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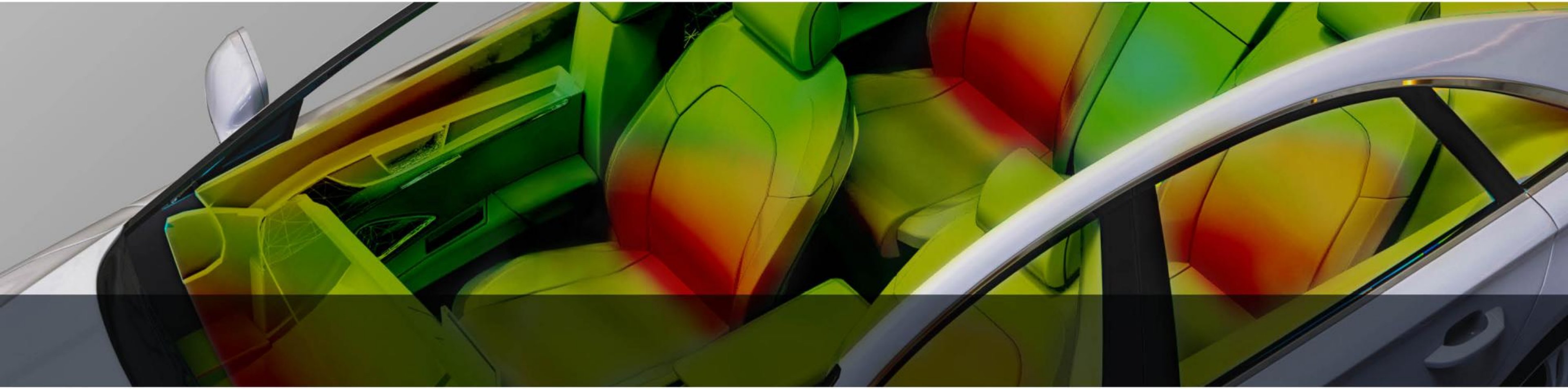

Thermal Management Systems Symposium

Co-located with SAE Energy & Propulsion Conference & Exhibition

October 14-15, 2025 | Ypsilanti, Michigan

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Thermal Management & HVAC

PFAS Ban: Impact on Thermal System Development

Agenda

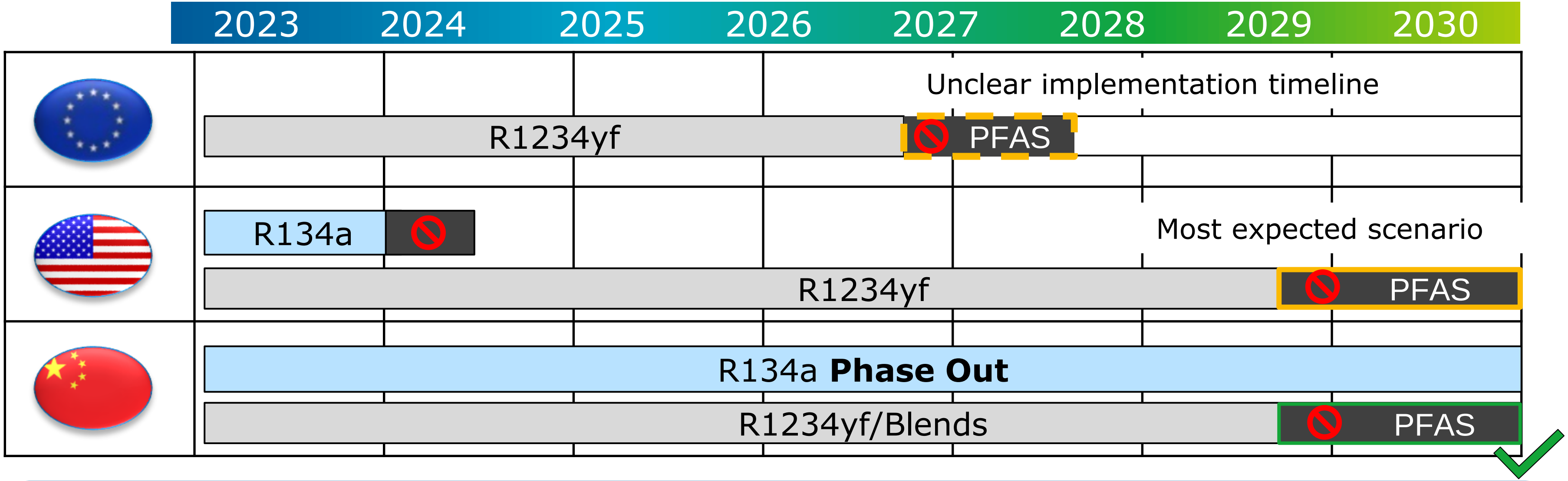
1. Overview PFAS BAN
2. Challenges with Alternative Refrigerant
3. R1234yf vs. R290 vs. R744
4. Benchmark and ID4 Vehicle Model
5. Control Software: Predictive Cabin Thermal Management

Chapter 1

Overview PFAS BAN

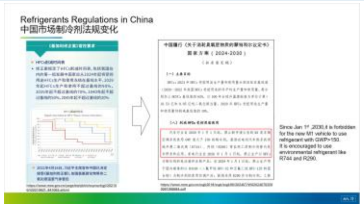
PFAS Restrictions / ban

Overview – (expected) timeline



PFAS ban not 100% clear.

- China legislation already implemented PFAS ban from 2029
- in US seems to be similar like China
- in EU still a risk of earlier implementation

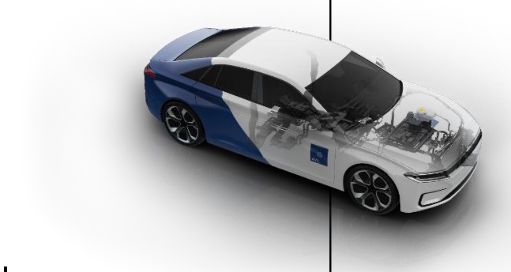


Chapter 2

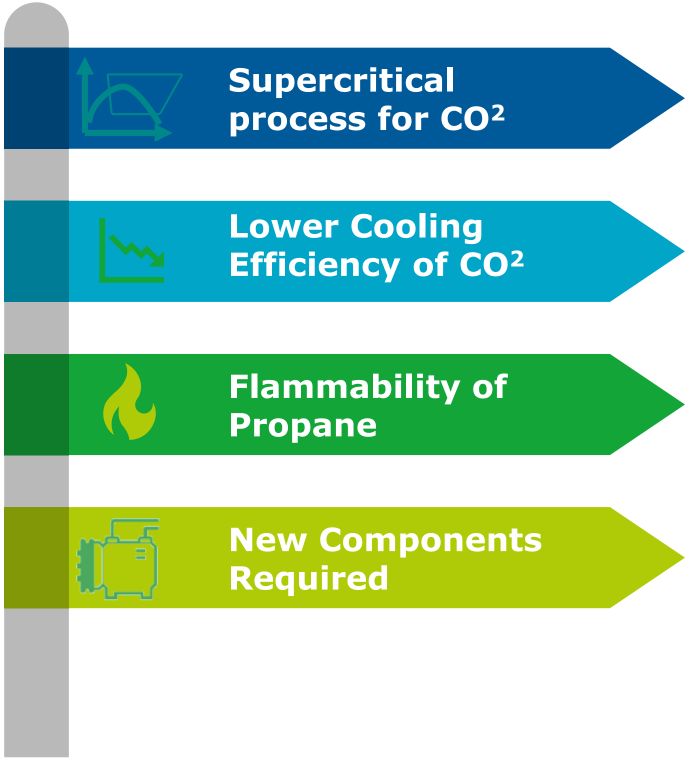
Challenge PFAS Restriction

Challenges With Alternative Refrigerants

- Extreme **challenging timing**
- Definitive **enforcement in China**
  - US seems to follow
  - EU still risk of earlier implementation
- **Component** Challenge
  - adaptation of components due to new refrigerant.
- **Integration** Challenge
  - high potential for entire system change/development – similar to completely new system integration
  - Vehicle integration boundaries – NVH, safety – crash



Challenges Alternative Refrigerants



Supercritical > 31°C

The supercritical process required the control on optimum high pressure instead of subcooling or superheating. No high-pressure receiver possible. Heat cannot be transferred a constant temperature to other sinks.

