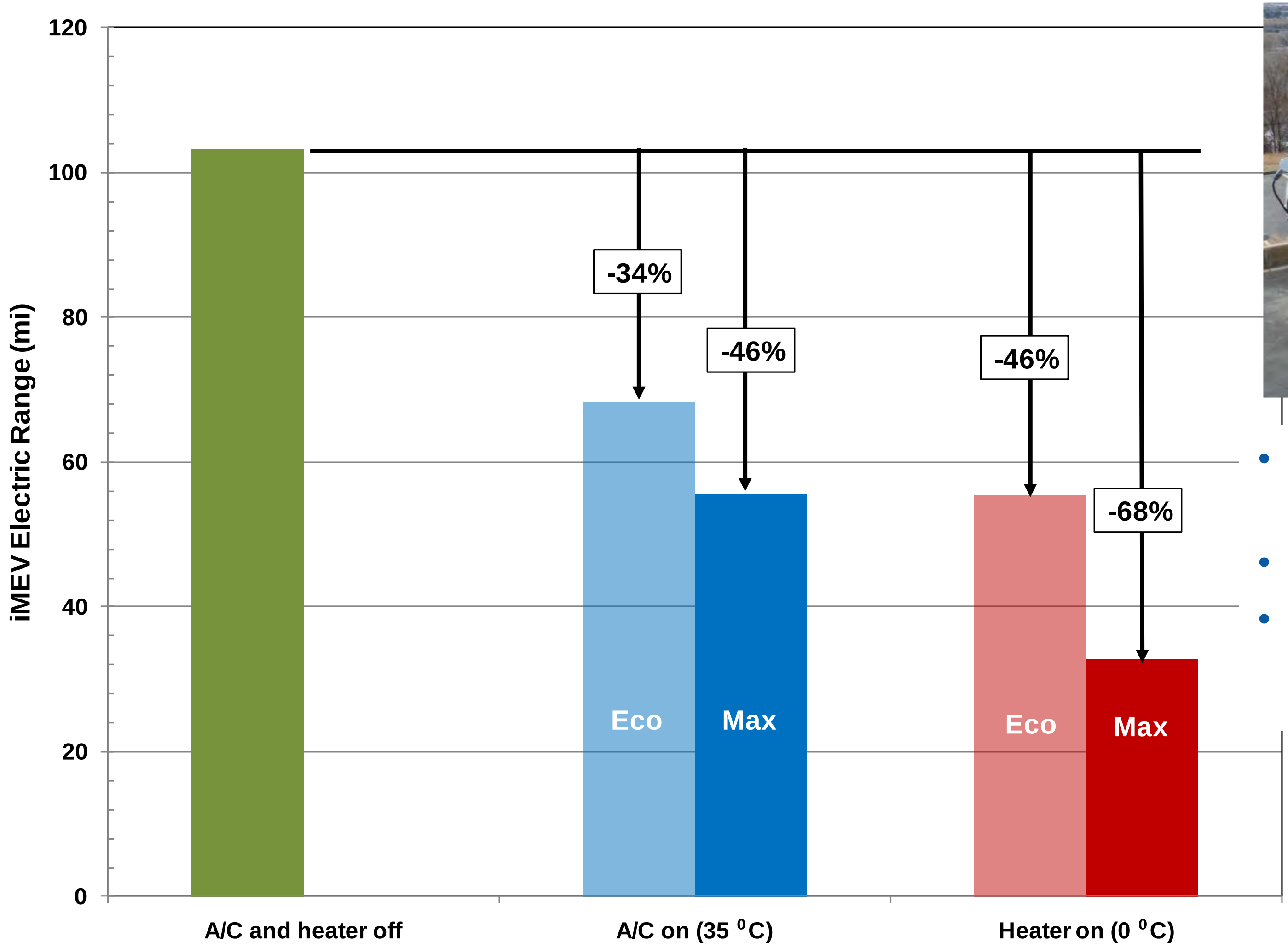


Relevance – The PHEV/EV Thermal Challenge

- Plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) have increased vehicle thermal management complexity
  - Separate coolant loop for APEEM (advanced power electronics and electric motors)
  - Thermal requirements for ESS
- Multiple cooling loops may lead to reduced effectiveness of fuel-saving control strategies
  - Increased, weight, volume, aerodynamic drag, and fan/pump powers
  - Reduced electric range
- Cross-cutting system designs are challenging, involving separate teams at OEMs and suppliers

Photo Credit: Mike Simpson, NREL

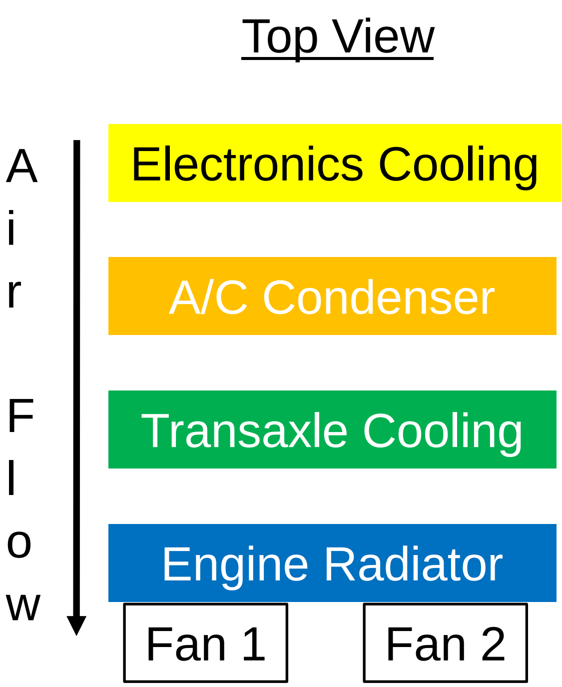
Relevance – Passenger Compartment A/C and Heating Significantly Impact EV Range

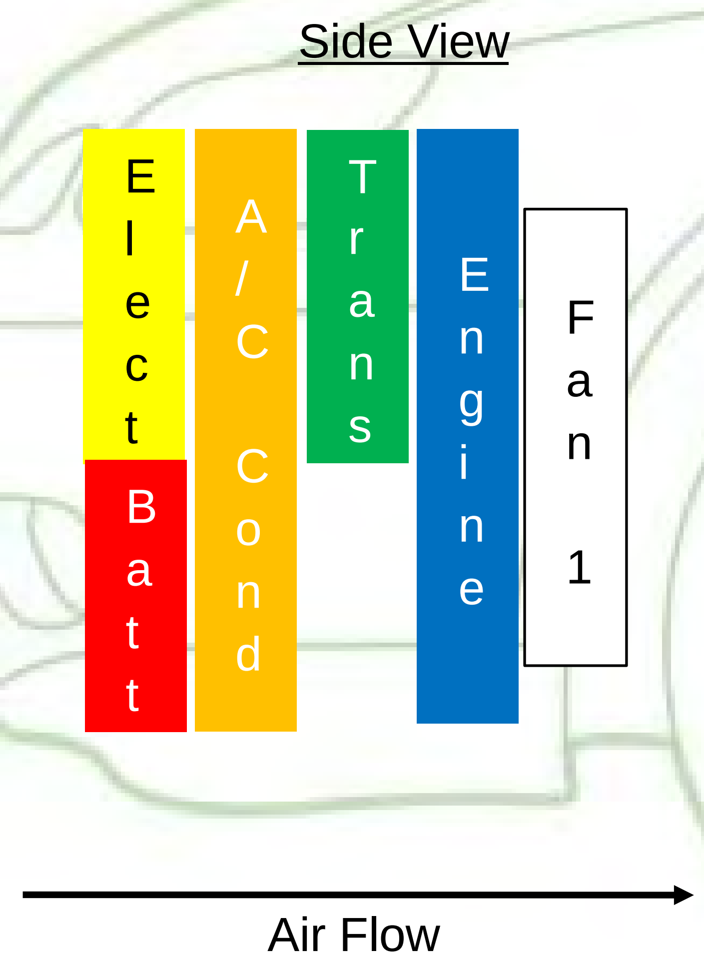


- Vehicle: Mitsubishi iMEV
- Drive Cycle: 10-15
- Impact on range
  - A/C: -34 % to -46%
  - Heating: -46% to -68%

