U.S. DOE 2016 Annual Merit Review and Peer Evaluation Meeting
June 8, 2016

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MAHLE Behr Troy Inc.

UTEMPRA – Unitary Thermal Energy Management for Propulsion Range Augmentation

DOE DE-EE0006840

Project ID:VS157

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Overview

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Timeline

Start Date: October 1, 2014
End Date: September 30, 2017

» Percent Work Complete: 39%

Barriers

Severe Range Penalty of GCEDVs in Cold Weather (up to 40% range reduction at -10°C)

- Resistive heating is the typical heat source for passengers and battery – low-efficiency (COP<1.0) & significant drain on battery
- Must reduce customers' range anxiety for greater GCEDV acceptance

Budget

Award No. : DE-EE0006840

Contract Value (80/20):	$ 3,170,379
▪ Gov't Share (with National Lab)	$ 2,536,303
▪ Delphi Team Share (with National Lab)	$ 634,076

BP-1 & 2 Budget	$ 2,469K
BP-1 & 2 Spent	$ 1,781K

As of April 8, 2016

Partners

FCA FIAT CHRYSLER AUTOMOBILES

NORGREN

NREL NATIONAL RENEWABLE ENERGY LABORATORY

DELPHI → MAHLE

(Delphi Thermal was acquired by MAHLE on July 1, 2016)

Relevance and Project Objective

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Overall Objective

UTEMPRA targets to **increase 15% BEV drive range at -10°C** with equivalent cabin comfort

- Scavenge waste heat from electronics and electric motor
- Provide thermal management to all power components
- Implement a simplified A/C and Heat Pump System with flexible coolant-based distribution
  - Coolant-based system can be synergized with other energy-saving technologies (e.g. PCM-based thermal storage)
- Demonstrate technology for a 2015MY BEV with an OEM partner (FCA) to calculate energy benefit. Develop system for mass production by 2020. Bring project TRL from 3 to 7

Relevance and Project Objective

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Specific Annual Objectives – Budget Period 1

- **Budget Period 1 (Oct. 1st -14 to Oct. 31st -15): Technology Development Phase**
  - Program management & sub-contracts with partners **- Complete**
  - Review vehicle requirements & develop system specification, explore vehicle packaging **- Complete**
  - Instrument & test baseline vehicle to set performance targets **- Complete**
  - Design system components (Heat exchangers, Compressor, Valves, Pumps) **- Complete**
  - Develop flux-less braze equipment specification & order equipment (long-lead) **- Complete**
  - Develop Matlab-Simulink system model to study Baseline and UTEMPRA systems **- Complete**

Specific Annual Objectives – Budget Period 2

- **Budget Period 2 (Nov. 1st -15 to Oct. 31st -16): System Development Phase**
  - Program management
  - MMFC Prototype Design and Build **– In Progress**
  - Braze Equipment Installation and Qualification **– In Progress**
  - Component Builds and Tests (Heat exchangers, Compressor, Valves, Pumps) **– In Progress**
  - System Bench Performance Tests
  - Complete CoolSim UTEMPRA system Model and use for Vehicle Controls Development **– In Progress**

Approach – Activity Flow/Timeline

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Task Name	Baseline Start	Baseline Finish	% Work Complet
Budget Period 1	10/7/14	10/28/15	100%
Vehicle Requirements	10/7/14	10/29/14	100%
Refrigerant, Lubricating Oil, Coolant & Compressor Selection	10/14/14	11/13/14	100%
Vehicle CAD Data	10/14/14	7/27/15	100%
Vehicle Baseline Tests (HVAC Performance, Energy Usage, Range Effect)	11/13/14	2/24/15	100%
System & Component Specifications	2/2/15	3/17/15	100%
Heat Exchanger Design, Analysis & Optimization	3/17/15	5/6/15	100%
Unitary System Vehicle Modeling	2/24/15	9/2/15	100%
Flow Control (Coolant)	2/17/15	10/16/15	100%
Brazing Equipment Spec and Order	1/5/15	10/28/15	100%
Budget Period 2	11/2/15	10/26/16	23%
Prototype Design / Build	11/2/15	8/30/16	41%
Brazing Equipment Qualification, Tooling & Component Build	11/2/15	4/7/16	58%
Component & System Tests	4/26/16	6/9/16	0%
System Bench Performance Tests	6/9/16	10/26/16	0%
Vehicle Controls Study	6/9/16	9/15/16	0%
Human Machine Interface or Information Display	7/14/16	9/1/16	0%
Budget Period 3	11/1/16	9/22/17	0%
Vehicle Controls	11/1/16	1/17/17	0%
Design Durability Validation - Components	11/1/16	1/16/17	0%
Manufacturing Plan & Cost Estimates	11/1/16	1/26/17	0%
Vehicle Build	1/18/17	2/14/17	0%
Vehicle Testing	2/15/17	8/31/17	0%
Final Technical Analysis & Vehicle Delivery	6/7/17	9/22/17	0%

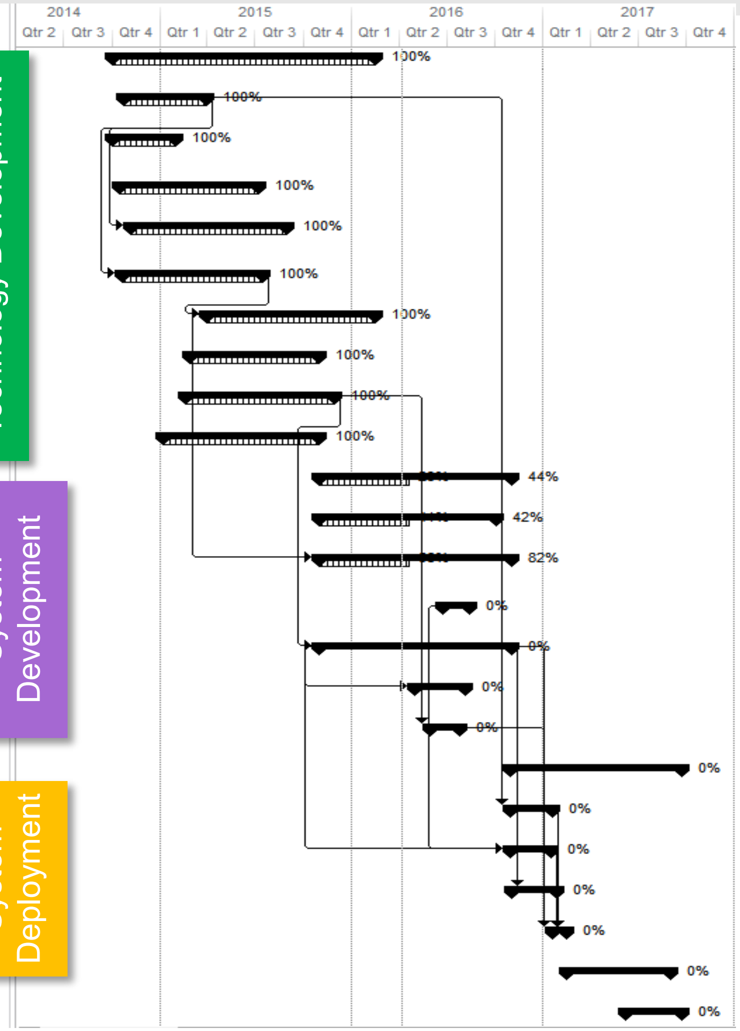
Complete

On Track

Technology Development

System Development

System Deployment



❑ <u>Status (as of April 6, 2016)</u>: approximately 1 month behind baseline schedule

Project Approach – Baseline BEV

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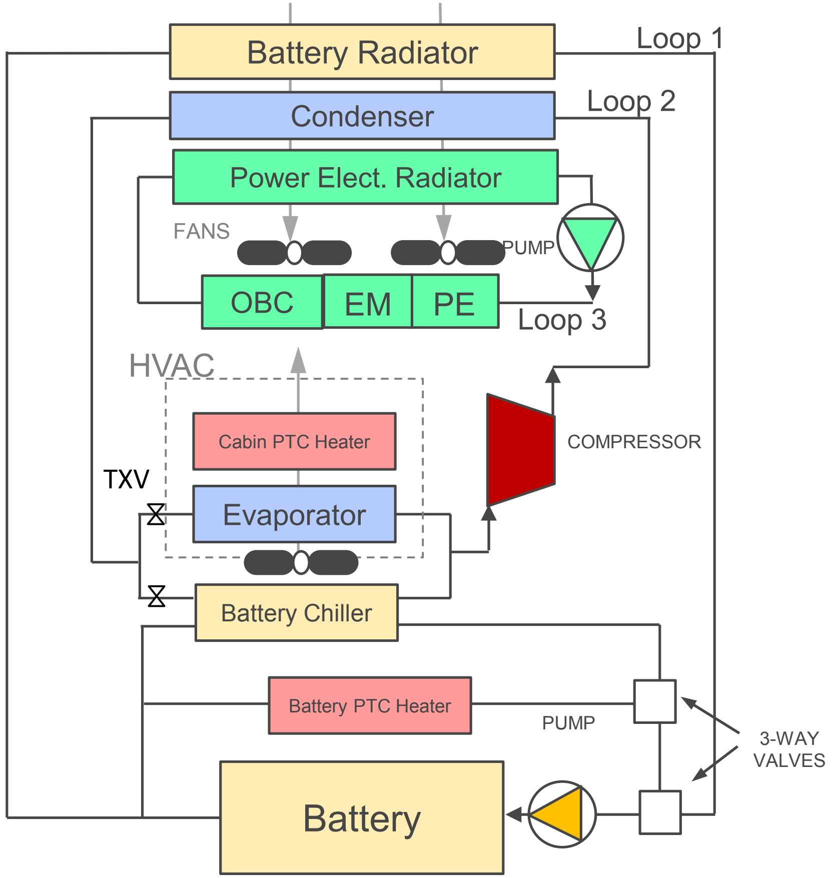
2015MY Fiat 500e BEV

- Cooling: Traditional Direct A/C System
  Heating: PTC Heater (qty. 2)
- Thermal Conditioning of Battery, Power Electronics and Cabin are independent
- Two PTC (Resistive) Heaters for the Cabin and Battery - significant drain on the battery
- Relatively simple control but no heat recovery/thermal optimization applied



2015 Fiat 500e Thermal Management System

OBC – On-board Charger
EM – Electric Motor (Vehicle Propulsion)
PE – Power Electronics (Inverter)