≈ 30% lower efficiency at > 35°C

Internal heat exchanger is a must. Suage for hot markets to be evaluated in detail.

Flammability >2% vol% at 470°C

Low ignition energy leads to high risk. Only low amount of filling mas expected but no clear limit yet defined. Currently just indirect system under detailed evaluation.

Compressor
EXV
Pipes and Sealings

Especially for CO^2 are new components required which could handle operating pressure up to 120 bar.

Safety Concept

R744

- Pressure release valve at low- and high-pressure side of compressor
- Pyrotechnical element to isolate cabin heat exchanger from rest of system to avoid CO_2 inflow to cabin in case of crash scenario
- CO2 sensor in co-driver footwell area

R290

- IEC 60335-2-89: Standard for commercial refrigerant circuits → max. 150g filling mass without any additional legal required safety measures such as forced air flushing and leakage detection
- Integrity against crash → pure indirect system with less critical crash area within the vehicle

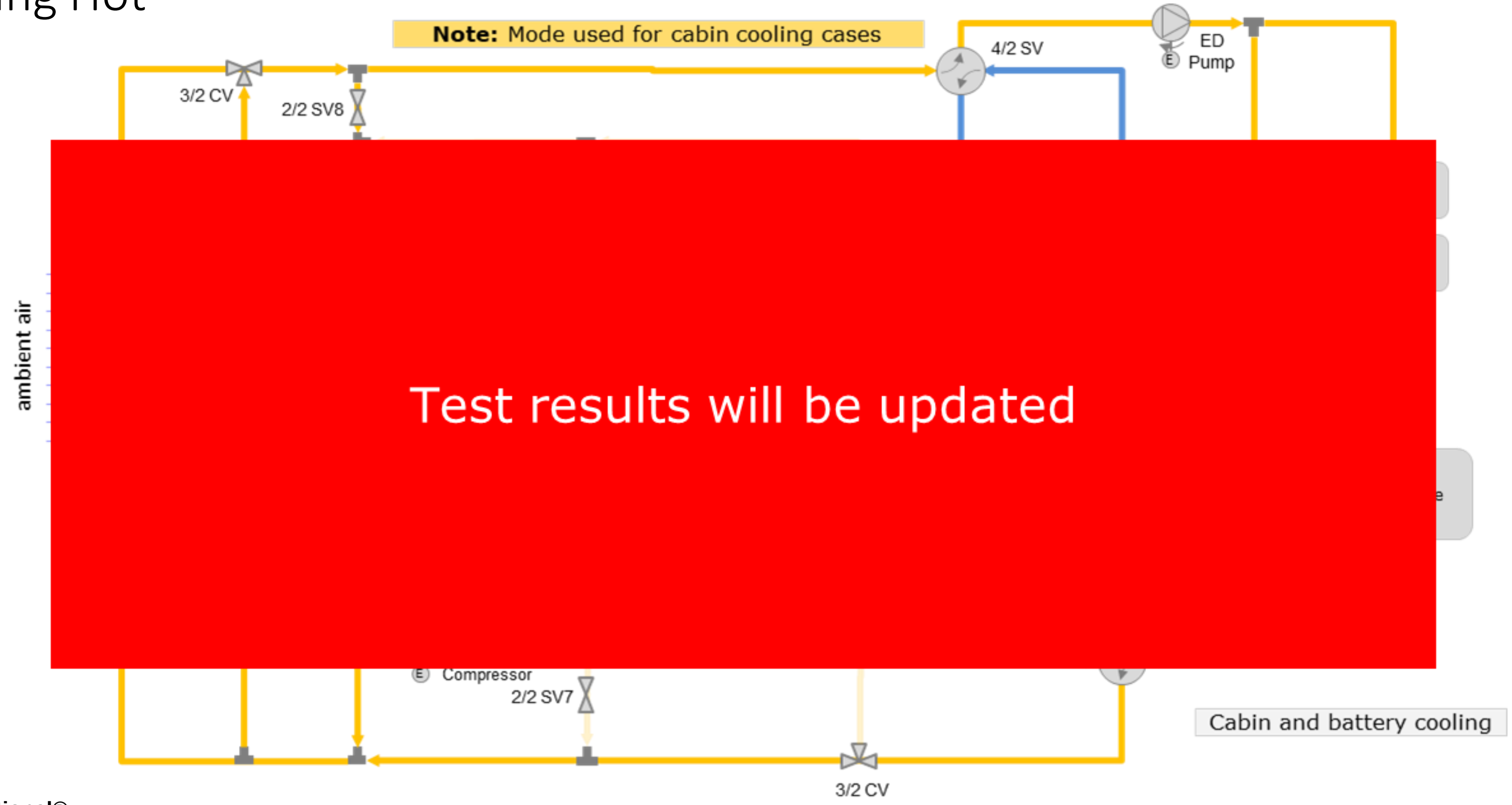
Chapter 3

R1234yf vs. R290 vs. R744

R290 Thermal Architecture

Battery coolant circuit
E-drive coolant circuit
Heating coolant circuit
A/C refrigerant circuit