Data Credit: Kohei Umezu and Hideto Noyama, Mitsubishi, Presented at the 2010 SAE Automotive Refrigerant and System Efficiency Symposium
Photo Credit: Mike Simpson, NREL

Relevance – Multiple Cooling Loops Result in Complicated Front-End Airflow





Data Credit: www.gm-volt.com

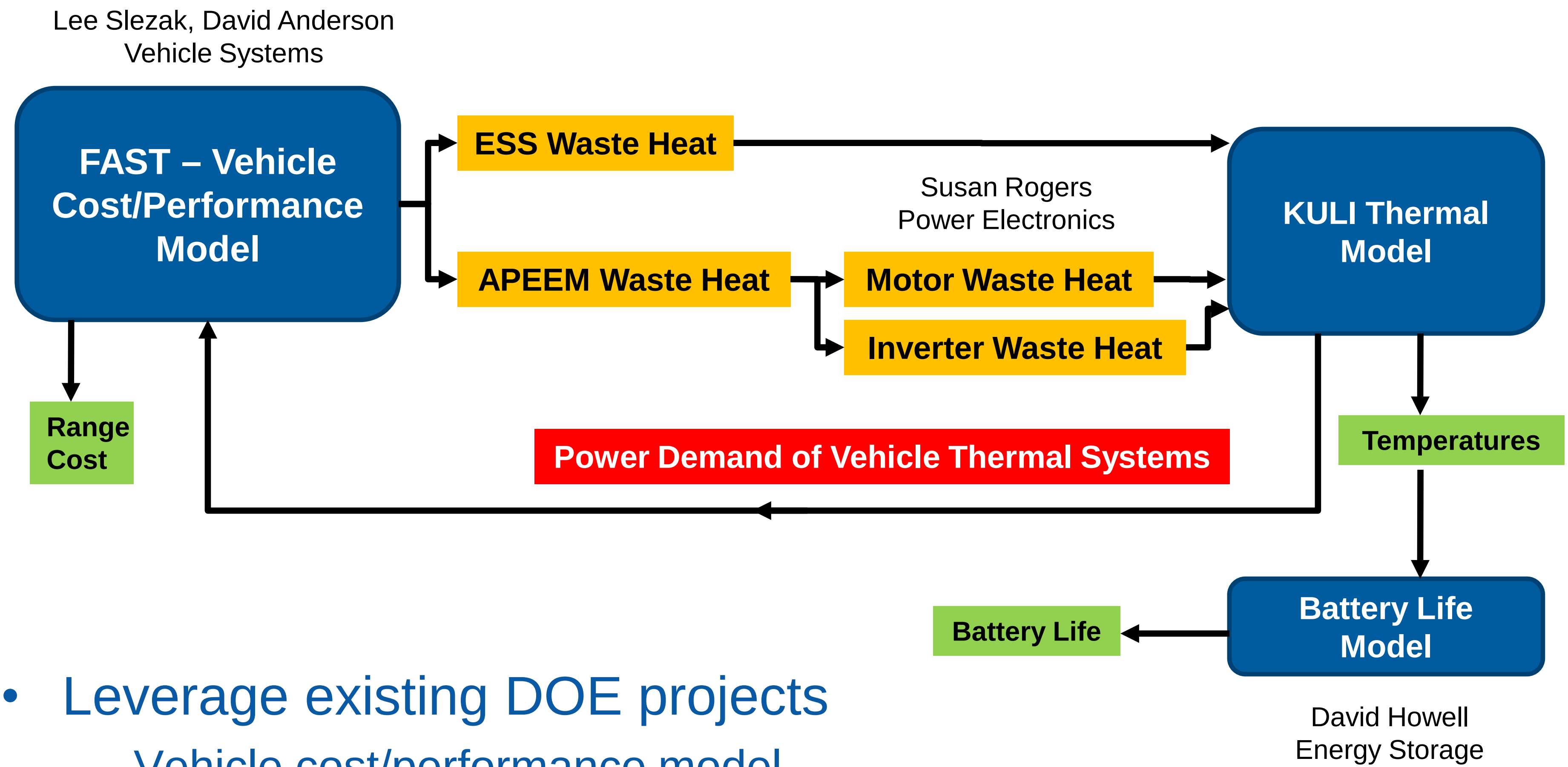
Relevance – VTM Objectives

- Overall Objectives
  - Work with industry partners to research the synergistic benefits of combining thermal management systems in vehicles with electric powertrains
    - Improve PHEV and EV performance (reduced weight, aero drag, and parasitic loads)
    - Reduce cost and volume
    - Improve battery life
- FY11 Objectives
  - Develop a 1-D (lumped mass, uniform flow) thermal model using commercial software to assess the benefits of integrated vehicle thermal management and identify research opportunities

Approach

- Build a 1-D model (using KULI software) of the APEEM, energy storage, engine, transmission, and passenger compartment thermal management systems
- Combine with vehicle performance/cost and battery life models
- Identify the synergistic benefits from combining cooling systems
- Select the most promising combined thermal management system concepts and perform a detailed performance assessment with production-feasible component data
- Assess technical feasibility
  - Vehicle performance impact
  - Battery life impact
- Acquire additional OEM and supplier partners

Approach – Analysis Flow Chart

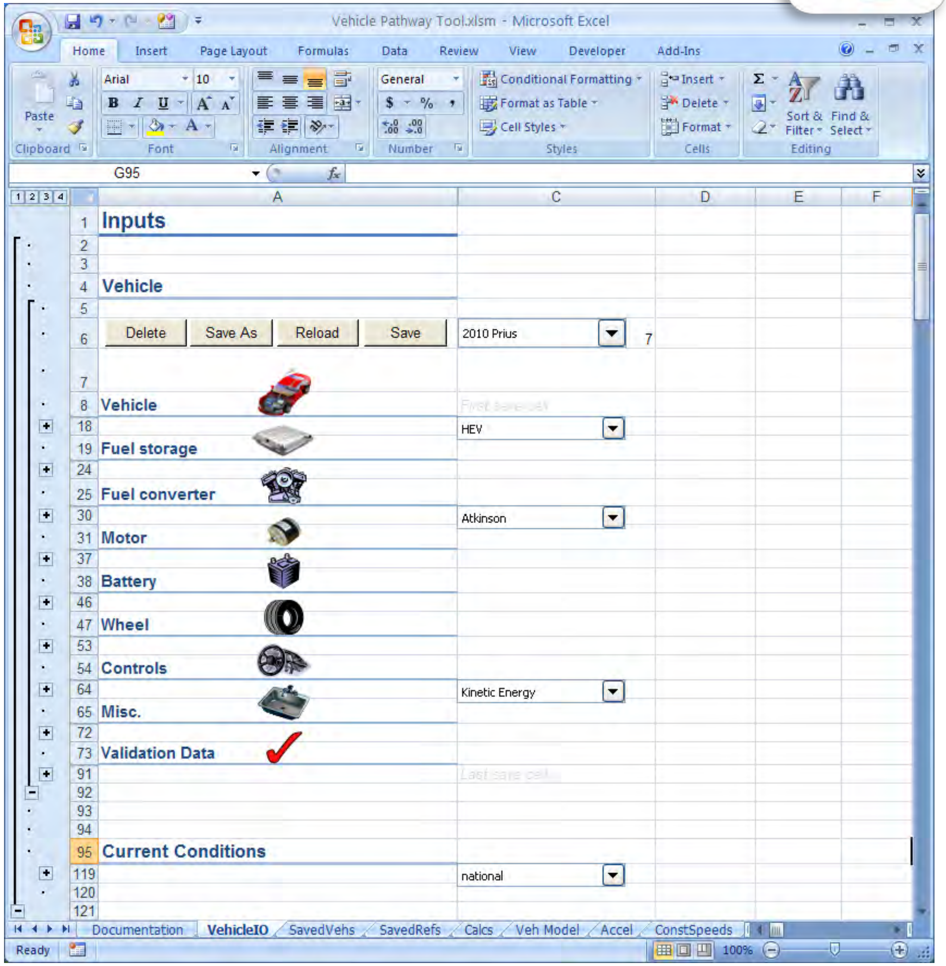


- Leverage existing DOE projects
  - Vehicle cost/performance model
  - Lumped parameter motor thermal model
  - Battery life model