Project Approach – UTEMPRA

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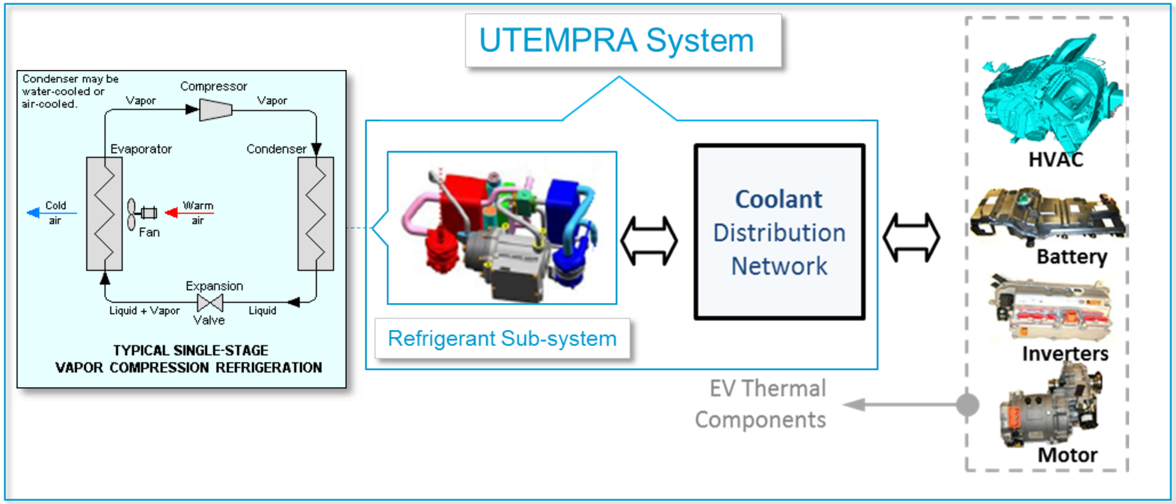
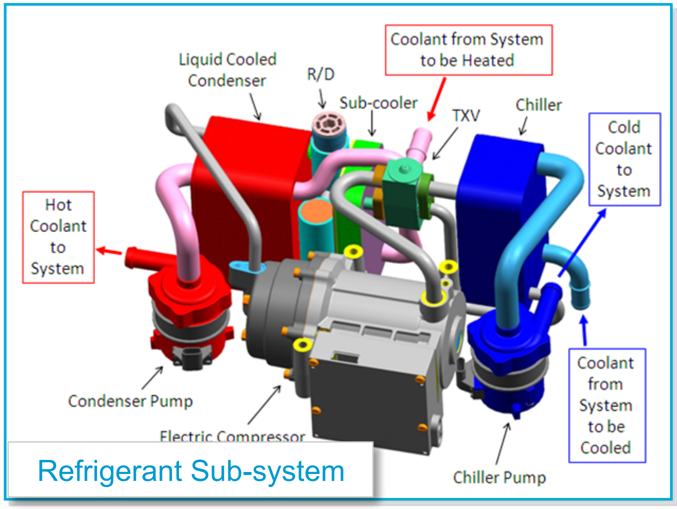
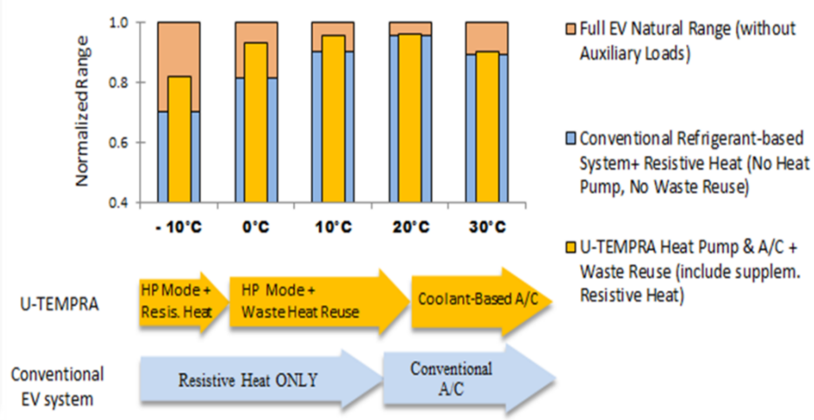




UTEMPRA Benefits

- Compact refrigerant sub-system generates heating and cooling – continuously available and deployable
- Coolant architecture enables heat scavenging – improved fuel economy
- Coolant-based heat pump system is more simple and more flexible vs. refrigerant-based heat pump systems
- Significant refrigerant savings (est. 50% vs. ref. based heat pump systems) – cost and environmental benefit

Expected Range Improvement



Project Approach – UTEMPRA

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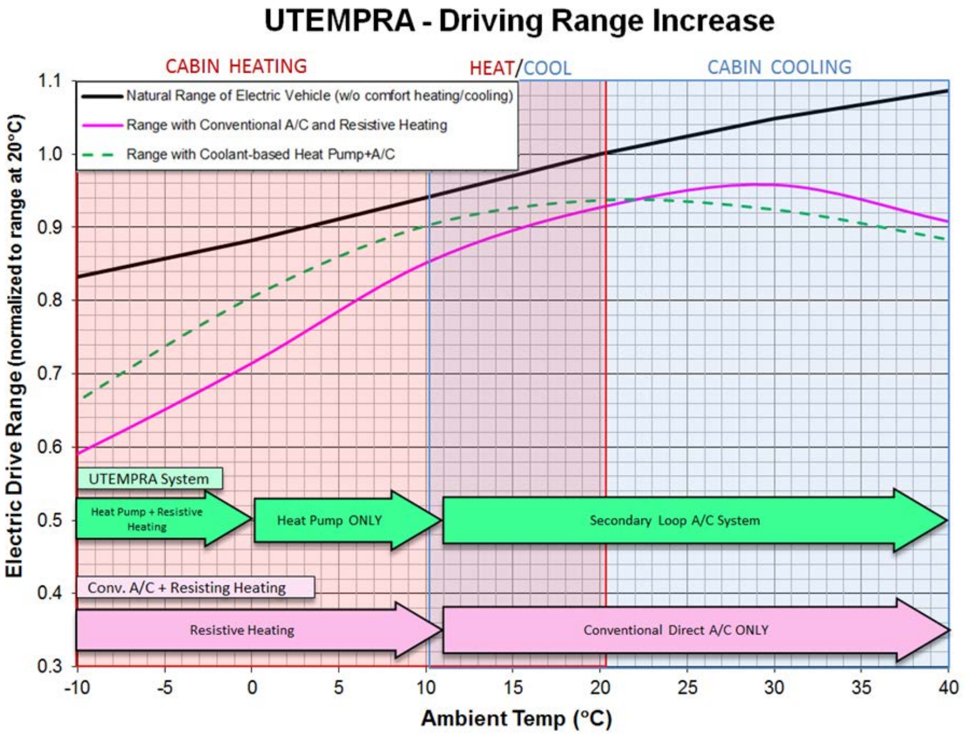
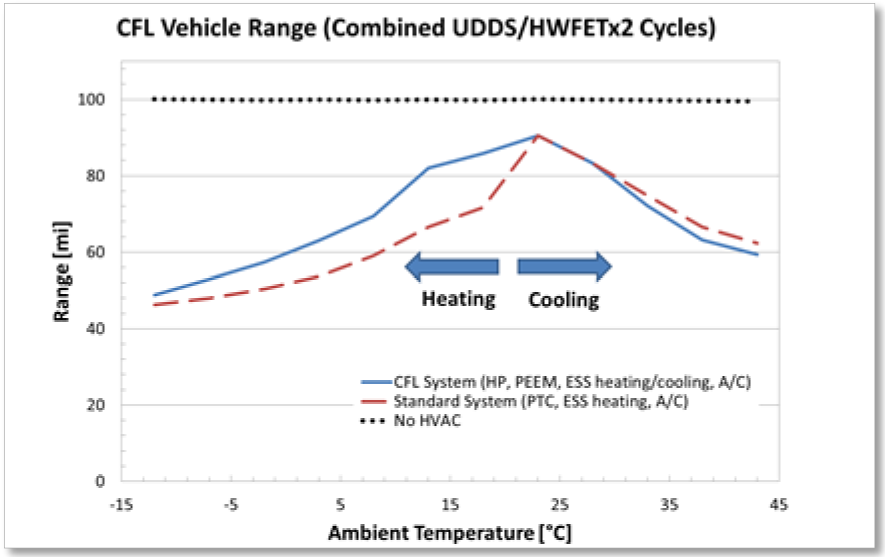


Combined Flow Loop - DOE (VSS046)

NREL Bench Test + Simulation Study

- 9% Range improvement overall
- ~12% improvement at -10^{o}C (components and system not optimized)



D. Leighton et al. SAE 2014

- Internal studies and NREL study has shown 15% range improvement target is quite feasible
- A Coolant-based thermal loop system that is commercially viable will enable use of other energy saving technologies such as PCM storage, idle-stop savings etc.

Approach – Milestones

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Date	Milestone	Status
Nov-14	Milestone 1: Rough Vehicle Packaging Study	Complete (Dec-15)
Feb-15	Milestone 2: System Specification	Complete (Mar-15)
Apr-15	Milestone 3: Component Design	Complete (Jun-15)
Jul-15	Milestone 4: Proof-of-Concept (POC) Manifold and Valve Design	Complete (Aug-15)
Oct-15	Milestone 5: and **Go-No-Go 1**: POC Manifold and Valve Build	Complete (Oct-15)
Jan-15	Milestone 6: Braze Equipment Installed and Qualified	Delayed (Apr-15)
May-15	Milestone 7: Heat Exchanger and Compressor Build	*On Track*

Vehicle Baseline Testing

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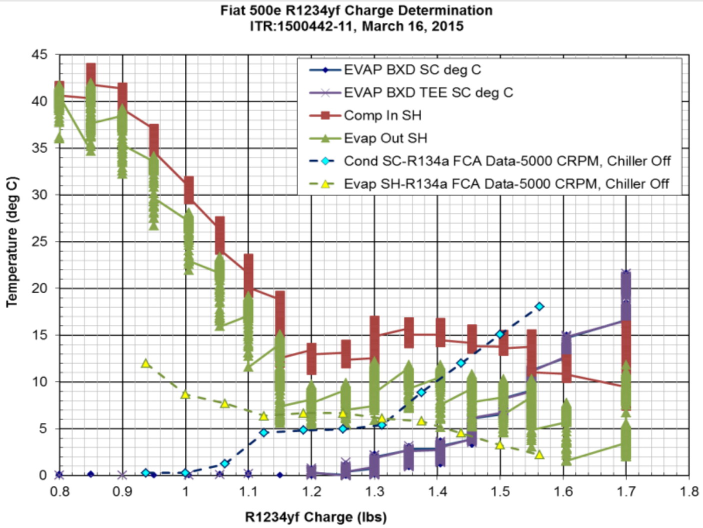
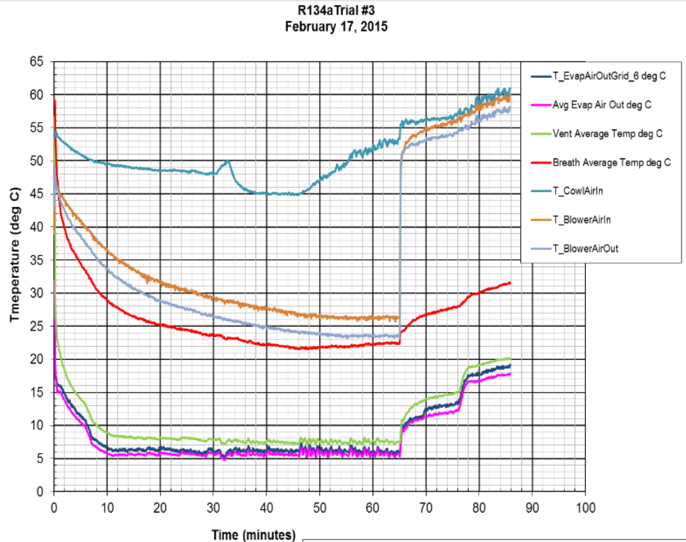
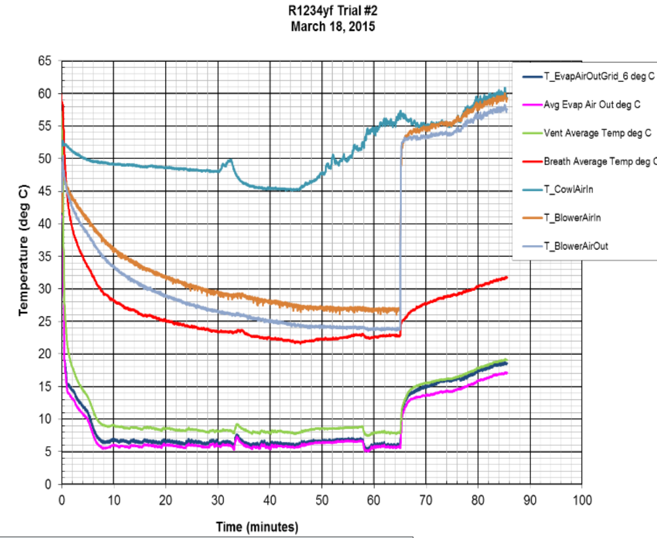
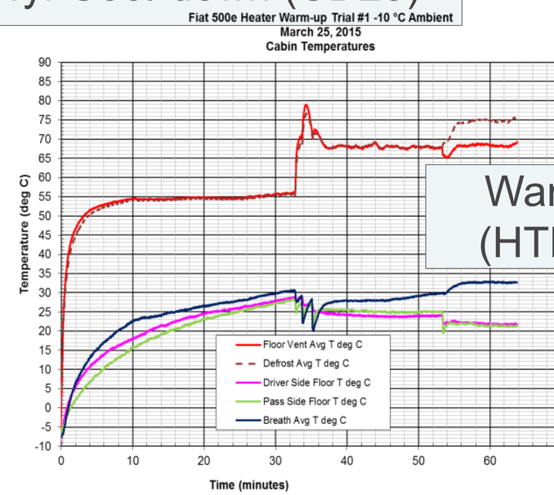