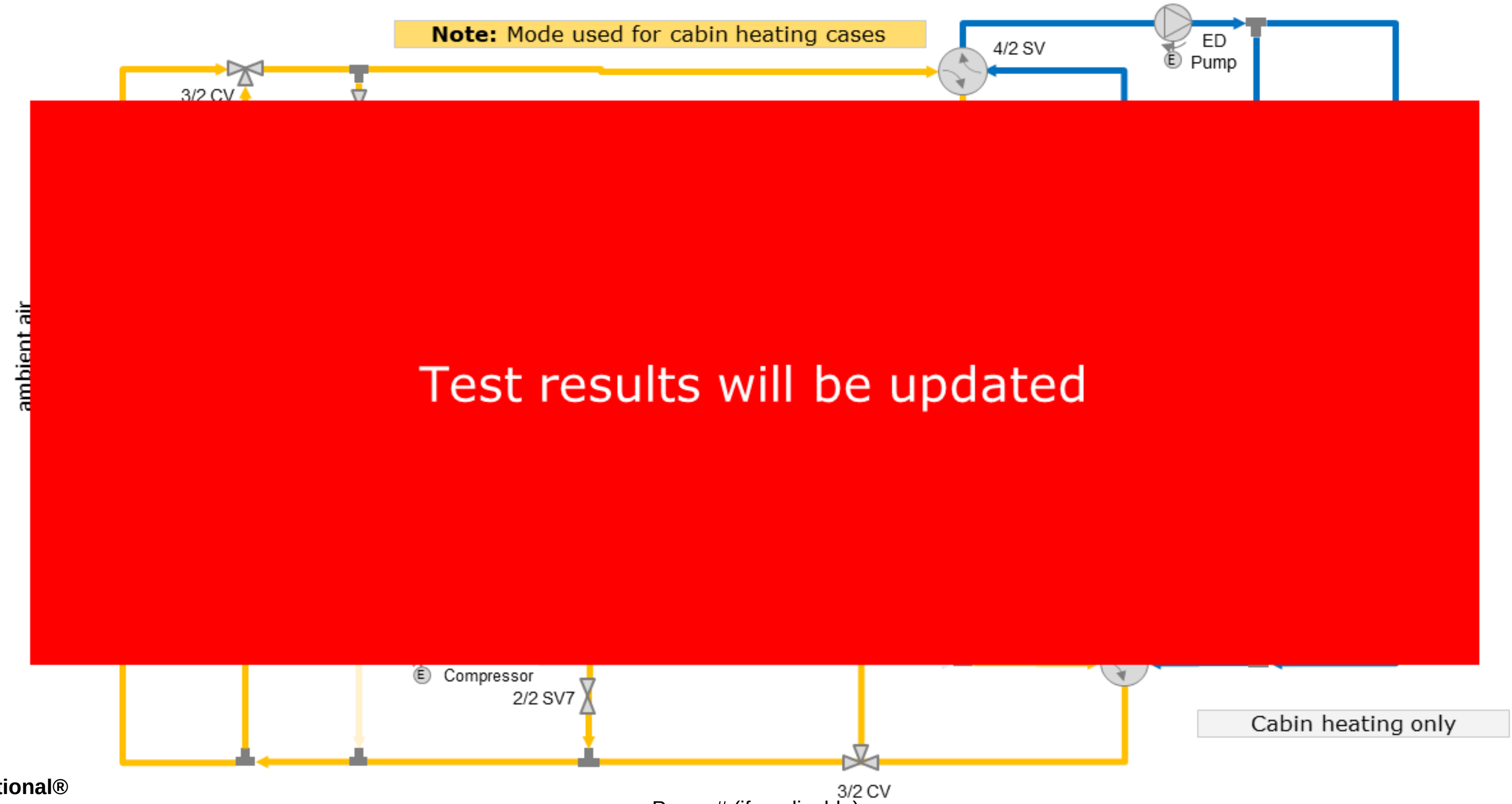
Cooling Hot



R290 Thermal Architecture

Battery coolant circuit
E-drive coolant circuit
Heating coolant circuit
A/C refrigerant circuit

Cabin Heating HP Ambient

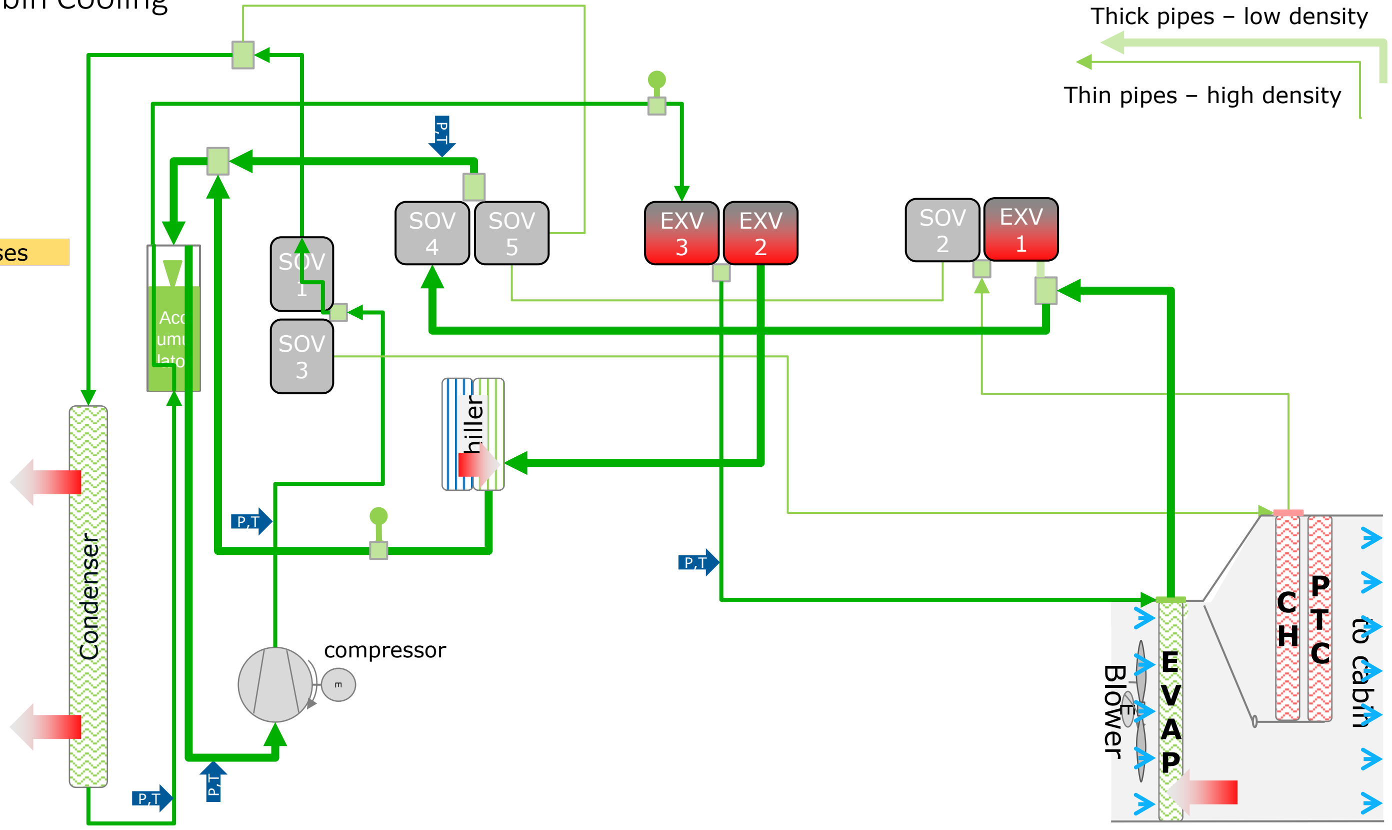


Thermal Management Functionalities

A/C System: Battery and Cabin Cooling

Both cabin and chiller cooling are active in combination.
Expansion is operated by EXV 2 and EXV 3 and heat is rejected to ambient in the outer condenser/gas cooler.