FAST = Future Automotive Systems Tool

Approach – Future Automotive Systems Tool

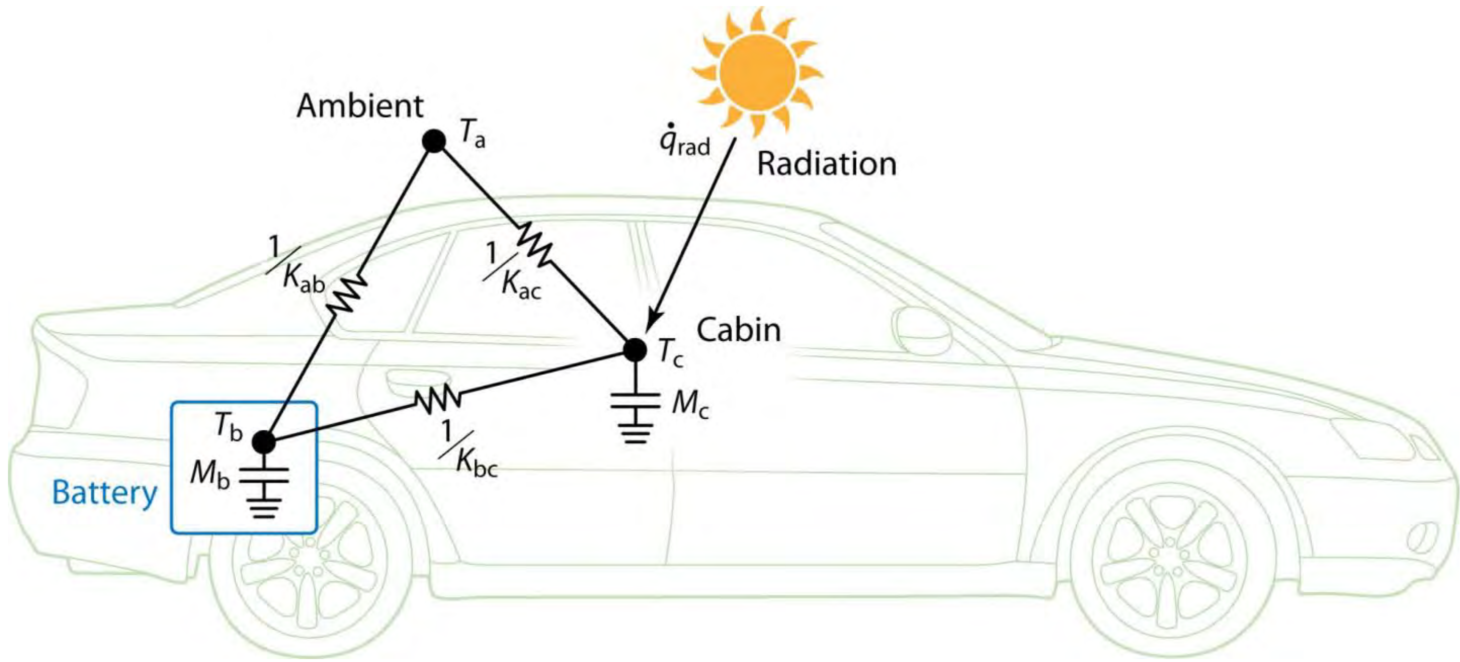
- Simplified vehicle simulation plus cost and battery life
- Approach: Include most critical parameters
  - Powertrain components (engine, electric motor, battery)
  - Auxiliary loads
  - Regenerative braking
  - Speed vs. time simulation
  - Battery life estimates
  - Cost estimates



- Application to vehicle thermal management project
  - Calculate heat generation
  - Assess impact of combined cooling loop strategies on vehicle range while maintaining equivalent cost

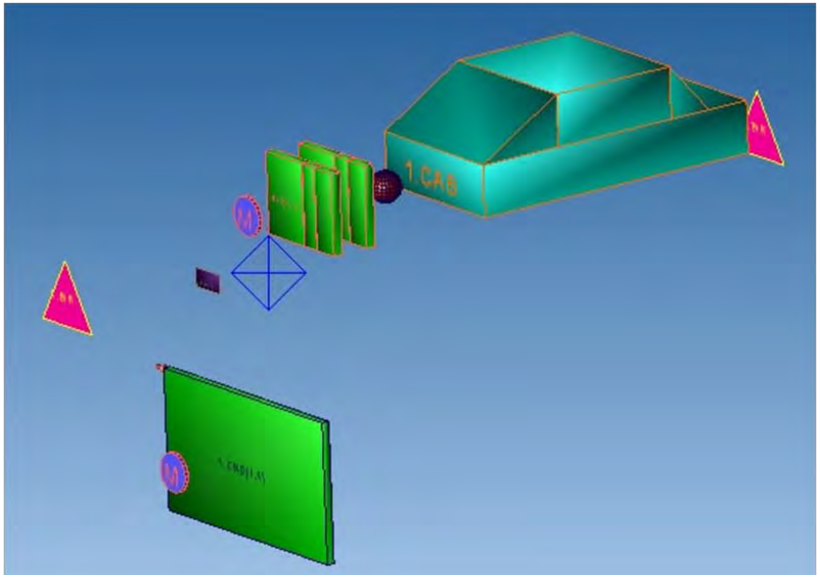
Approach – Battery Life Model

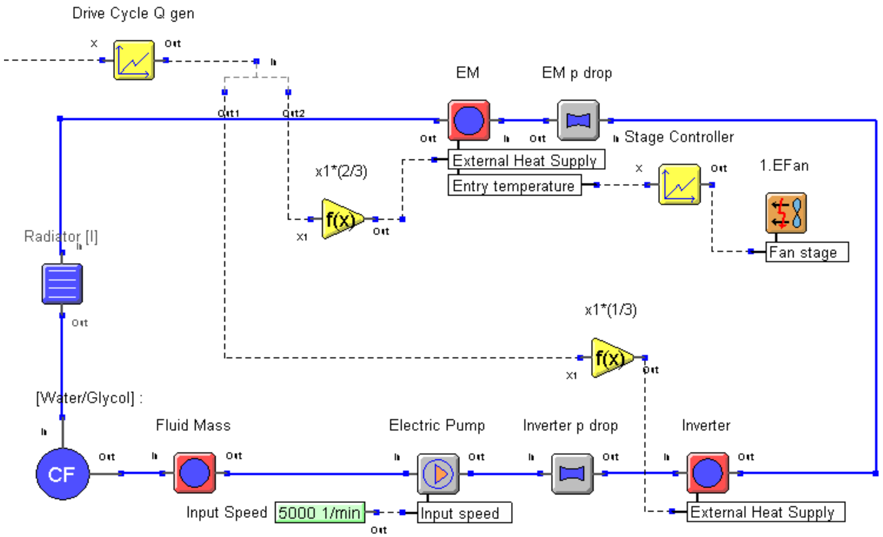
- Assesses the impact of temperature on battery life
- Accounts for degradation due to
  - Resistance growth
  - Capacity fade
- Includes life prediction using real-world Li-ion test data



Approach – KULI Thermal Model

- 1-D thermal/fluid models using automotive industry commercial software package (KULI)
- Incorporate multiple vehicle cooling systems
  - Heating and cooling (HVAC)
  - Passenger compartment
  - Energy storage
  - Engine
  - Power electronics
  - Electric machines
  - Transmission