R1234yf Charge Determination





R134a vs R1234yf Cool-down (CD25)



Warm-up (HTRWU)

Highlights:

- R134a and R1234yf cool-down performance was similar. IHX was deemed not necessary.
- Tests were repeatable. However, battery SOC and battery temperature state were variables difficult to control over tests.
- All modes of Battery and PEEM Pumps were tested during the ACC tests to understand/verify operating logic

Vehicle Baseline Testing

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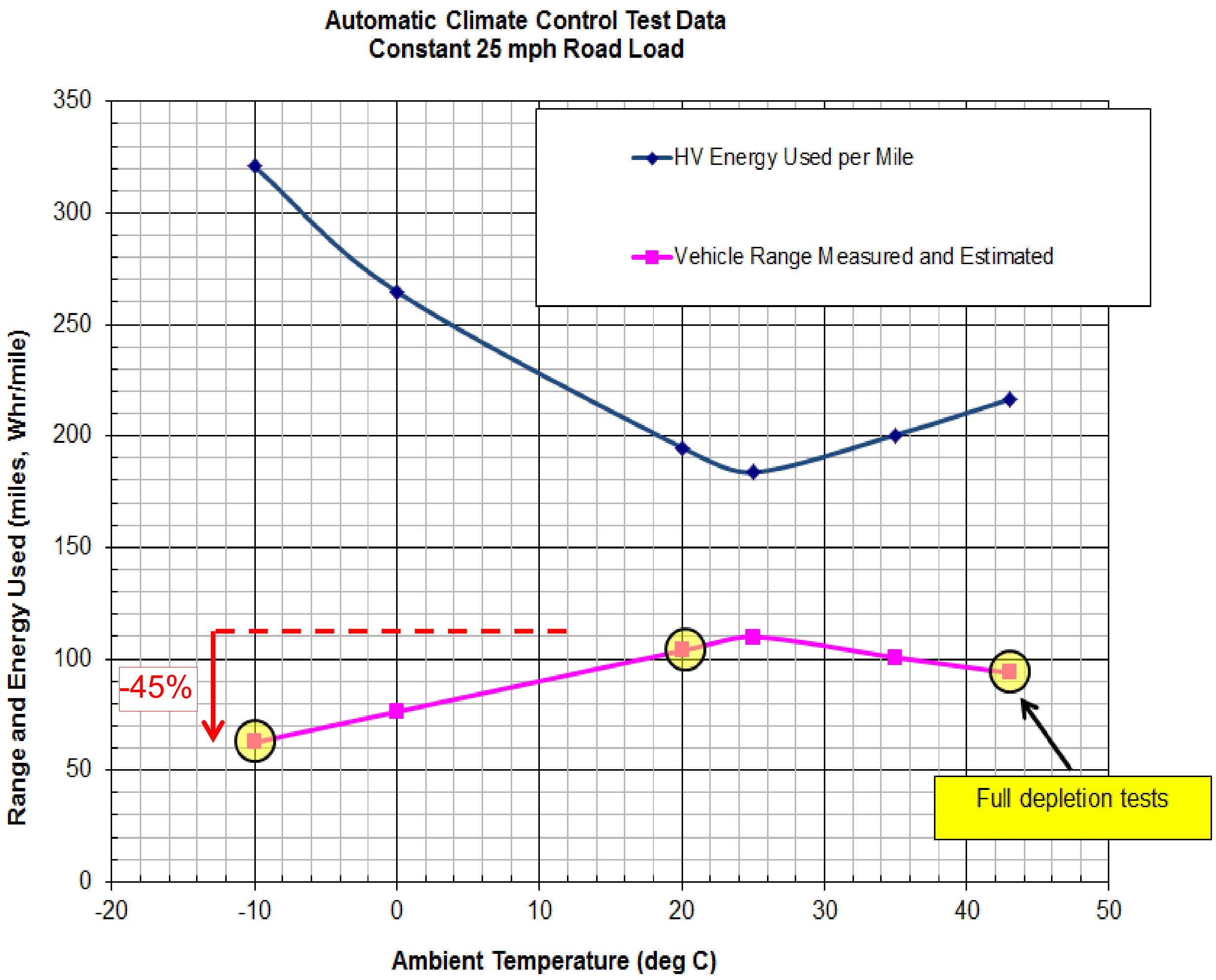

The ACC25 test data was used to estimate the impact of ambient temperature on the vehicle range. These tests were run at a constant 25 mph condition. Three of the tests were run to near full depletion. The range for the other tests are estimated using the Whr/mile energy usage.

UTEMPRA System

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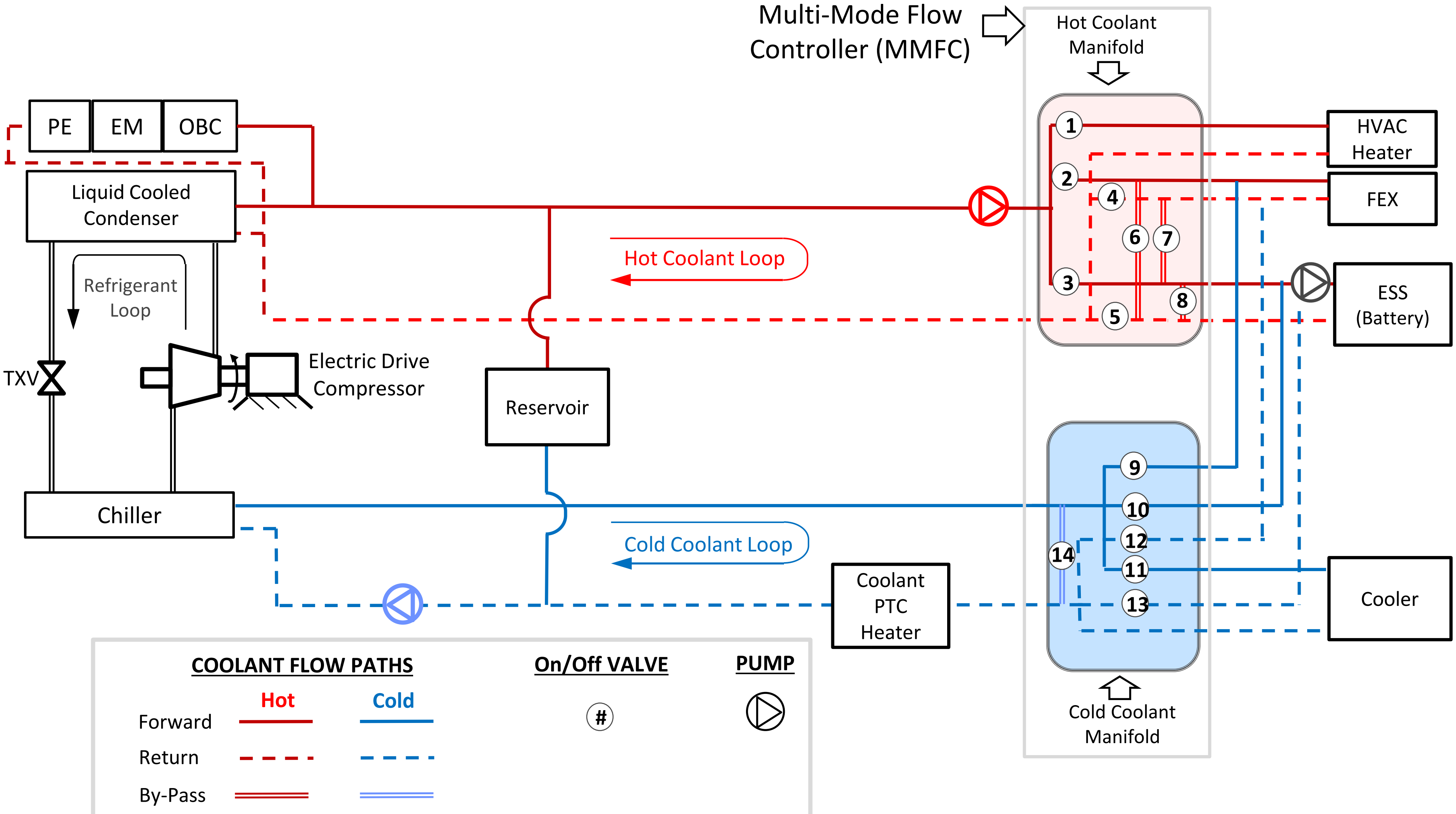

UTEMPRA System Modes

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- Cabin Conditioning:
  - Heating: using Heat Pump (HP) with FEX and/or PTC, PEEM heat scavenging
  - Cooling: using A/C with Chiller & Cooler (ultimately FEX rejects heat)
  - Heat-Cool (Dehumidifying/Defogging): using HP/PTC/PEEM + Cooler
  - OFF
- Battery Conditioning:
  - Heating: using HP/PTC/PEEM
  - Passive Cooling: using FEX
  - Active Cooling: using Chiller
  - Temperature equalization: using just battery pump
  - OFF
- PE-EM-OBC Conditioning:
  - Cooling: Hot Loop pump always ON when vehicle is ON/Charging
- FEX De-icing Mode
  - FEX is heated with hot coolant loop. HP is active – PTC heater and Battery is used as temporary heat source for HP
- Fail-Safe Mode (in case MMFC loses power)
  - Valve's normal (unpowered) position allows flow through PE-EM-OBC to FEX and Battery. Battery pump decides if battery gets flow