Note: Mode used for cabin cooling cases

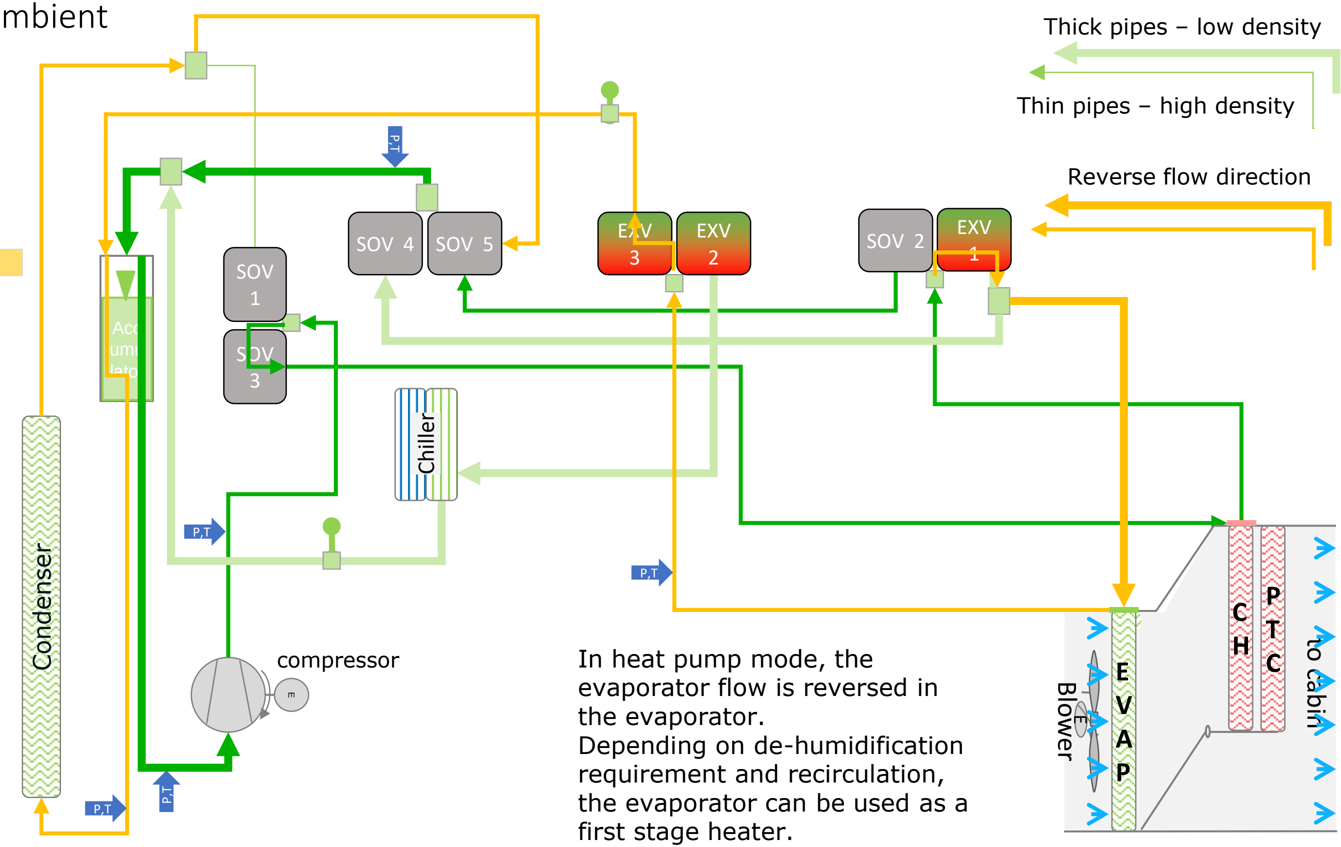


Thermal Management Functionalities

A/C System: Heat Pump with ambient

Heat pump is active for heating the cabin with heat recovered from ambient.
Heat first generated in the compressor is released to the cabin by the cabin air heater.

Note: Mode used for cabin heating cases

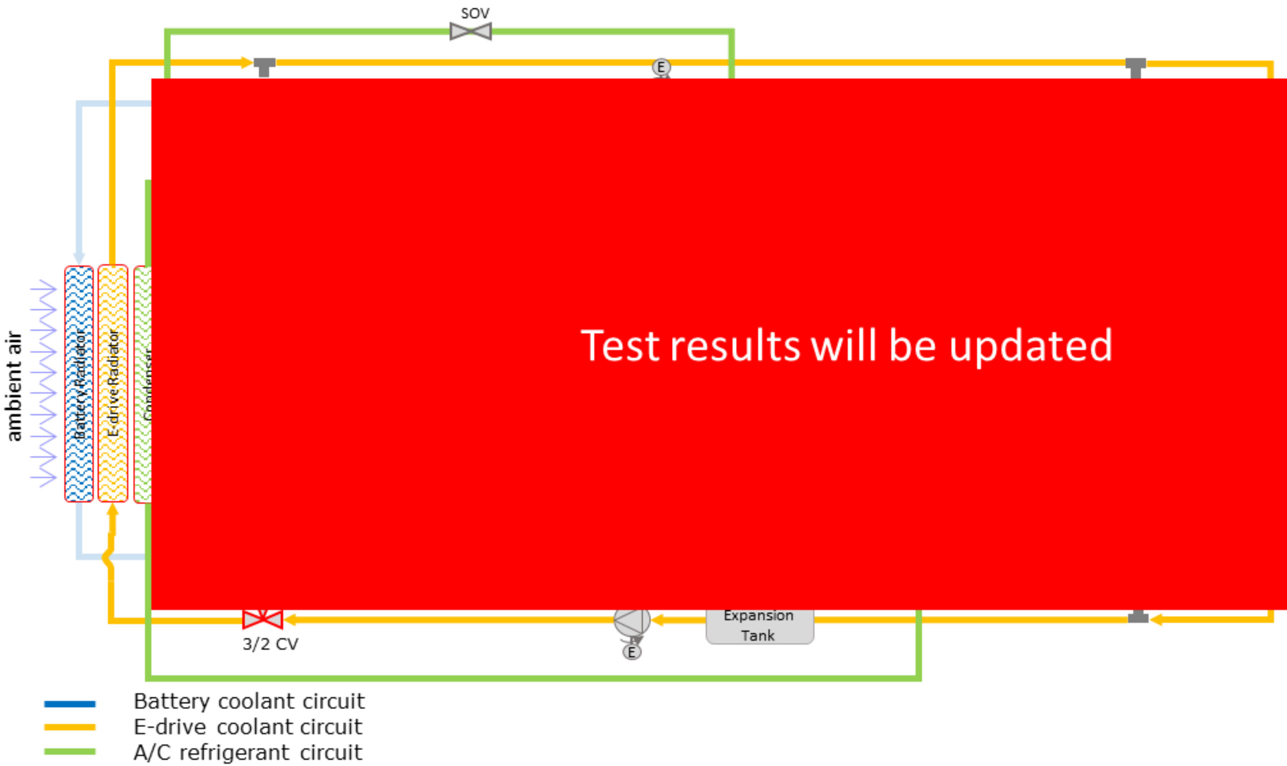


For heat recuperation from the ambient, flow through the outer heat exchanger is reversed.

In heat pump mode, the evaporator flow is reversed in the evaporator.
Depending on de-humidification requirement and recirculation, the evaporator can be used as a first stage heater.