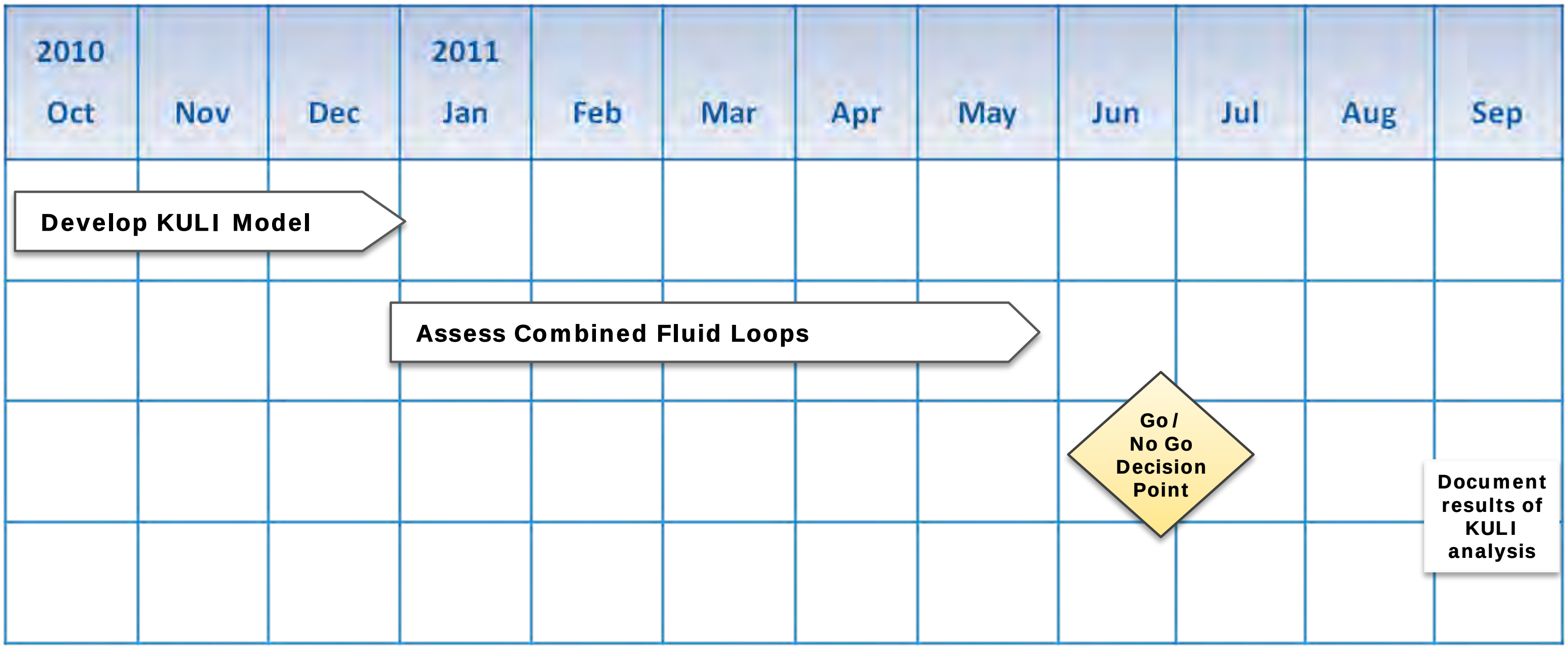




Approach – continued

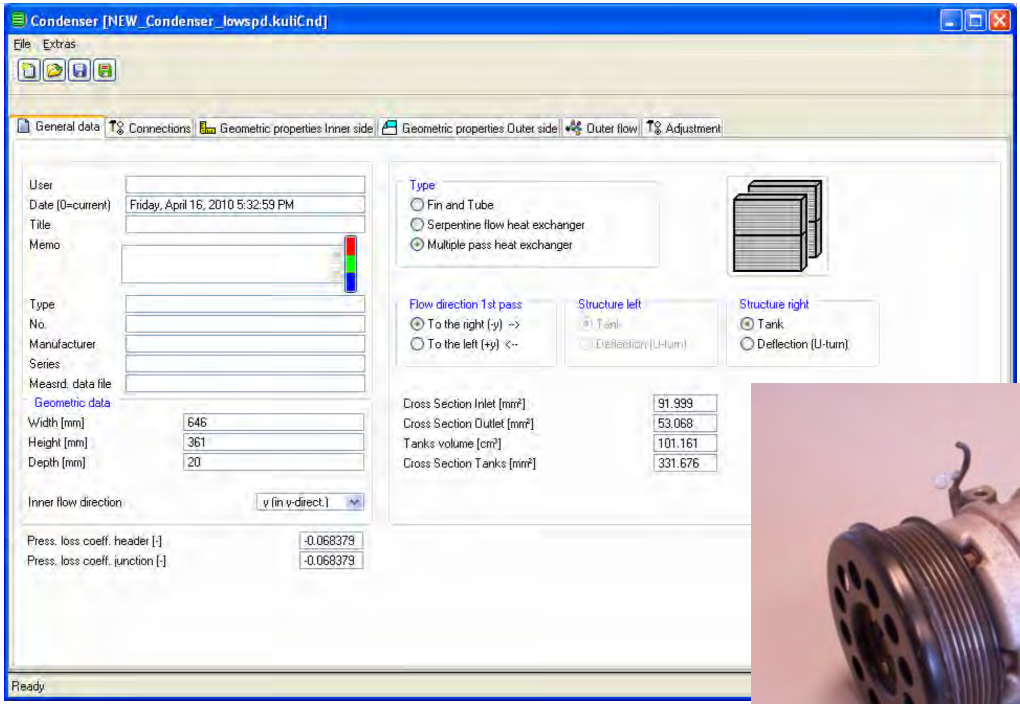
- Address Targets
  - Improved range at equivalent cost from combining thermal management systems
  - Reduce the APEEM coolant loop temperature without requiring a dedicated system
  - Reduced volume and weight
- Uniqueness
  - Combining APEEM, energy storage, engine, and passenger compartment thermal management systems

Approach – Go/No Go Decisions and Milestones



Accomplishment – Built A/C Component Models

- High quality detailed component data
  - Provided by Visteon (Tier 1 HVAC component supplier)
- Built component models in KULI



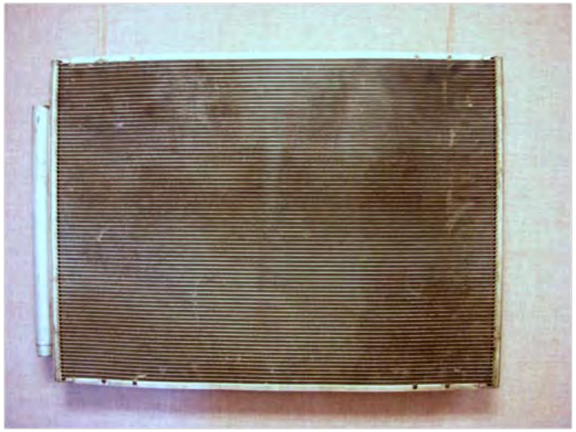
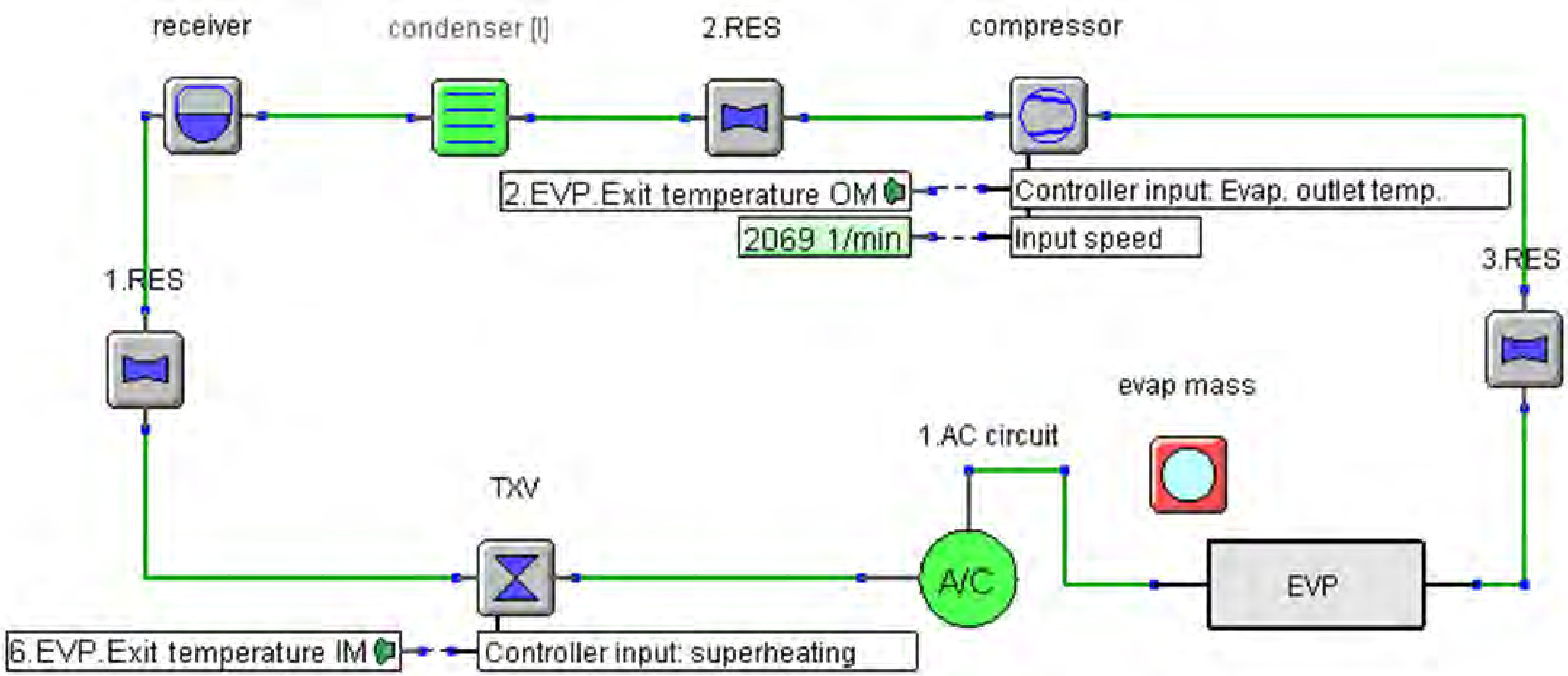
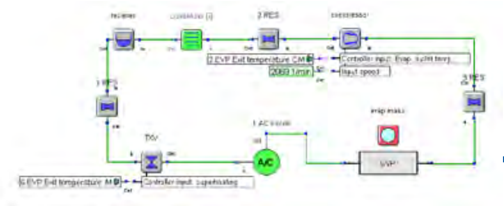