Baseline BEV has 20 modes of operation

UTEMPRA will have 21 modes including heat pumping, heat scavenging and a fail-safe mode

Components

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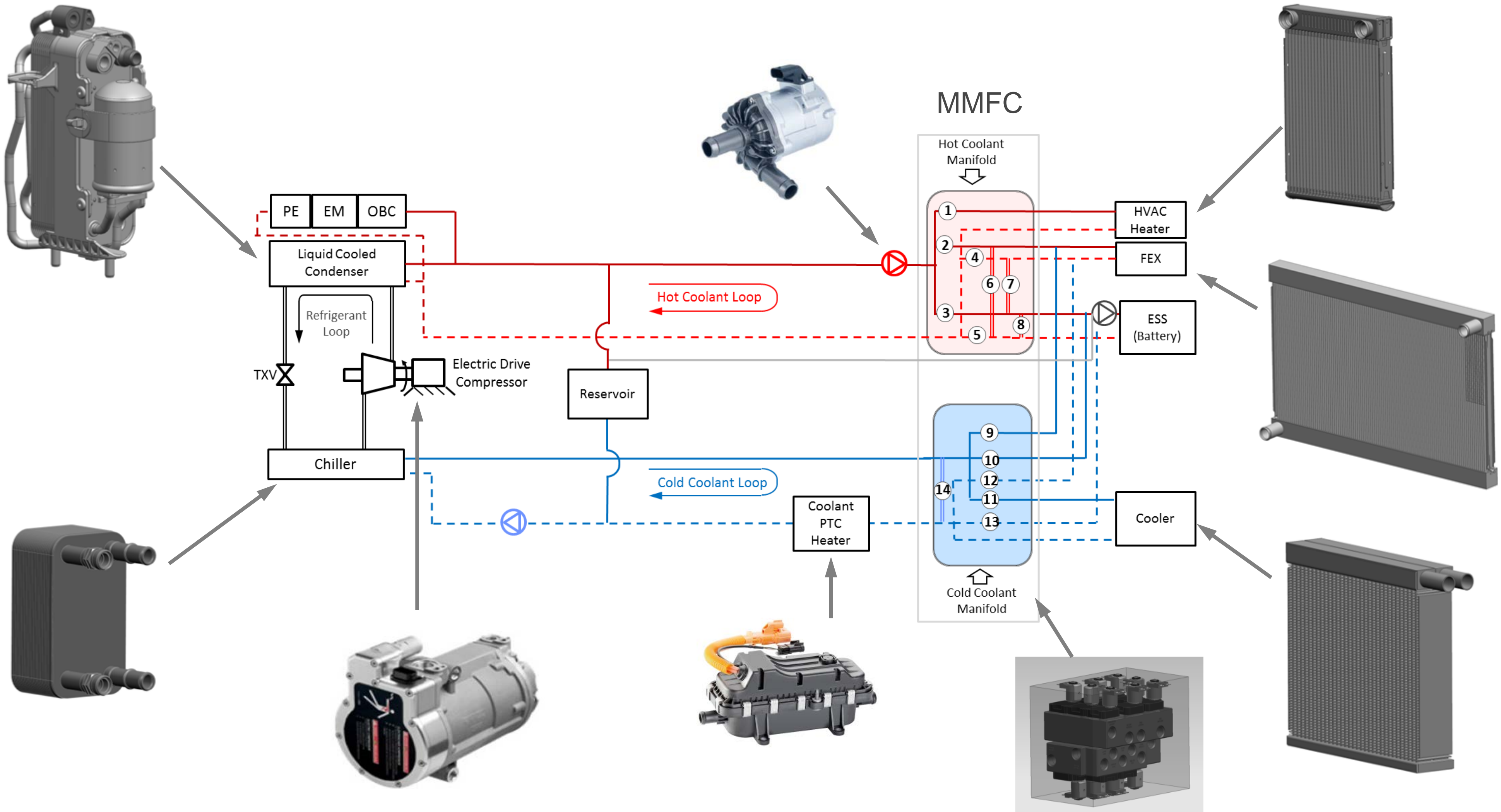

Components - MMFC

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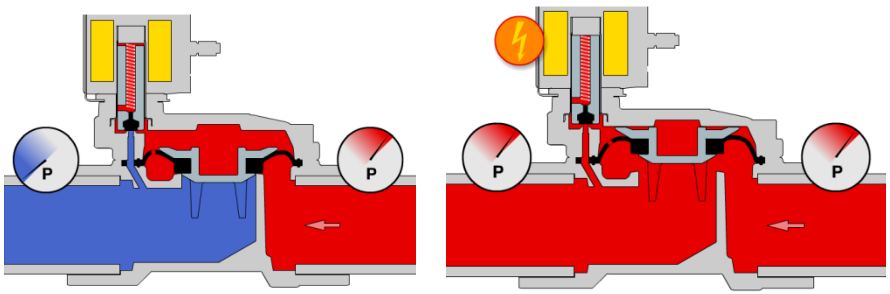
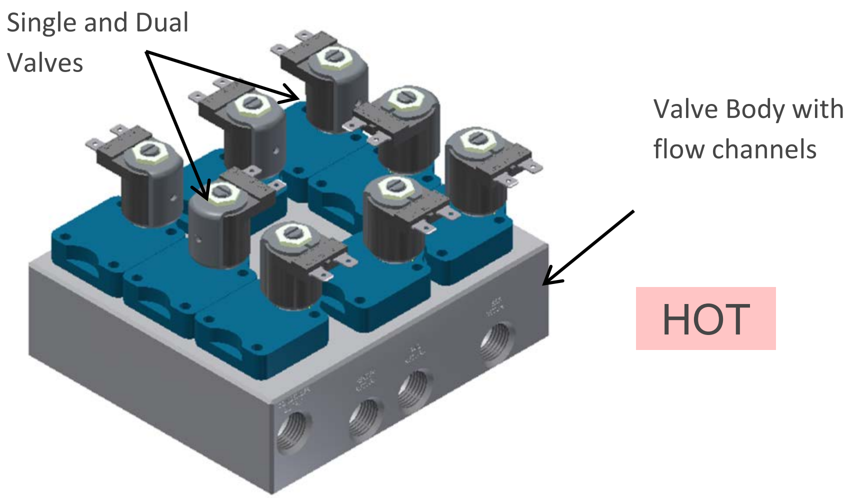


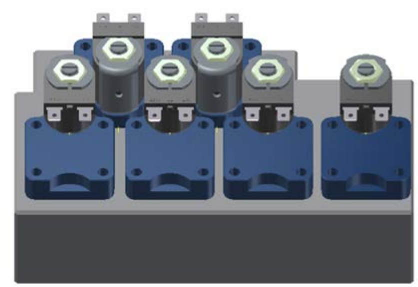
Closed State | Open State

NORMALLY CLOSED VALVES

- Indirect pilot-operated 2-way solenoid valves
- EPDM diaphragm material for chemical compatibility with coolant and for very low temperatures (- 40ºC)
- Lower spring tension and thinner diaphragms to reduce valve flow resistance.
- Projected peak wattage of MMFC <50 W.



HOT



COLD

Vehicle Packaging

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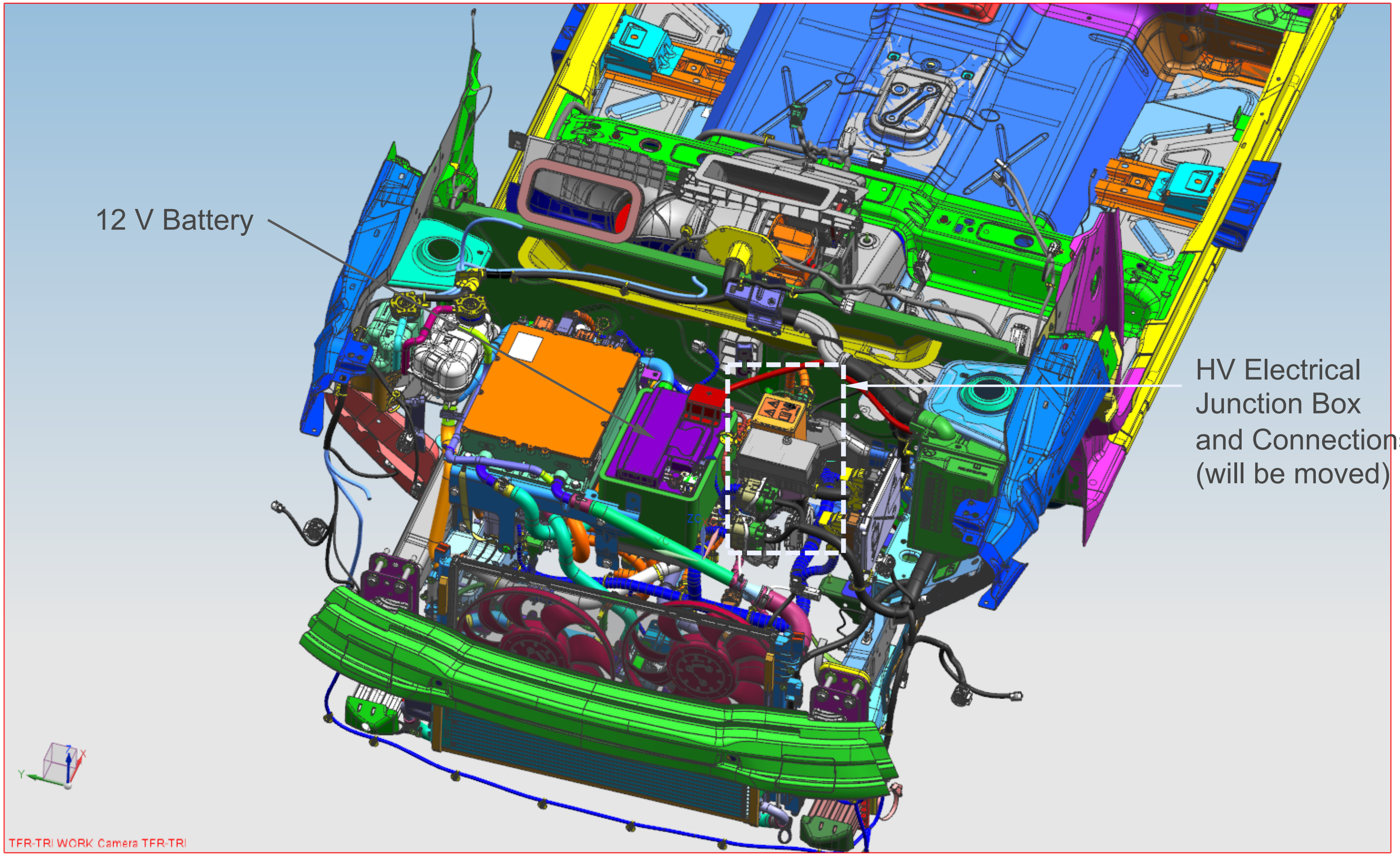