Analysis Model Variant 2 (Hyundai Kona)

Cooling Cabin + HV Battery

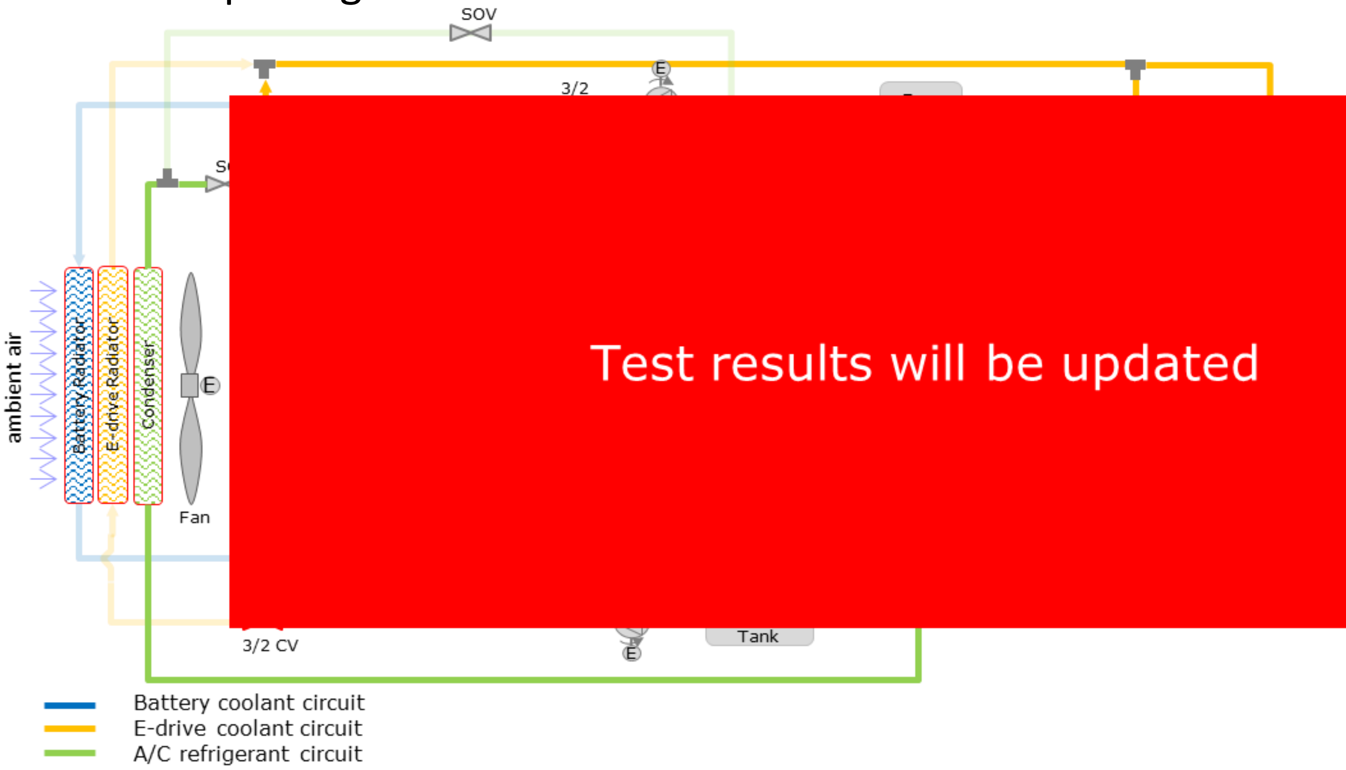


Test results will be updated

	Var 2
…olant e-	
…ir e-heater	
…irect	
…ater	
…bience	
…wertrain	
…direct waste	
…er	
…nser	
Heating with E-drive	

Analysis Model Variant 2 (Hyundai Kona)

Heat Pump using Ambience



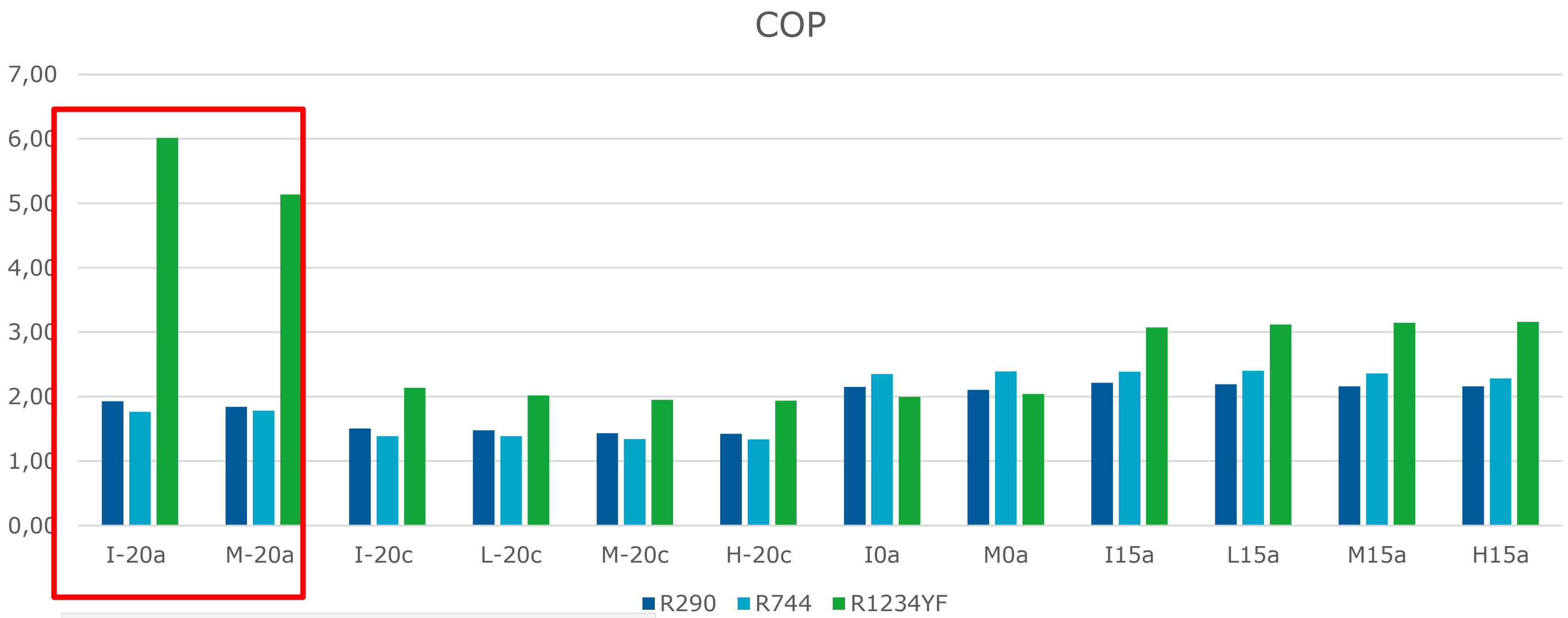
	Var 2
Cabin heating with coolant	
-	
ct	
er	
nce	
ect	
r	
Heating with E-drive	

Boundary Conditions - Cabin Cooling

	Outdoor Conditions				Indoor Conditions				HV Battery	E-Motor
Test Name	Amb Temp	Vehicle Speed	HX Temp Air In	Max Air Velocity	HX Temp Air In	Relative Humidity	Air Flow Rate	Target Temp at HX Air Off	Heat Generated	Heat Generated
	[°C]	[km/h]	[°C]	[m/s]	[°C]	[%]	[kg/min]	[°C]	[kW]	[kW]
I25c	25	0	25	1.5	30	50	6.5	3	0.1	0
M25c	25	80	25	3	30	50	6.5	3	1	1
H25c	25	120	25	4	30	50	6.5	3	1.5	2
I35a	35	0	35	1.5	35	40	9	3	0.1	0
M35a	35	80	35	3	35	40	9	3	1	1
H35a	35	120	35	4	35	40	9	3	2	2
I45	45	0	45	1.5	35	25	9	3	0.1	0
M45	45	80	45	3	35	25	9	3	1	1
H45	45	120	45	4	35	25	9	3	2	2