Photo Credits: John Rugh, NREL

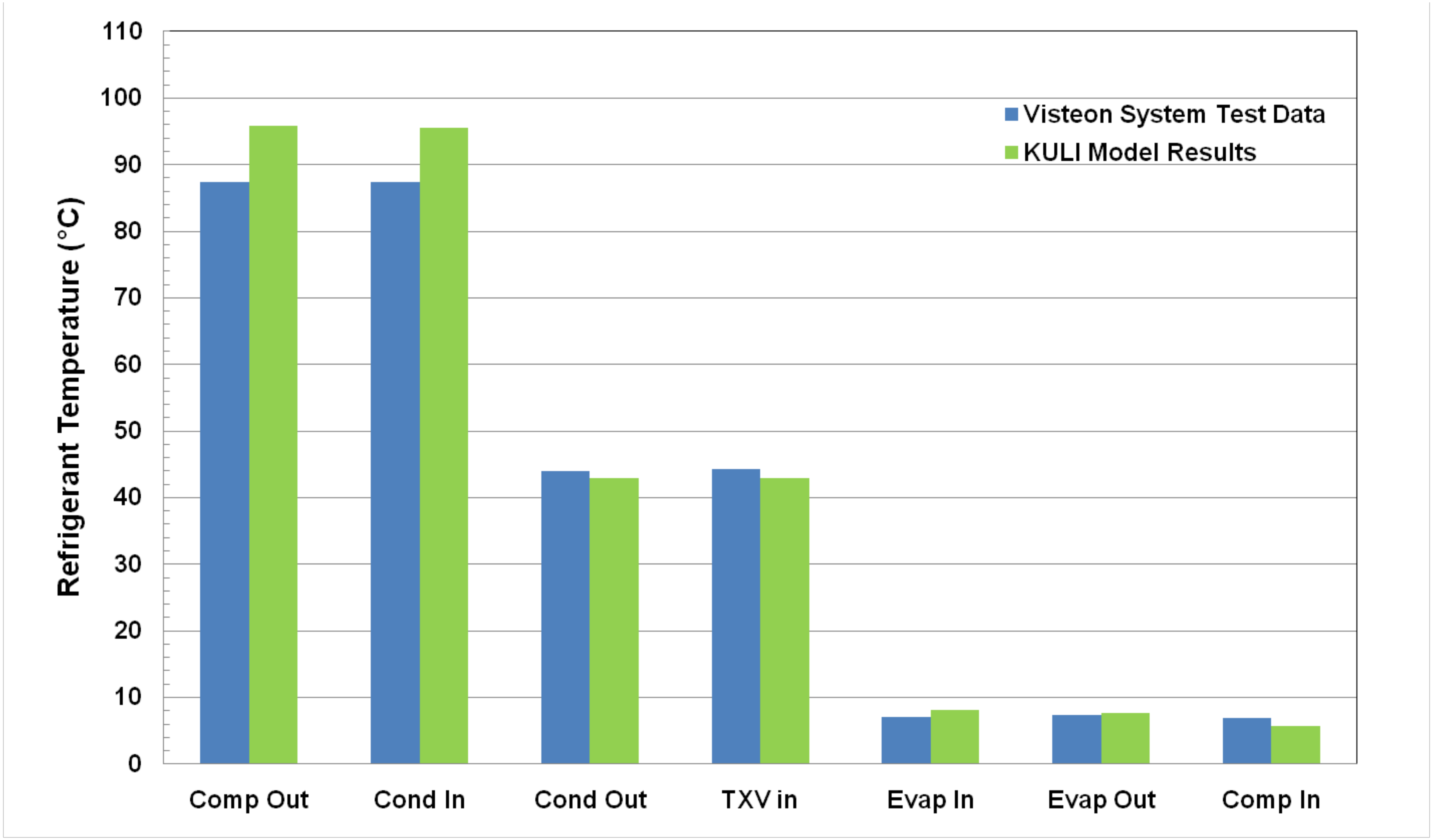
Accomplishment – Built A/C System Model



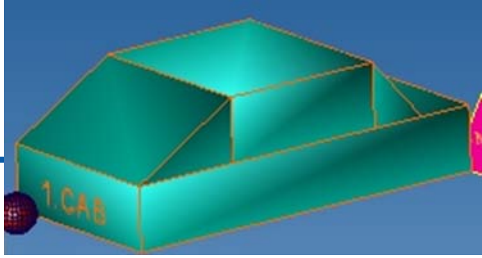
Accomplishment – A/C Model (cont.)