Vehicle Packaging

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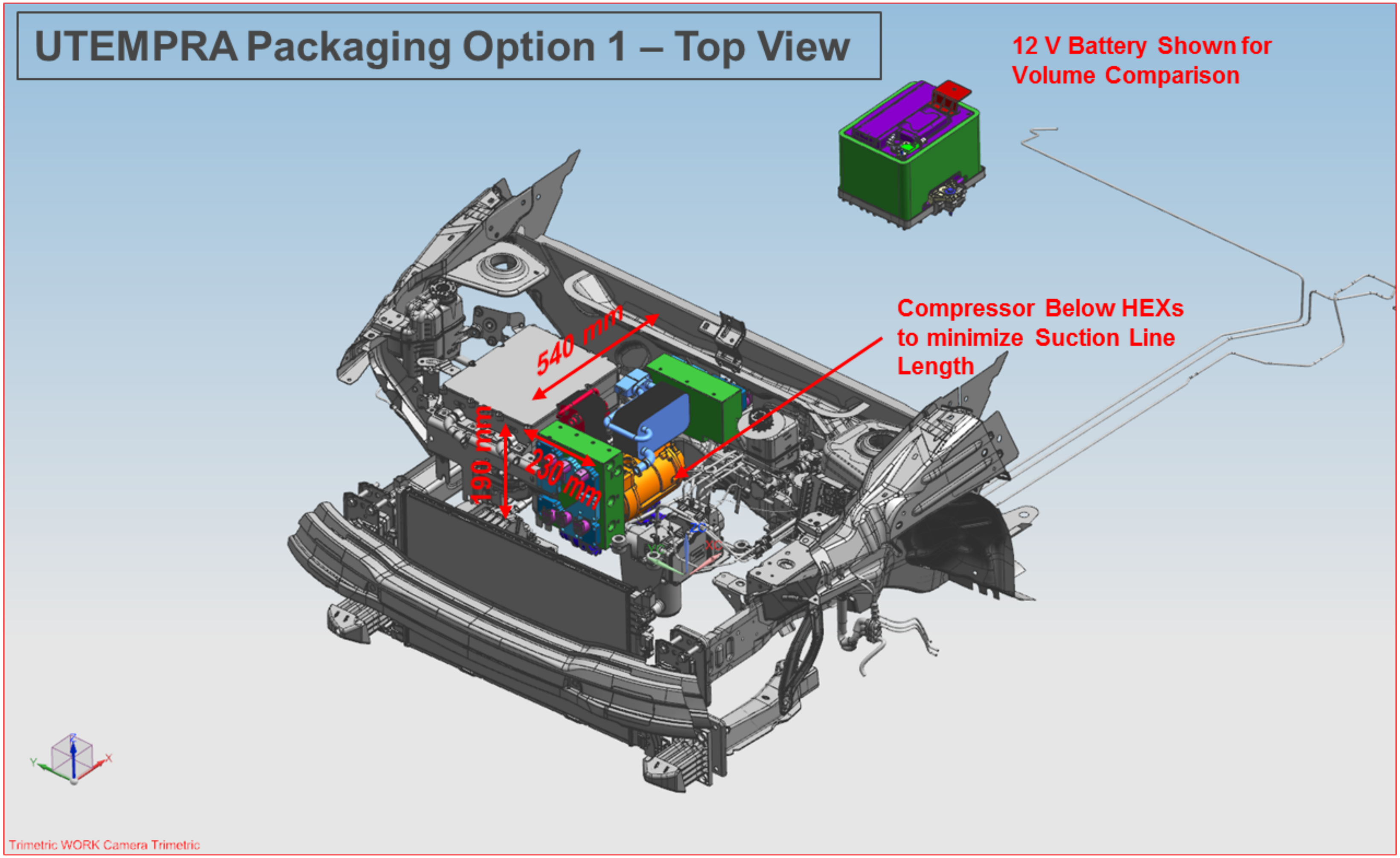

Baseline & UTEMPRA Modeling

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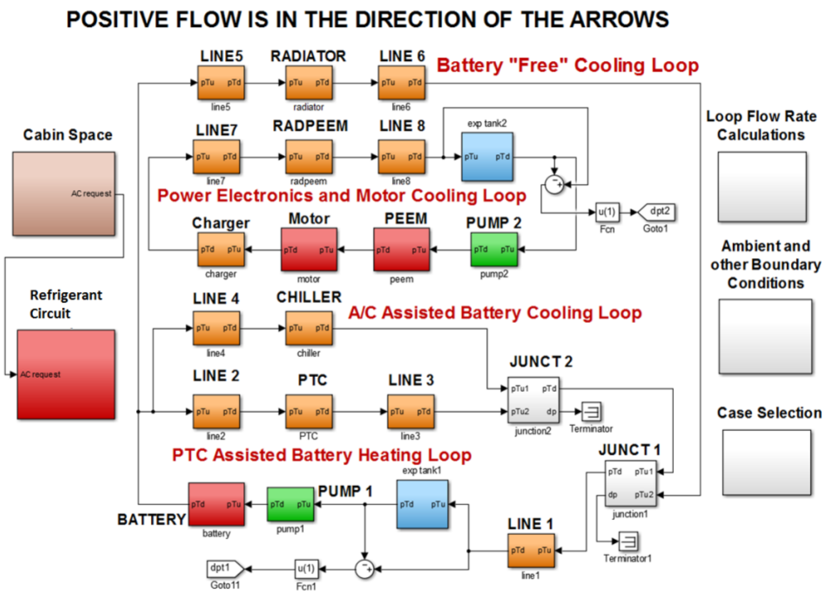
Modeling Objectives:

- Create (1) Baseline and (2) UTEMPRA system & vehicle model
- Analyze system behavior to understand control system design requirements
- Understand impact of changes in component design



NREL Baseline Fiat 500e Model (CoolSIM)

Baseline System Modeling

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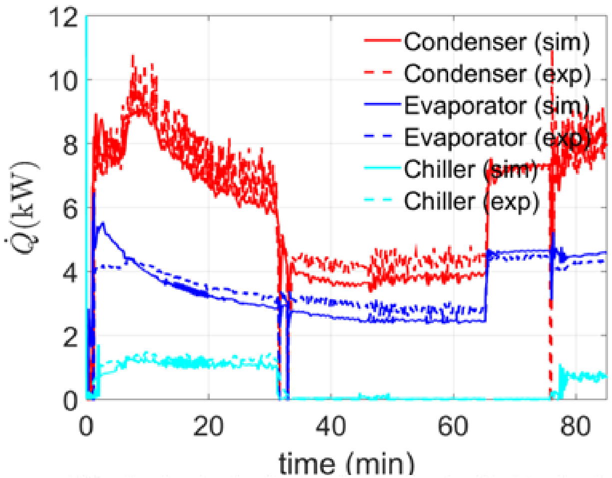

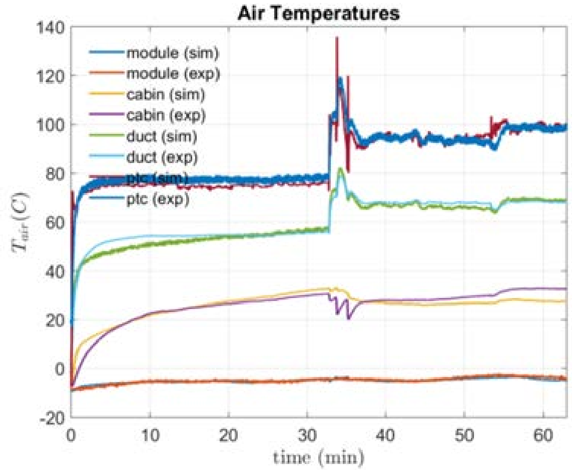

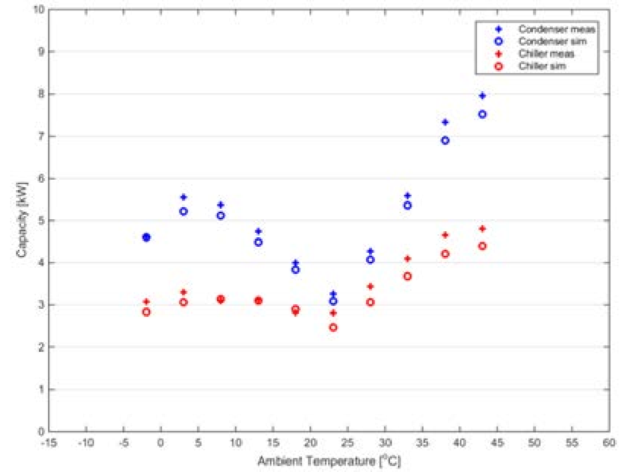

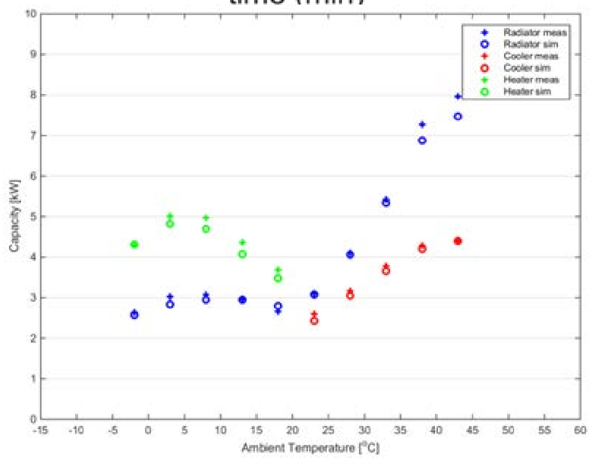

Baseline Model – Simulation vs test data using generic components

Achievements:

- Baseline BEV model is complete (includes mapped heat exchanger and components)
- Cabin, Battery and PEEM thermal response are calibrated with this model for use in UTEMPRA model
- Preliminary UTEMPRA model is complete. MAHLE has provided component mapping data to NREL
- UTEMPRA component sizes will be finalized based on model outcome