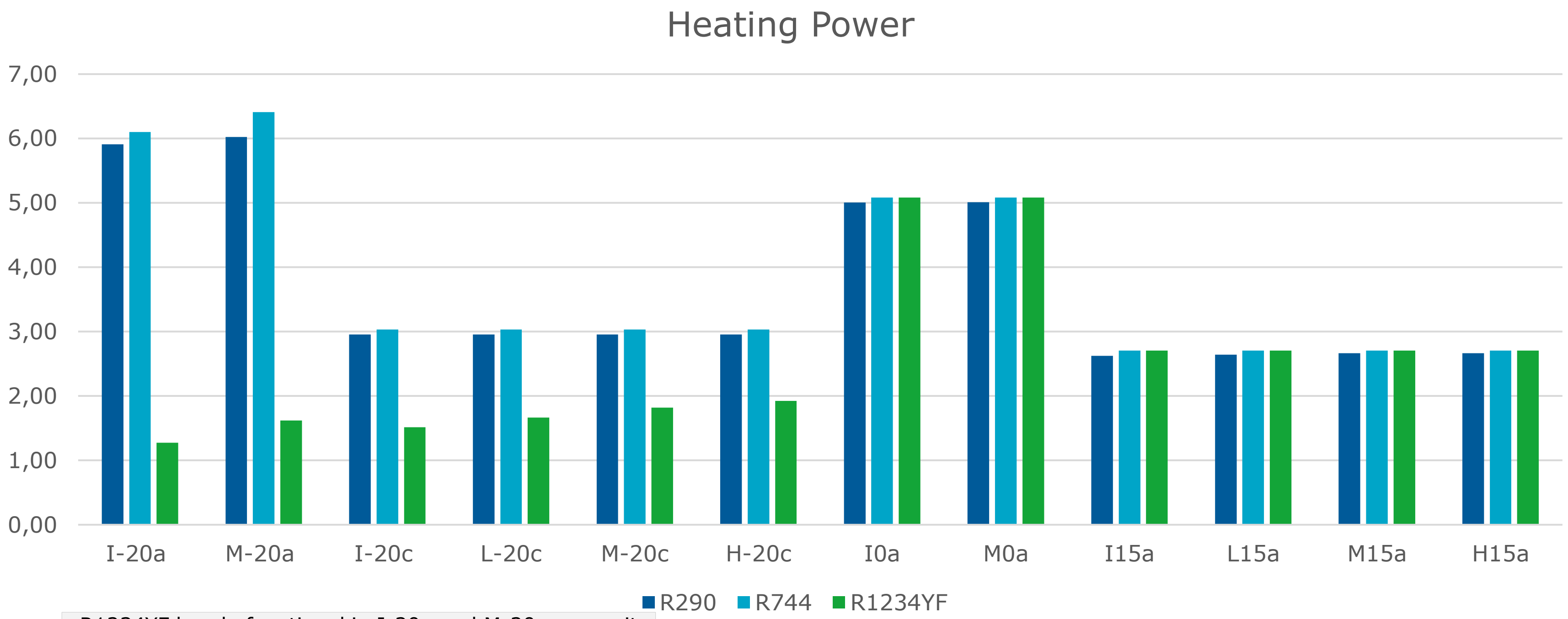
Same humidity for outdoor conditions considered as prescribed for indoor conditions.

Cabin Heating - COP [-]



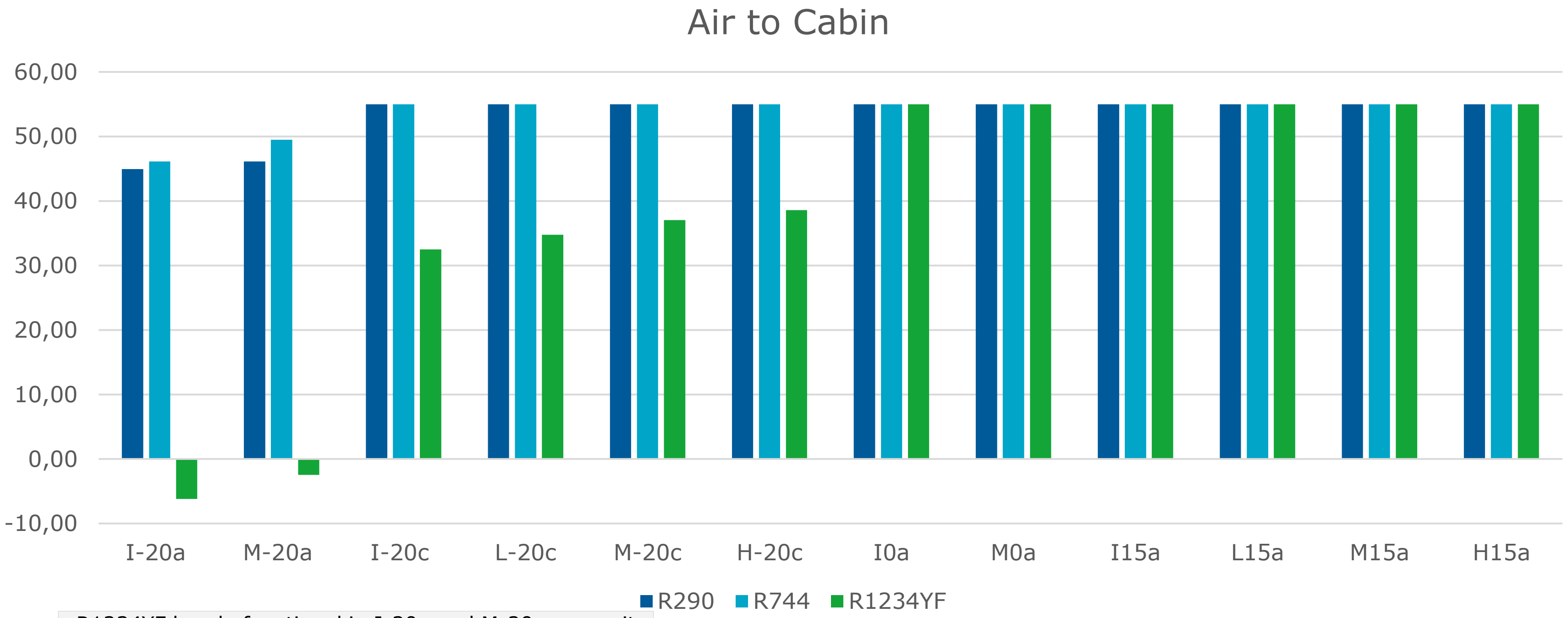
R1234YF barely functional in I-20a and M-20a cases, it also does not achieve the target air to cabin temperature in rest of the -20°C cases.

Cabin Heating - Heating Power [kW]



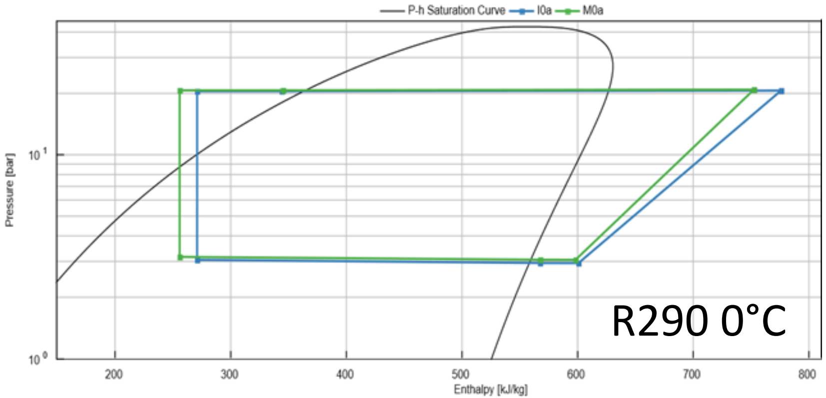
R1234YF barely functional in I-20a and M-20a cases, it also does not achieve the target air to cabin temperature in rest of the -20°C cases.