- A/C model results compared well to Visteon test data

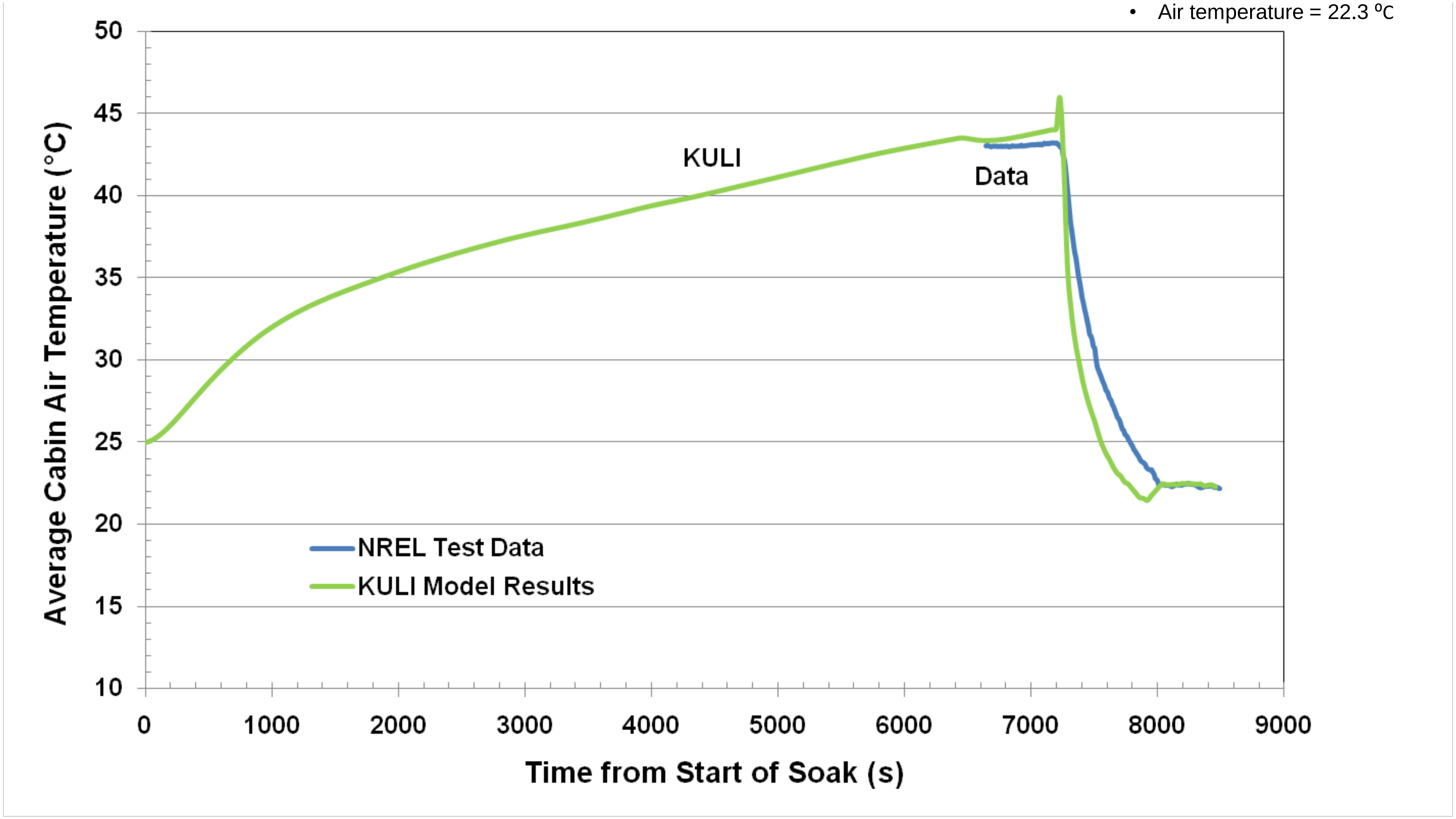


Accomplishment – Built Cabin Model



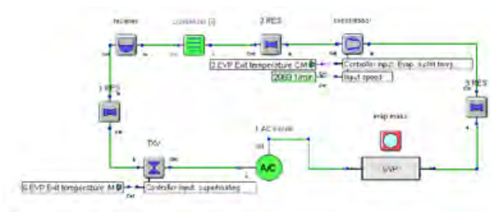
- Cabin soak and cooldown model results compared well to NREL test data

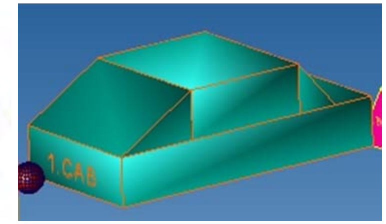
- Small sedan
- 2 hr soak, 21 minute cooldown
- Solar = 870 W/m^2
- Air temperature = 22.3 ºC