UTEMPRA Top Level Model View

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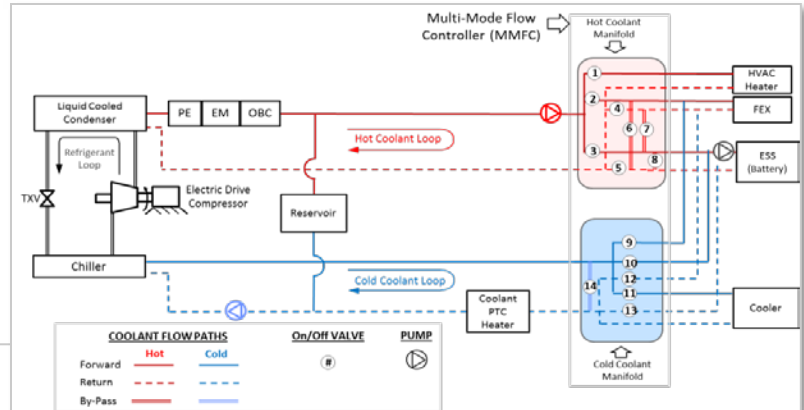
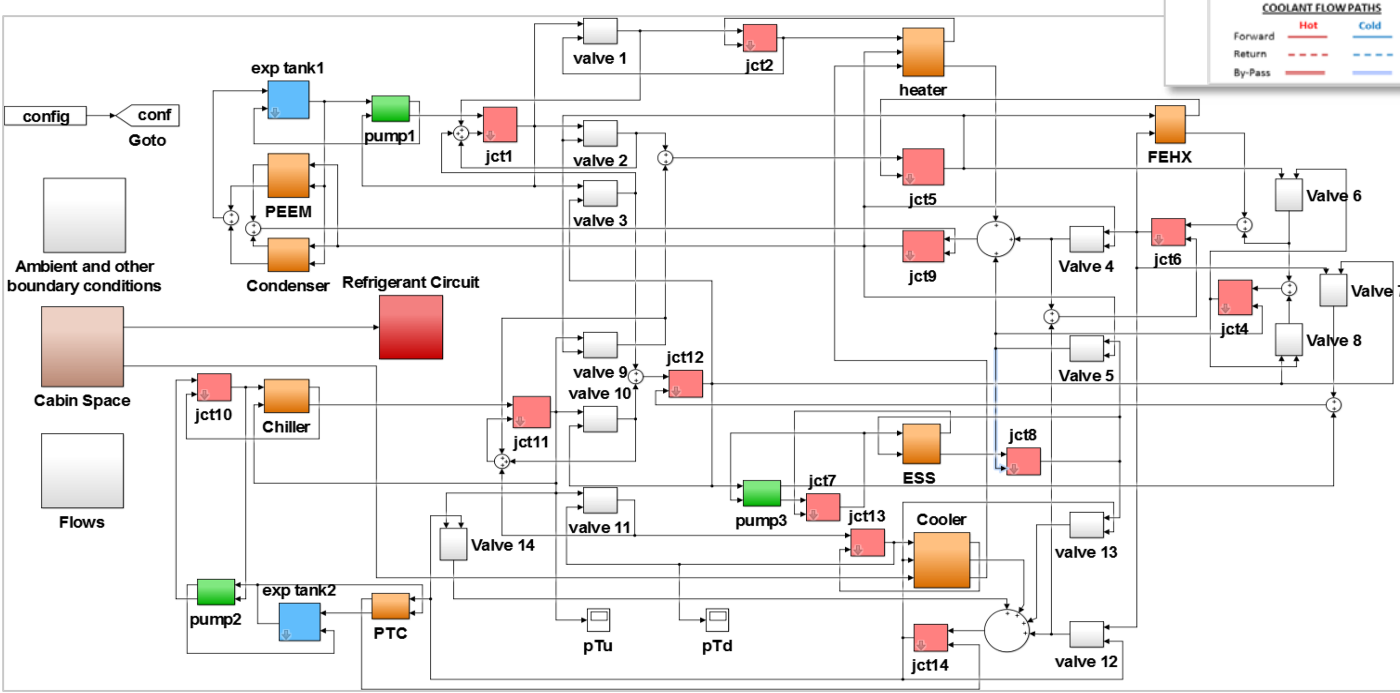
Model represents the system schematic





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Test Case Mode 5: Heat Pump Cabin Heating and Battery Thermal Equalization

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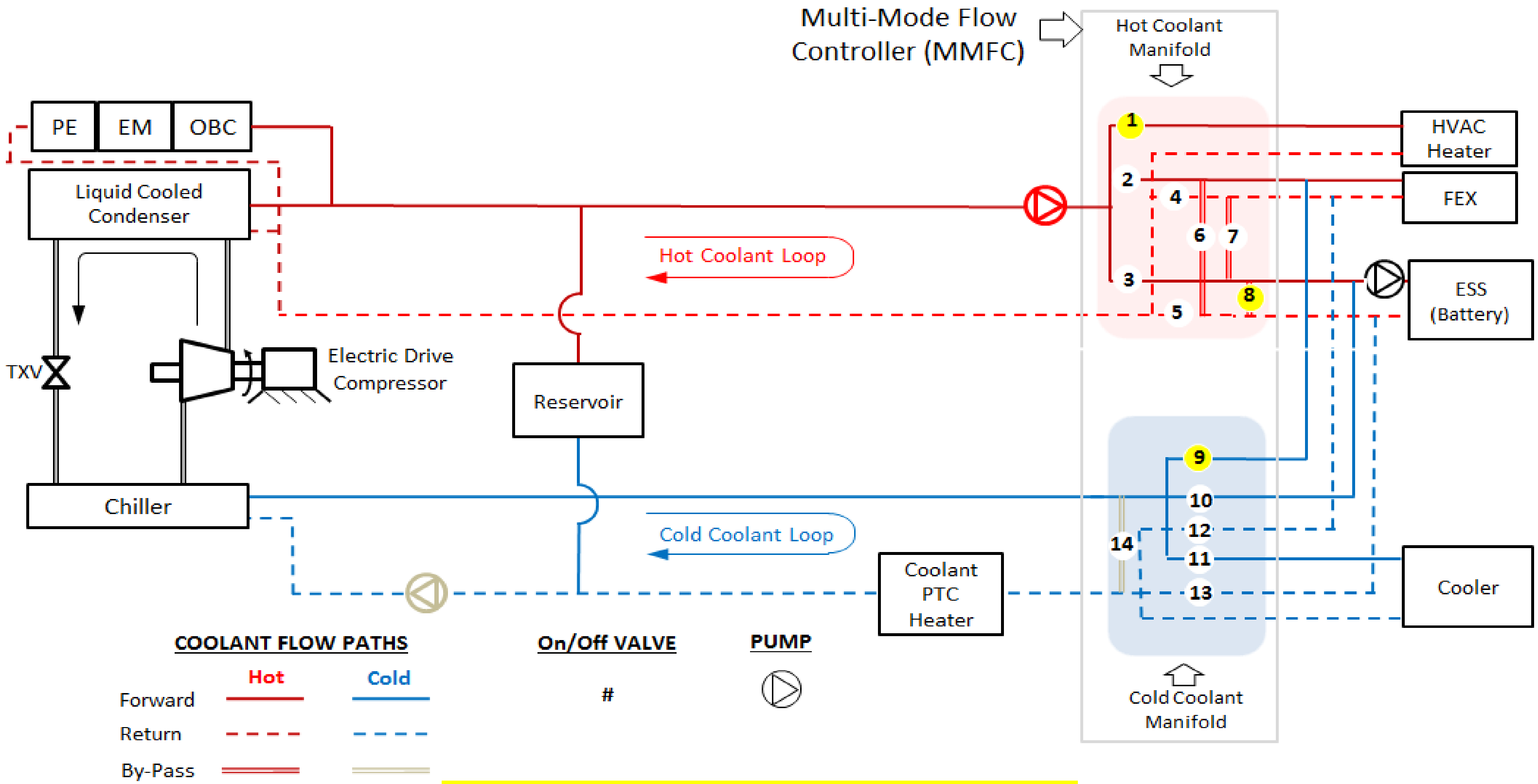

Yellow indicates open valves

Similar to the real system the UTEMPRA model operates with valves to alter modes on-the-fly

Test Case Mode 5: System Dynamics and Control

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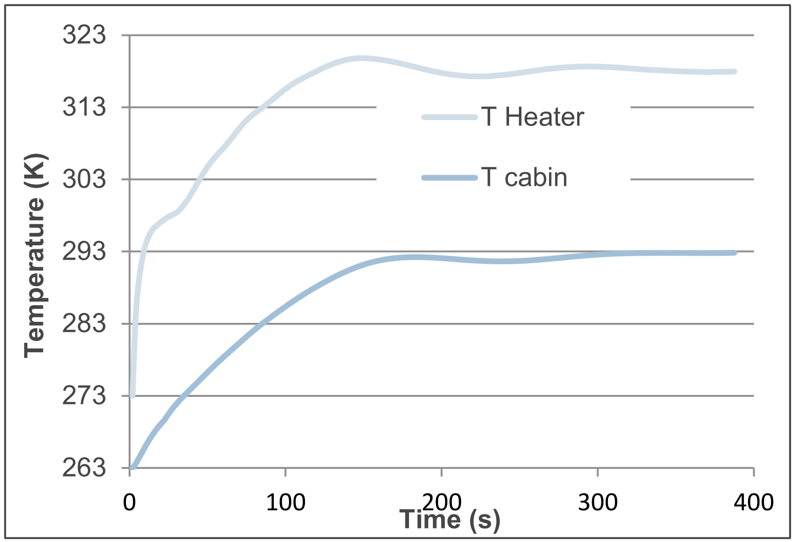
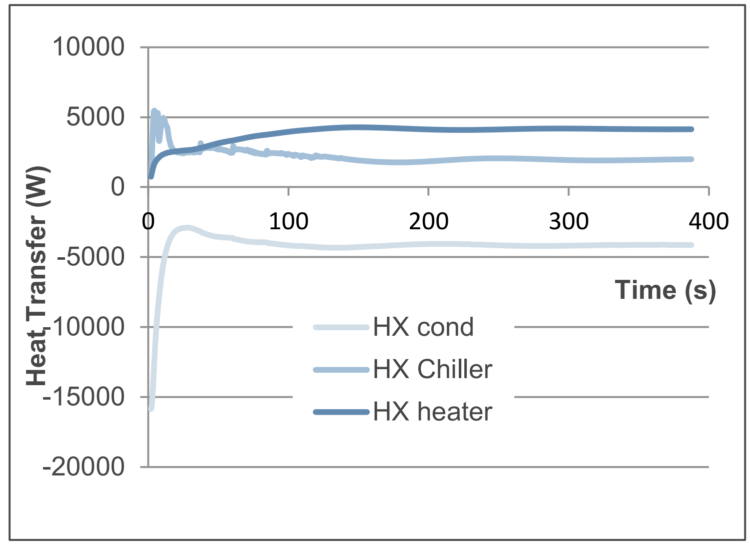
- The compressor RPM is controlled to attain a preset heater discharge temperature of 45°C. Full fresh air. Ambient temperature of -10°C.
- The blower flow rate is constant at 0.075 kg/s



Heater discharge and cabin air temperatures



Condenser, chiller and cabin heater heat exchange rates (capacities)

System controls ensure the preset temperature the cabin air

Test Case Mode 5: Refrigerant P-H and Coolant Loop Pressures

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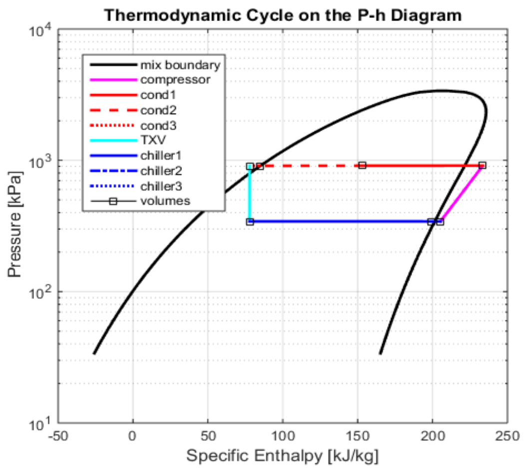