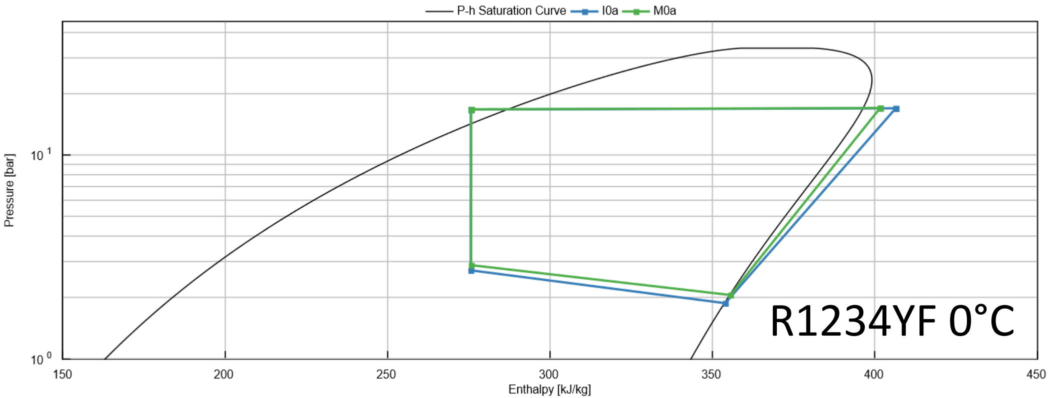
Cabin Heating - Air To Cabin Temperature [°C]

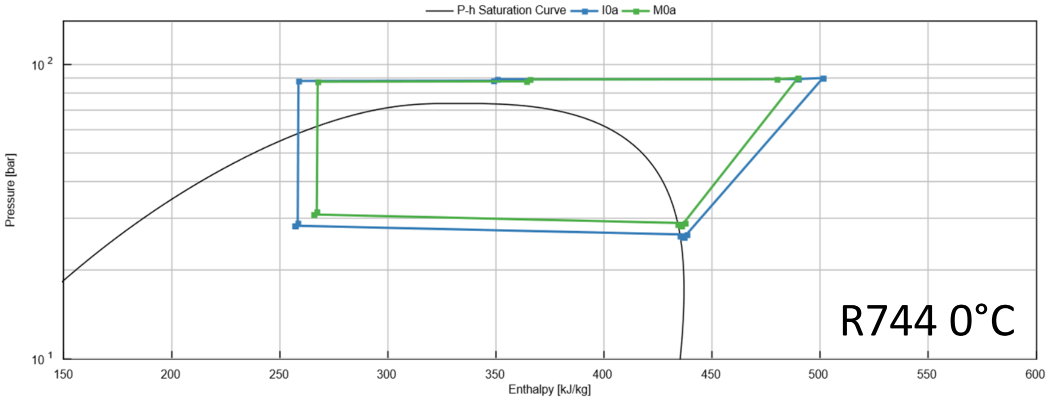


R1234YF barely functional in I-20a and M-20a cases, it also does not achieve the target air to cabin temperature in rest of the -20°C cases.

R290 vs. R744 vs. R1234YF at 0°C







Chapter 4

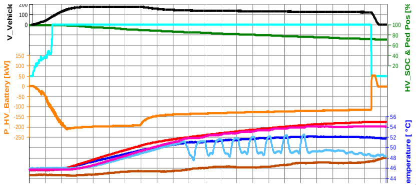
Benchmark and ID4 Vehicle Model

VTMS Simulation Methodology

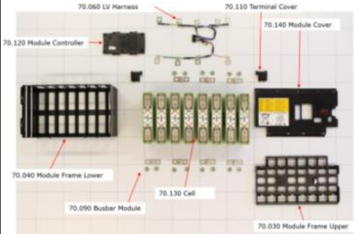
based on **Benchmark** and **Simulation** Studies

WP2: Powertrain and Thermal

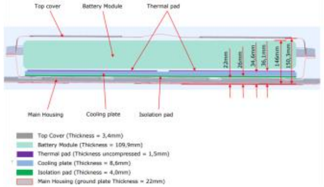
- Cell temperature traces
- Current limitation strategy