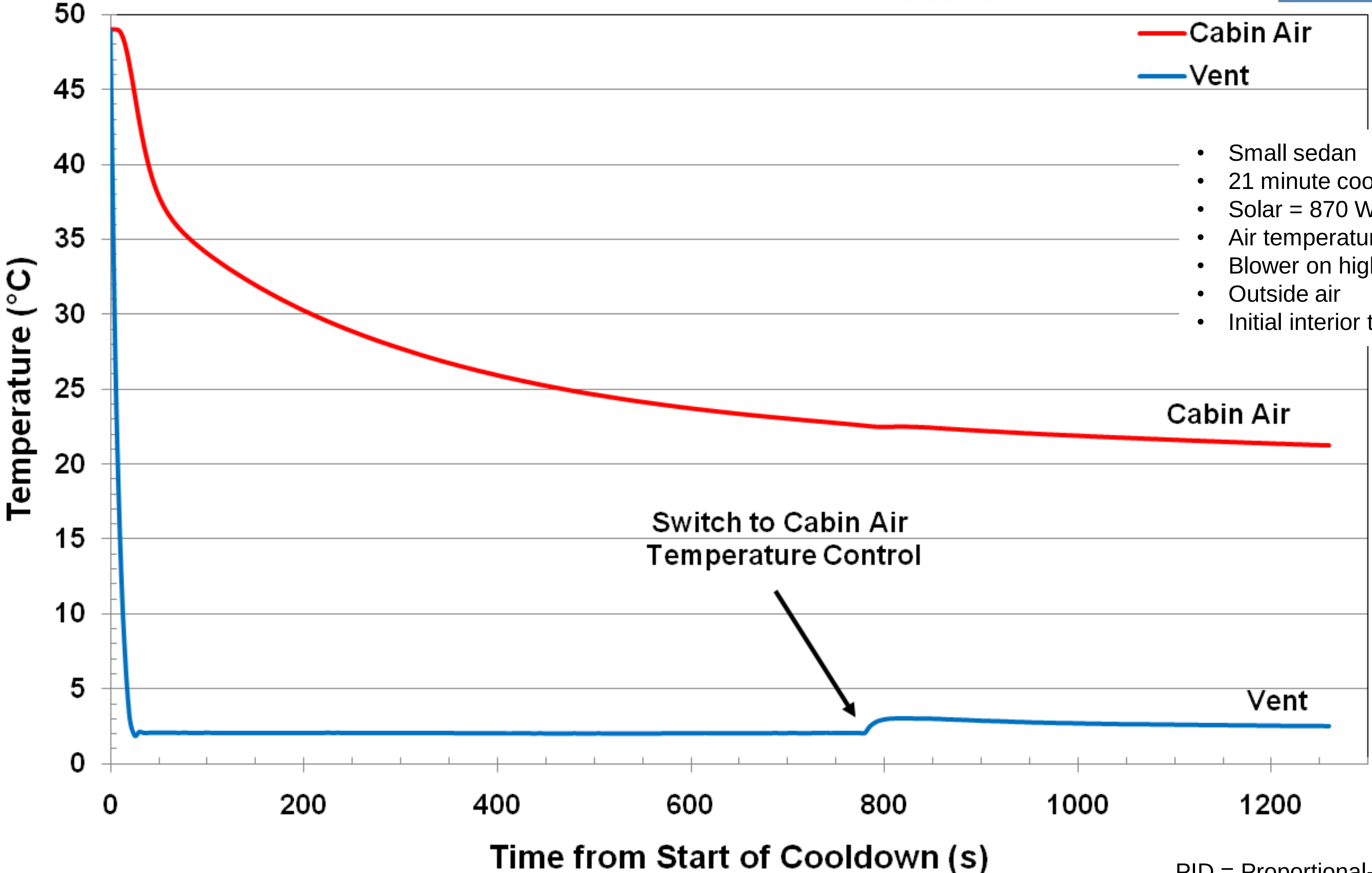


Accomplishment – Combined A/C and Cabin Models with PID Control

- Cooldown simulation demonstrates
  - Reasonable cooldown
  - Robust control



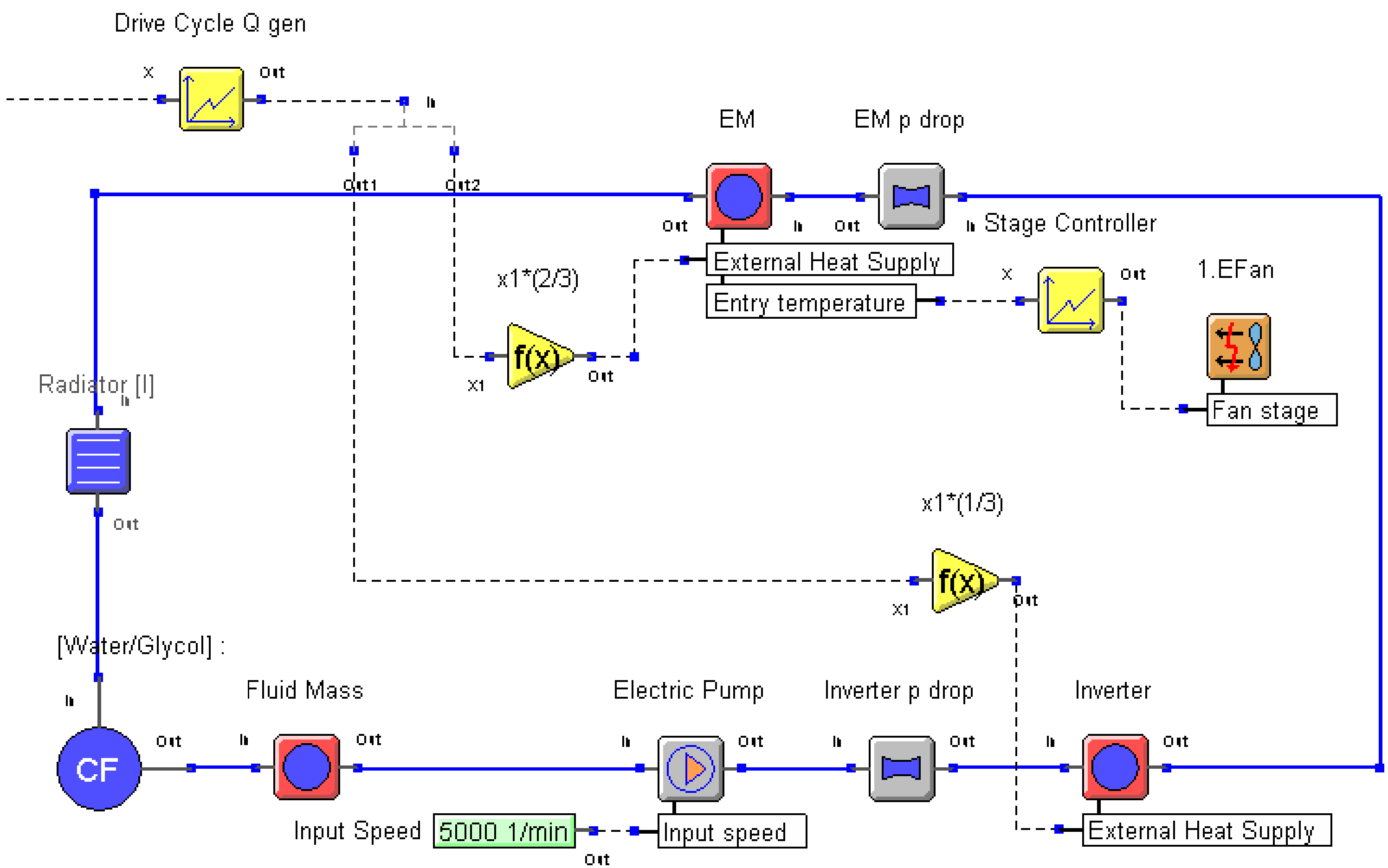




- Small sedan
- 21 minute cooldown
- Solar = 870 W/m^2
- Air temperature = 22.3 ^{o}C
- Blower on high flow
- Outside air
- Initial interior temperature = 49 ^{o}C