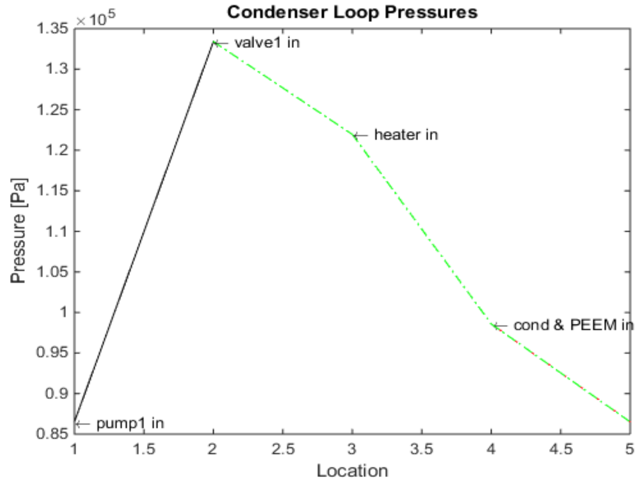

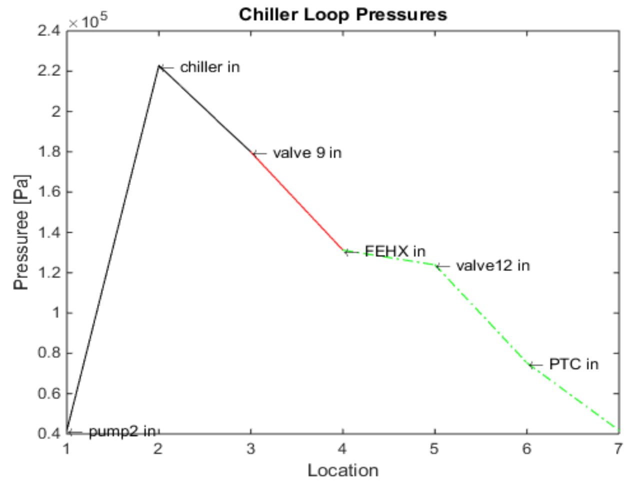

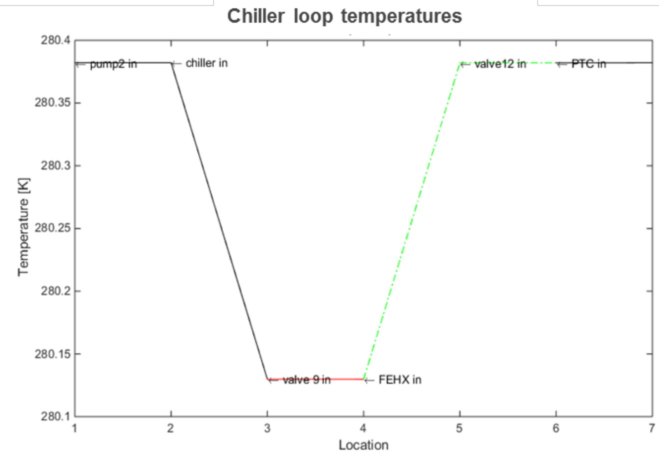

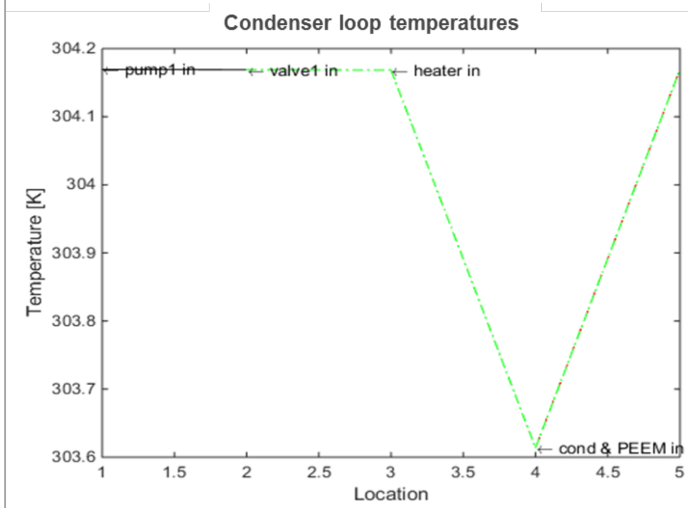

Marked are Inlet locations

Flux-less Brazing Furnace

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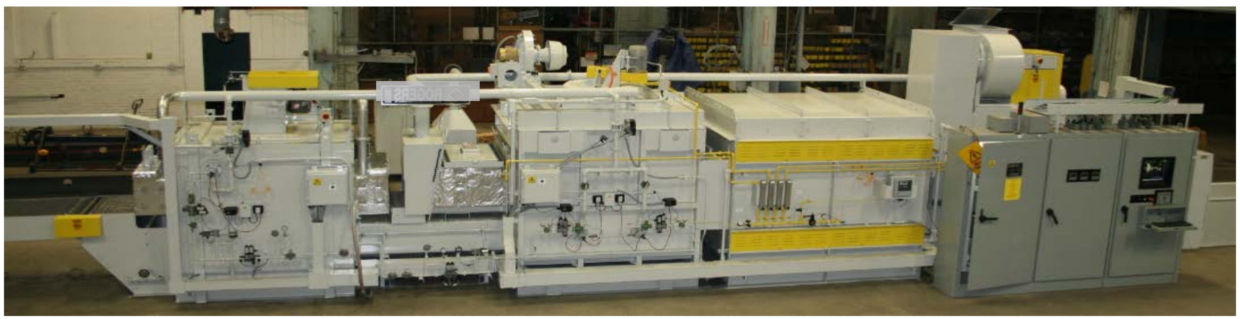
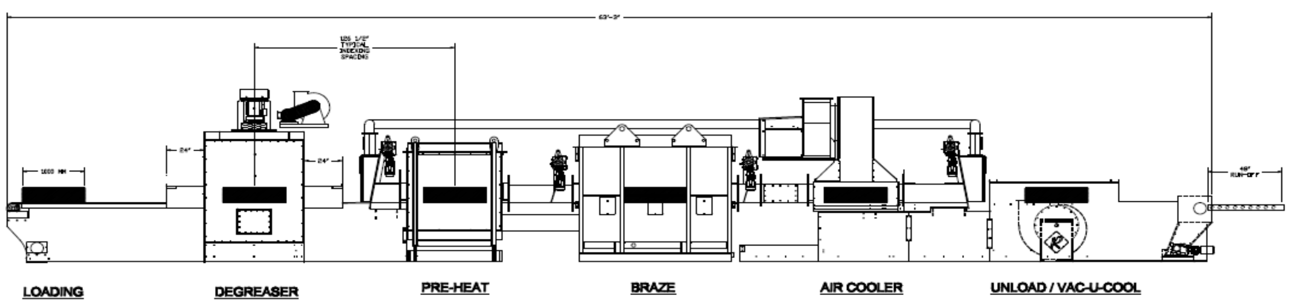
- Furnace supplier has been selected and furnace has been ordered in **June 2015**. Delivery occurred in **March 2016**. Currently the furnace is being installed.
- Furnace has required features to control O_2 levels and can be run in semi-continuous and continuous modes.

Similar 5-Zone Furnace



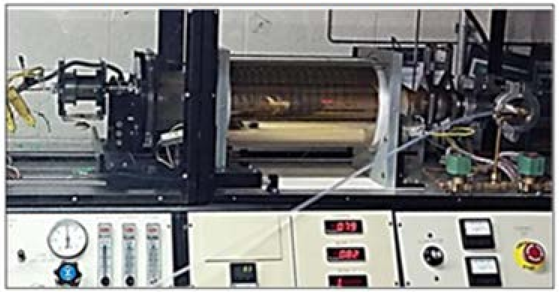
UTEMPRA Furnace Plan



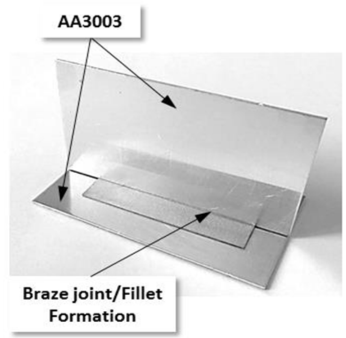
Flux-less Braze Material Selection

Laboratory Glass Furnace

Tube Glass Research Furnace used for fluxfree material development and evaluation

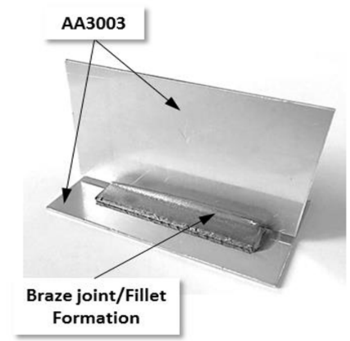


Supplier A



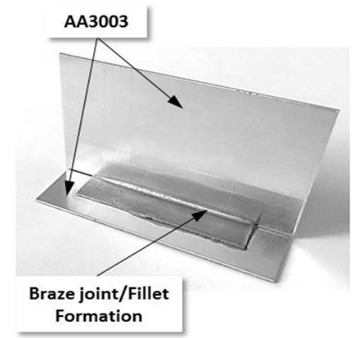
Notes:
1. Fillet size is very small
2. Surface melting is not sufficient
3. Good surface wetting is not noticed
4. Surface discoloration is not noticed
5. Fillet formation between bottom AA3003 and brazing sheet is not noticed

Supplier B



Notes:
1. Fillet size is desired
2. Surface melting is sufficient
3. Good surface wetting is noticed
4. Surface discoloration is noticed
5. Fillet between bottom AA3003 and brazing sheet is not uniform
6. 3 minutes dwell at peak brazing temperature is needed for surface activation

Supplier C



Notes:
1. Fillet size is desired
2. Surface melting is sufficient
3. Good surface wetting is noticed
4. Surface discoloration is noticed
5. Fillet between bottom AA3003 and brazing sheet is uniform
6. Surface activation occurred before peak temperature achieved

Summary:
1. Successful brazing of flux-less materials from three major suppliers: A, B, C
2. Supplier C flux-less material demonstrates a better brazing result based on the preliminary testing and examination

Braze Equipment at Supplier – Qualified

Driven by performance

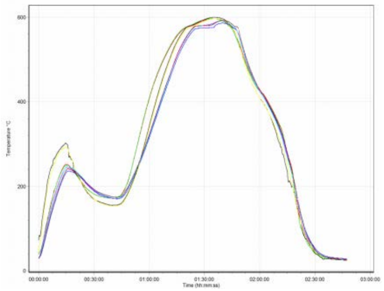
Equipment completed at supplier location end of <u>January 2016</u>

Demonstrated:

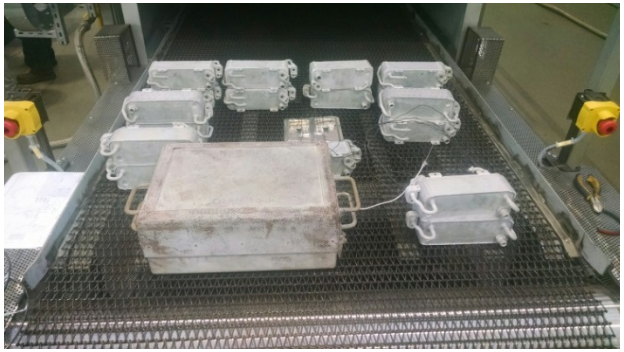
- < 10 ppm of O_2
- < -40°C Dew Point
- Acceptable Thermal profiles Initial qualification complete and accepted January

Equipment prepared for shipment to Lockport

Thermal Profile



Representative furnace loading



Braze Equipment Installation at Lockport

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Response to Previous Years Comments

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- ❑ Most comments are neutral/favorable; comments with some concerns are addressed here

Question 3: Collaboration and coordination with other institutions

- … "collaboration is okay, but could be improved upon with additional OEM input."