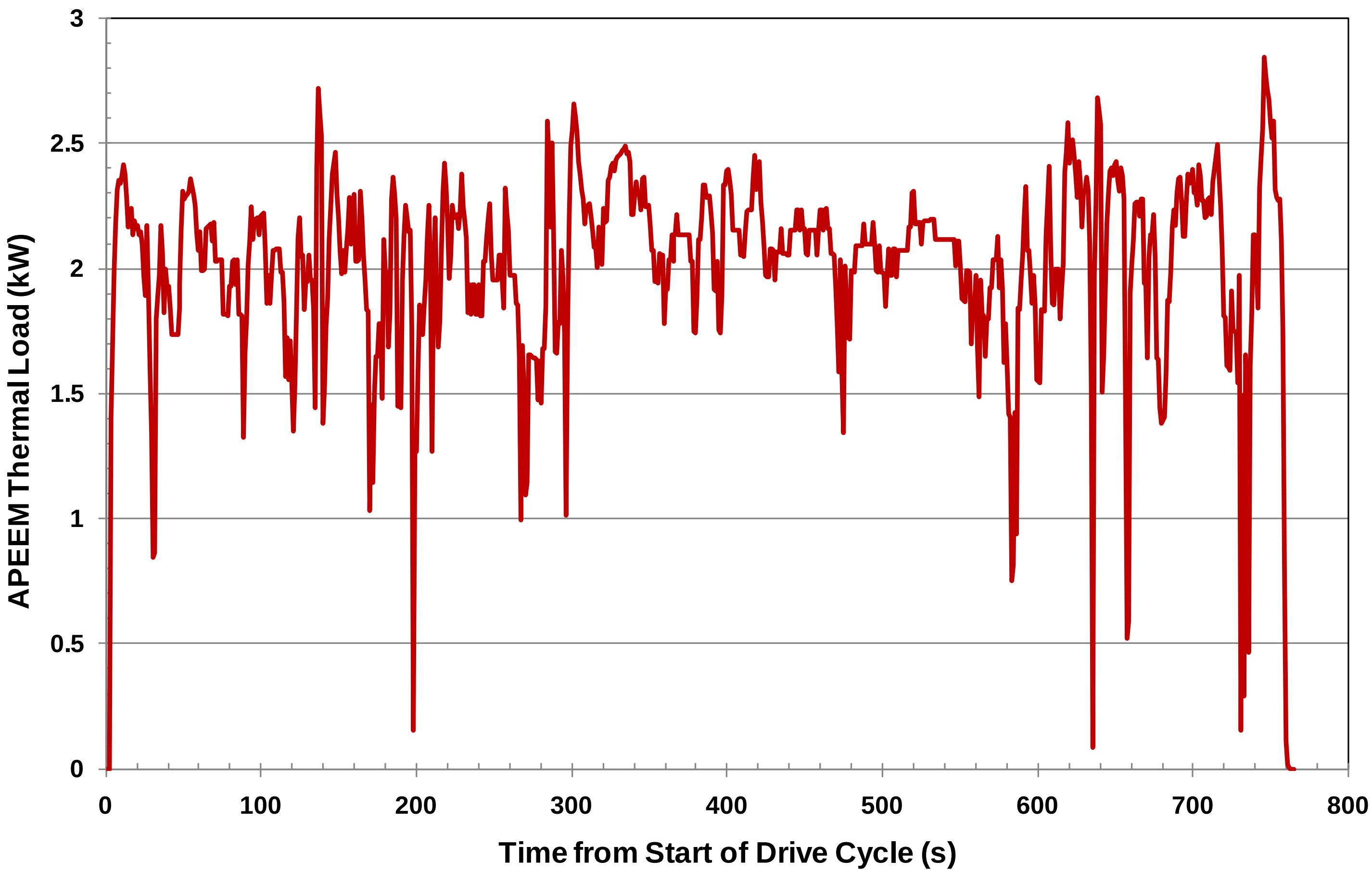
PID = Proportional-Integral-Derivative

Accomplishment – Built APEEM Cooling Loop Model



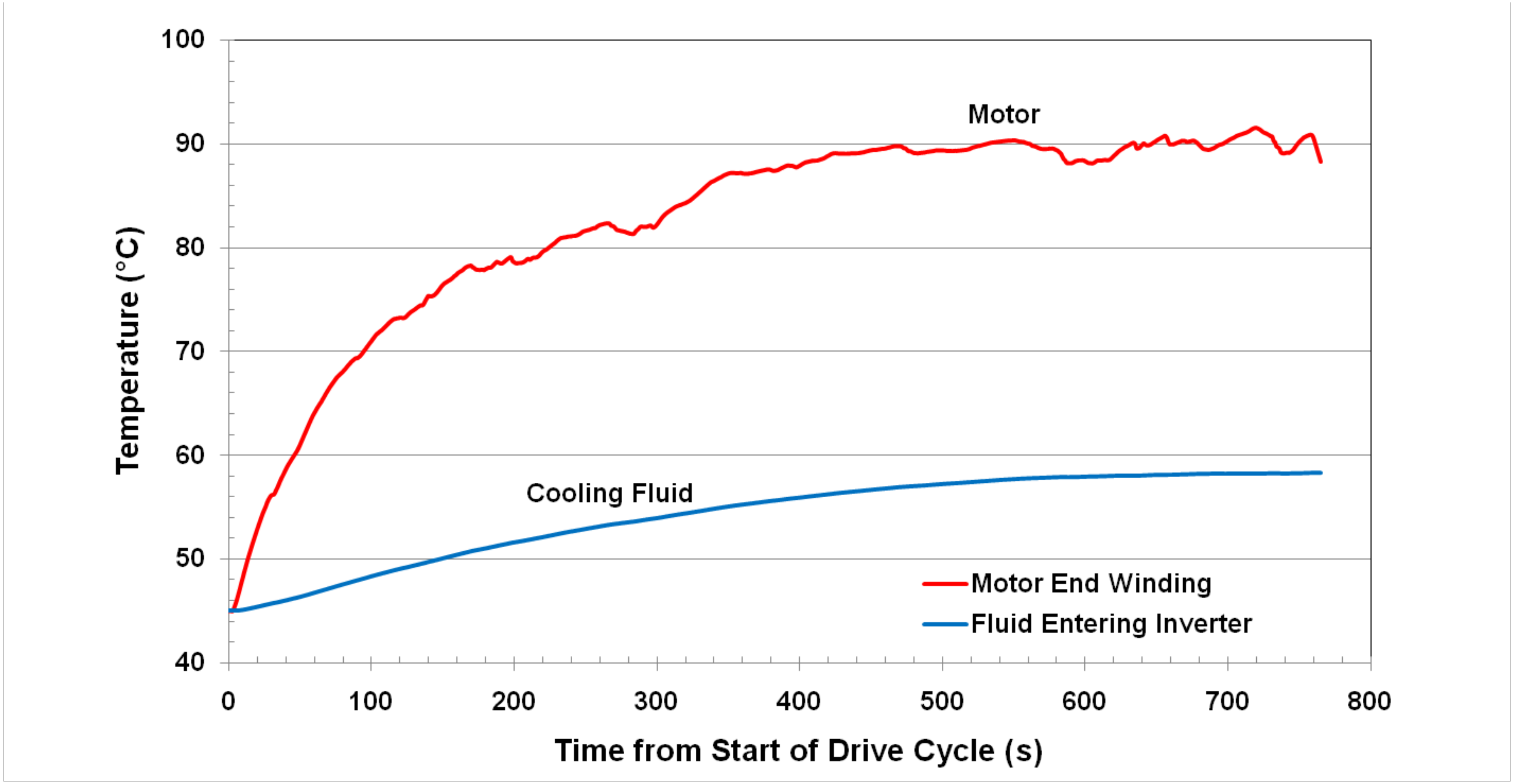
Accomplishment – Heat Generation in the APEEM Components Input into APEEM Model

- Vehicle performance model output
- Nissan Leaf
- Drive Cycle: EPA Highway Fuel Economy Test

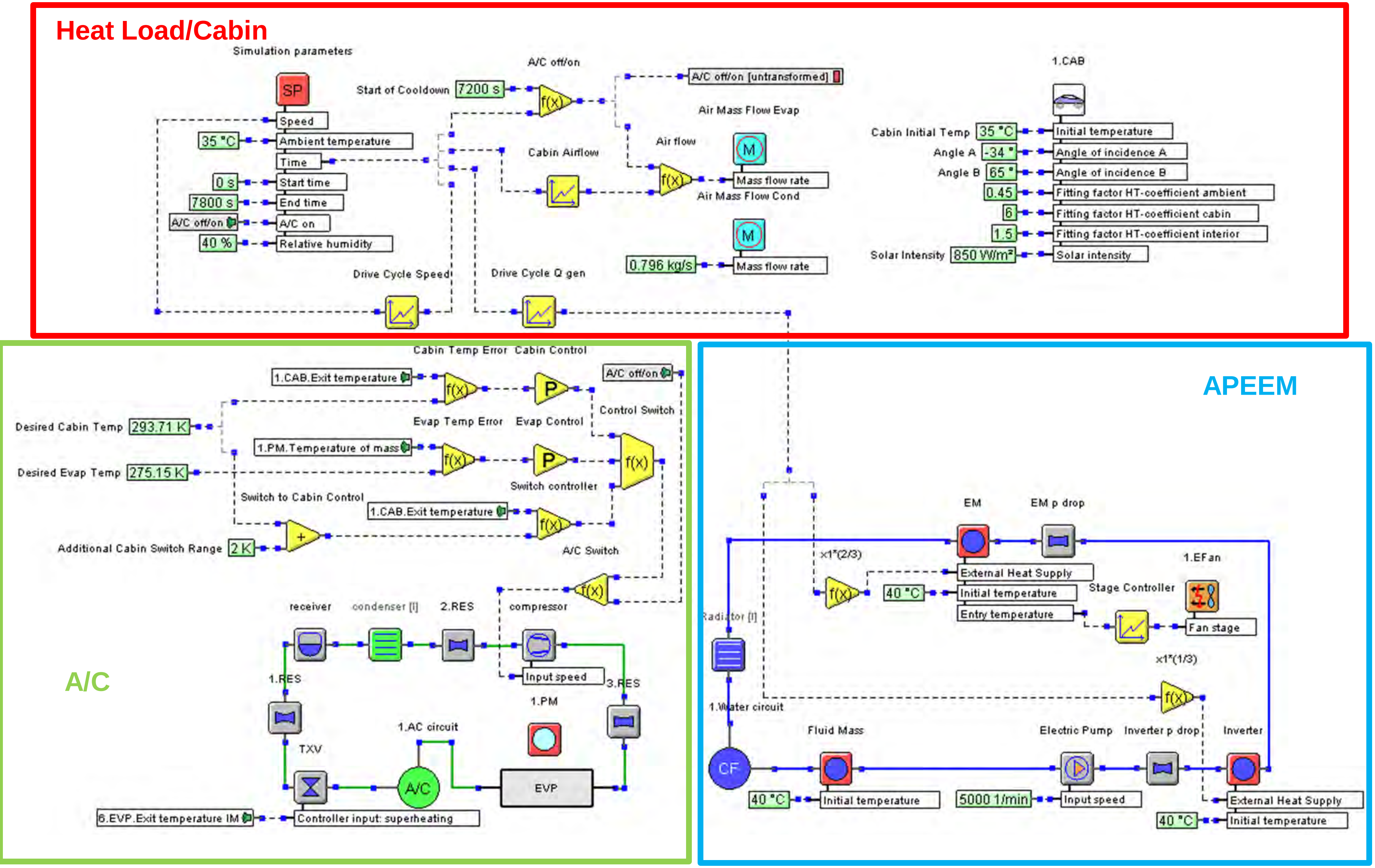


Accomplishment – APEEM Cooling Loop Model Produced Reasonable Fluid and Motor Temperatures

- Air temperature = 45 ^{0}C
- 5 L/min
- 50/50 Water – Ethylene Glycol



Accomplishment – Combined A/C, Cabin, and APEEM Cooling Loop



Collaboration

- Visteon
- EE Tech Team
- VTP Tasks
  - Vehicle Systems
  - Energy Storage
  - Advanced Power Electronics and Electric Motors

Future Work

- FY11 (March-September)
  - Build an ESS cooling loop model
  - Combine ESS model with A/C, cabin, and APEEM KULI models
  - Assess baseline thermal performance
  - Assess combined cooling loop strategies
- FY12
  - Based on the FY11 analysis, select, build, and evaluate a prototype system to demonstrate the benefits of an integrated thermal management system
  - Validate the KULI model with bench data and improve the model with updated component data as it becomes available
  - Engage automobile manufacturers and secure strong support from at least one OEM

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
- **Approach**
  - Build a 1-D model (using KULI software) of the 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 with production-feasible component data
  - 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
  - Built A/C and cabin KULI model
    - A/C and cabin models individually validated
    - Combined system produces reasonable cooldown
  - Built APEEM KULI cooling loop model
    - Produces typical component and fluid temperatures
  - Ran performance model of a Nissan Leaf to provide APEEM heat generation
- **Collaborations**
  - Collaborating closely with Visteon
  - 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

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EE Tech Team

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