RESPONSE: FCA involvement is significant in the beginning and end of the project. FCA participates in bi-weekly meetings and in depth reviews. They have provided full vehicle CAD information & vehicle requirements and guided/approved packaging and electrical changes to vehicle. Their main participation will be in vehicle range testing and road trials for final estimate of range benefit.

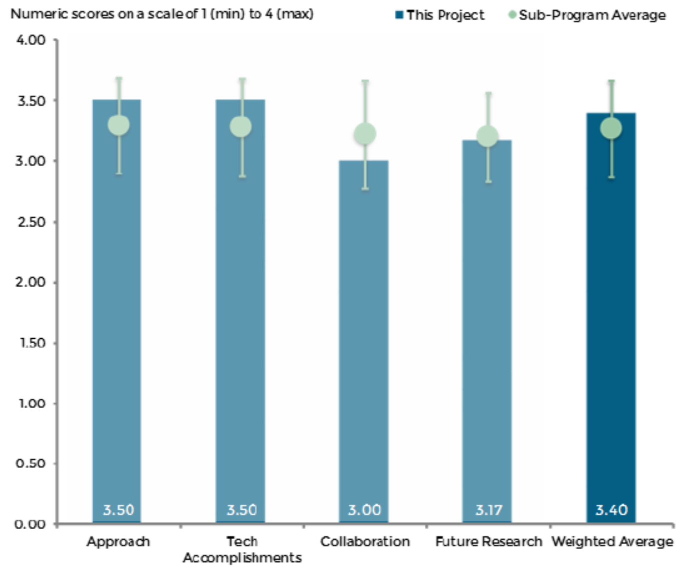
- … "commercial viability may require additional information about regional benefits and sensitivity to actual consumer usage profiles"

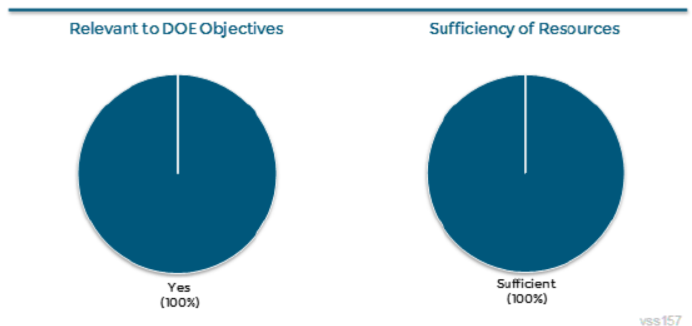
RESPONSE: UTEMPRA package will not be an "add on" option and will be integral to vehicle design available to all regions. FCA and other OEMs have shown interest in such an integrated thermal management system with wide-ranging benefits (compactness, reduced refrigerant use, highly controllable etc.) MAHLE had knowledge and expertise in determining competitive pricing and performance of components and system.

Question 6: Sufficiency of resources to meet milestone on time

- … "the progress is good and the plan is sound, the lack of novel technologies indicate that the system integration and packaging study are main deliverables….. the layered heat exchanger and unique braze process will be novel"

RESPONSE: Novelties are in development of (a) MMFC and coolant network control algorithm, (b) system integration & packaging and (c) layered heat exchangers devoid of flux residues. The proposed project intends to take it from TRL=3 to 7 with ensuring commercialization of this technology being the underlying theme.





2015 UTEMPRA scores

Summary of Technical Accomplishments in BP1 & BP2 (Partial)

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- Baseline BEV climatic wind tunnel testing was completed and reviewed with FCA. These provide performance targets for UTEMPRA system. (**MAHLE**, **FCA**)
- System design is complete with system modes identified for proof-of-concept build. (**MAHLE**, **NREL**, **Norgren**)
- Components have been identified/designed. Final sizing is being verified with simulation model. (**MAHLE**, **NREL**)
- MMFC design is reconfigured. Prototype design is nearly final. (**Norgren**, **MAHLE**)
- Baseline system model is completed. UTEMPRA model is complete and being refined. (**NREL**, **MAHLE**)
- Plumbing and location of components in vehicle components are established. Fixture designs are currently being worked on. (**MAHLE**, **FCA**)
- Flux-less Braze Furnace is received and installed. Flux-less material has been chosen based on coupon tests (**MAHLE**)

Risk Management

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- On the technical development side, the design of the UTEMPRA system continues to be on target.

- Commercial and technical viability of the MMFC:
  - After detailed systems tests, check valves and single-operator valves will be needed for flow isolation of the loops. Prototype design will have two levels. Level 1 is near complete. Level 2 will be mass manufacturable version (i.e. final version) with plastic body.
  - MMFC remains commercially viable

- Several suppliers of flux-less materials are considered. Coupon tests indicate commercially viable material possible.

- Furnace specification and design was reviewed a large team of braze experts and CAE tools (CFD, FEA) were used to understand key parameters for furnace loading and control sensors inside the furnace

- Program Management meetings are being conducted every 2 weeks to manage the project, ensure quality, and document/address action items. Additional bi-weekly meetings with Norgren and NREL to address technical issues. In depth technical reviews with FCA are conducted as needed.

Issues/Roadblocks

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- There are no major issues considered as roadblocks at this time.
  - An update of systems cost is needed with new design update of MMFC to ensure commercial viability
  - The projected spending is within 6% of the total budget.
  - The project is about 1 month behind in timeline.

It is our intent to maintain the quality of the project while being judicious use of salary hours.

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Thank you !

Technical Backup Slides

Vehicle Baseline Testing

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UTEMPRA Fiat 500e - Baseline Vehicle Thermal Performance Tests						
Test I.D.	Tunnel 2 (Hot Ambient)					
	Date	Refrigerant	Test Name	Karti	IBOX	Tunnel Data
1	2/13/2015	R134a	Charge Determination	x	unavail.	1500442-02
2	2/16/2015	R134a	CD25 (Trial 1) at 43.3Cx19%rhx1000W/m2-solar	x	unavail.	1500442-03
3	2/16/2016	R134a	CD25 (Trial 2)	x	unavail.	1500442-04
4	2/17/2015	R134a	CD25 (Trial 3)	x	unavail.	1500442-06
5	2/17/2015	R134a	ACC Cooldown at 43.3Cx19%rhx1000W/m2-solar	x	unavail.	1500442-05
	2/17/2015	----------- Swapped production TXV with R1234yf TXV (FCA-provided) -----------				
6	2/18/2015	R1234yf	Charge Determination	x	unavail.	1500442-08
7	2/18/2015	R1234yf	CD25 (Trial 1) (Probably excess charge)	x	unavail.	1500442-09
8	2/19/2015	R1234yf	Charge Determination @ Zero Speed & 0.1 lb step	x	unavail.	1500442-10
9	3/16/2015	R1234yf	Charge Determination @ Zero Speed & 0.05 lb step	x	x	1500442-11
10	3/18/2015	R1234yf	CD25 with 1.32 lb charge (2 high-side lines) (Trial 2)	x	x	1500442-13
11	3/19/2015	R1234yf	ACC25-72F Cooldown at 43.3Cx19%rhx1000W/m2-solar (Full Depletion)	x	x	1500442-15
12	3/23/2015	R1234yf	ACC25-72F Cooldown at 35Cx40%rhx800W/m2-solar (Partial Depletion)	x	x	1500442-17
13	3/23/2015	R1234yf	ACC25-72F Cooldown at 25Cx60%rhx300W/m2-solar (Partial Depletion)	x	x	1500442-18
	3/24/2015	---------- Change-over to Tunnel 5 -----------				
	Tunnel 5 (Cold Ambient)					
14	3/25/2015	NA	HTRWU at -10C	x	x	1501415-02
15	3/25/2015	NA	ACC Warmup at 0C (Partial Depletion)	x	x	1501415-03
16	3/25/2015	NA	Vehicle Charging at -10C	x	x	NA
17	3/26/2015	NA	HTRWU (Repeat) at -10C	x	x	1501415-04
18	3/26/2015	NA	ACC25-72F Warmup at -10C (Full Depletion)	x	x	1501415-05
19	3/27/2015	NA	ACC25-72F Warmup at +20Cx80%rhxZero Solar (Full Depletion)	x	x	1501415-06

UTEMPRA System Modes

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Mode	Mode description	Valves OPEN	Valves ENERGIZED	Pumps Operating	PTC Heater Operating	Compressor Operating
1	Fail Safe	2,4,6,7	None	ESS, Hot	No	No
2	PEEM cooling	2,4	6-7	Hot	No	No
3	ESS equalization [plus PEEM cooling]	2,4,8	6-7,8	ESS, Hot	No	No
4	ESS equzliation and cabin cooling	2,4,8,11	6-7,8,11	ESS, Hot, Cold	No	Yes
5	ESS equzliation and cabin heating	1,8,9,12	1,2-4,6-7,8,9-12	ESS, Hot	No	Yes
6	ESS equalization and cabin heating and cabin cooling	1,8,9,11,12	1,2-4,8,11,9-12	ESS, Hot, Cold	Yes/No	Yes
7	ESS passive cooling	2,4,6,7	None	ESS, Hot	No	No
8	ESS passive cooling and cabin cooling	2,4,6,7,11	11	ESS, Hot, Cold	No	Yes
9	ESS passive cooling and cabin heating	1,6,7,14	1,2-4,14	ESS, Hot, Cold	Yes/No	Yes
10	ESS passive cooling and cabin heating and cabin cooling	1,6,7,11	1,2-4,11	ESS, Hot, Cold	Yes/No	Yes
11	ESS active cooling	2,4,10,13	6-7,10-13	ESS, Hot, Cold	No	Yes
12	ESS active cooling and cabin cooling	2,4,10,11,13	6-7,11,10-13	ESS, Hot, Cold	No	Yes
13	ESS active cooling and cabin heating	1,9,10,12,13	1,2-4,6-7,9-12,10-13	ESS, Hot, Cold	No	Yes
14	ESS active cooling and cabin heating and cabin cooling	1,9,10,11,12,13	1,2-4,6-7,9-12,10-13,11	ESS, Hot, Cold	No	Yes
15	ESS active heating	3,5,9,12	2-4,3,5,6-7,9-12	ESS, Hot, Cold	Yes	Yes/No
16	ESS active heating and cabin cooling	3,5,9,11,12	2-4,3,5,6-7,9-12,11	ESS, Hot, Cold	Yes	Yes
17	ESS active heating and cabin heating	1,3,5,9,12	1,2-4,3,5,6-7,9-12	ESS, Hot, Cold	Yes	Yes
18	ESS active heating and cabin heating and cabin cooling	1,3,5,9,11,12	1,2-4,3,5,6-7,9-12,11	ESS, Hot, Cold	Yes	Yes
19	ESS NTM and cabin cooling	2,4,11	6-7,11	Hot, Cold	No	Yes
20	ESS NTM and cabin heating	1,9,12	1,2-4,6-7,9-12	Hot, Cold	Yes	Yes
21	ESS NTM and cabin heating and cabin cooling	1,9,11,12	1,2-4,6-7,9-12,11	Hot, Cold	Yes/No	Yes
22	De-ice	1,2,4,10,13	1,6-7,10-13	ESS, Hot, Cold	Yes	Yes