WP6: Tear Down

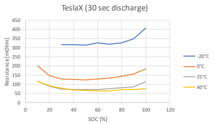


- Detailed Geometry
- Material Data

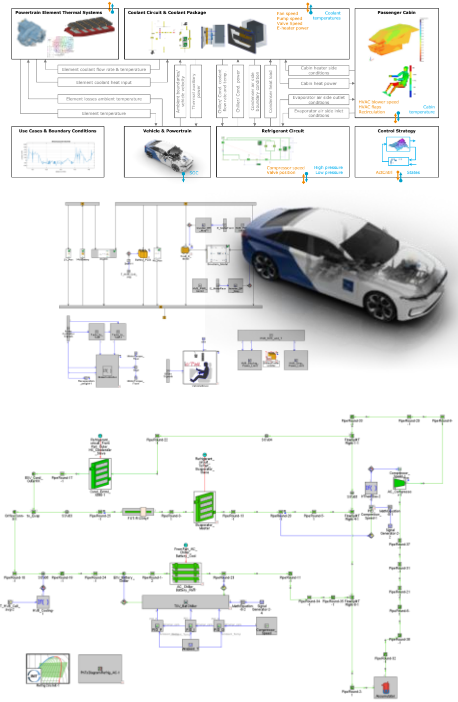


WP8: Cell Testing

- Open Circuit Voltage
- Cell Resistance



Simulation Model



Reuse of models in customer projects for cooling system development

Vehicle Main Data

VW ID.4 GTX 2021

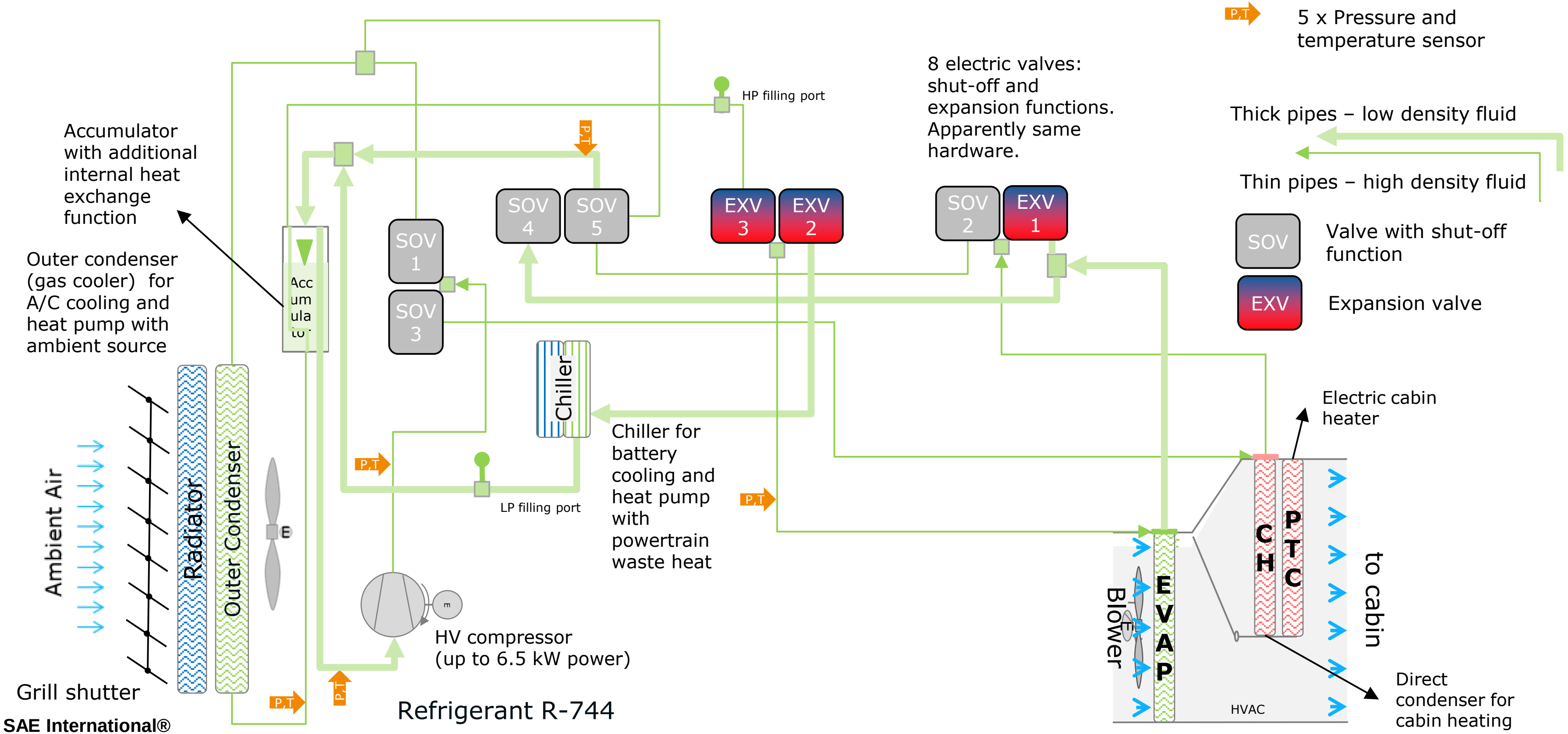
SUV

All wheel drive

With Heat-pump

Vehicle Data	Max. System Power/Torque	kW/Nm	220/460
	Max. Power/Torque, front	kW/Nm	80/162
	Max. Power/Torque, rear	kW/Nm	150/310
	Top Speed	Kph	180
	Acceleration 0-100 kph	s	6.2
	Range WLTP (COC)	Km	466 km
	Official Battery Cons. (CoC)	kWh/100km	16.3
	Official Grid Cons. (CoC)	kWh/100km	18.9
	Wheelbase (CoC)	mm	2769
	Curb Weight (CoC)	kg	2311
Battery Data	Official Capacity (installed/usable)	kWh	82/76.6
	Battery Voltage (nominal)	V	394.2
	Battery Weight	kg	495
	Module Weight	kg	370
	Cell type		Pouch
	Cell chemistry		Graphite/NMC712
	Cell number		288, 12 modules x 24cells
	Cell configuration		96s3p
	Thermal Layout		Liquid Cooling
	Max. DC Charging Power	kW	125
Thermal System	Number of coolant circuits		1
	Coolant Radiator		1
	Heat Pump w/ ambient		Yes
	Heat Pump w/ waste heat		Yes
	Battery Heating		PTC
	Cabin Heating		Direct gas cooler + PTC
	Coolant Type		WG 50/50 9.3 kg
	Refrigerant type		R744 (CO_2) (420g)
	Max. HV Compressor Power	kW	6.5

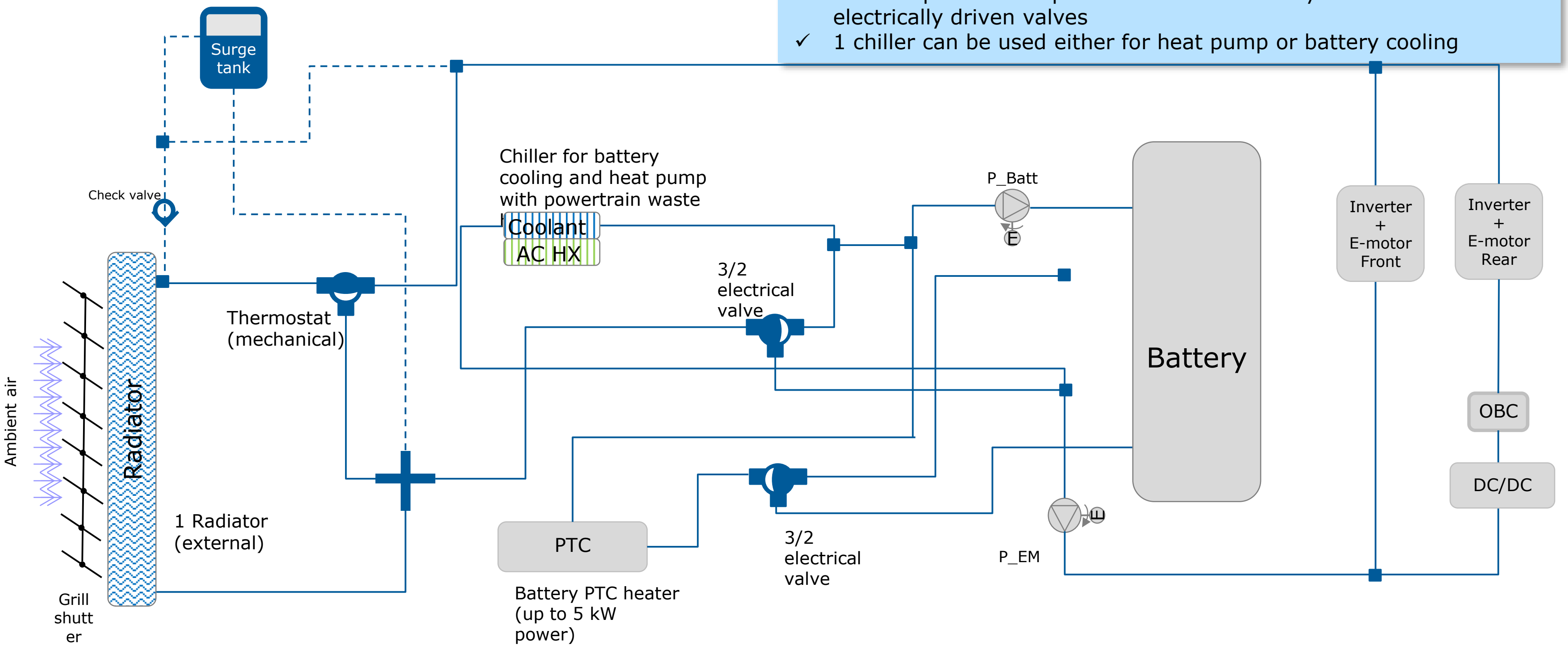
A/C circuit



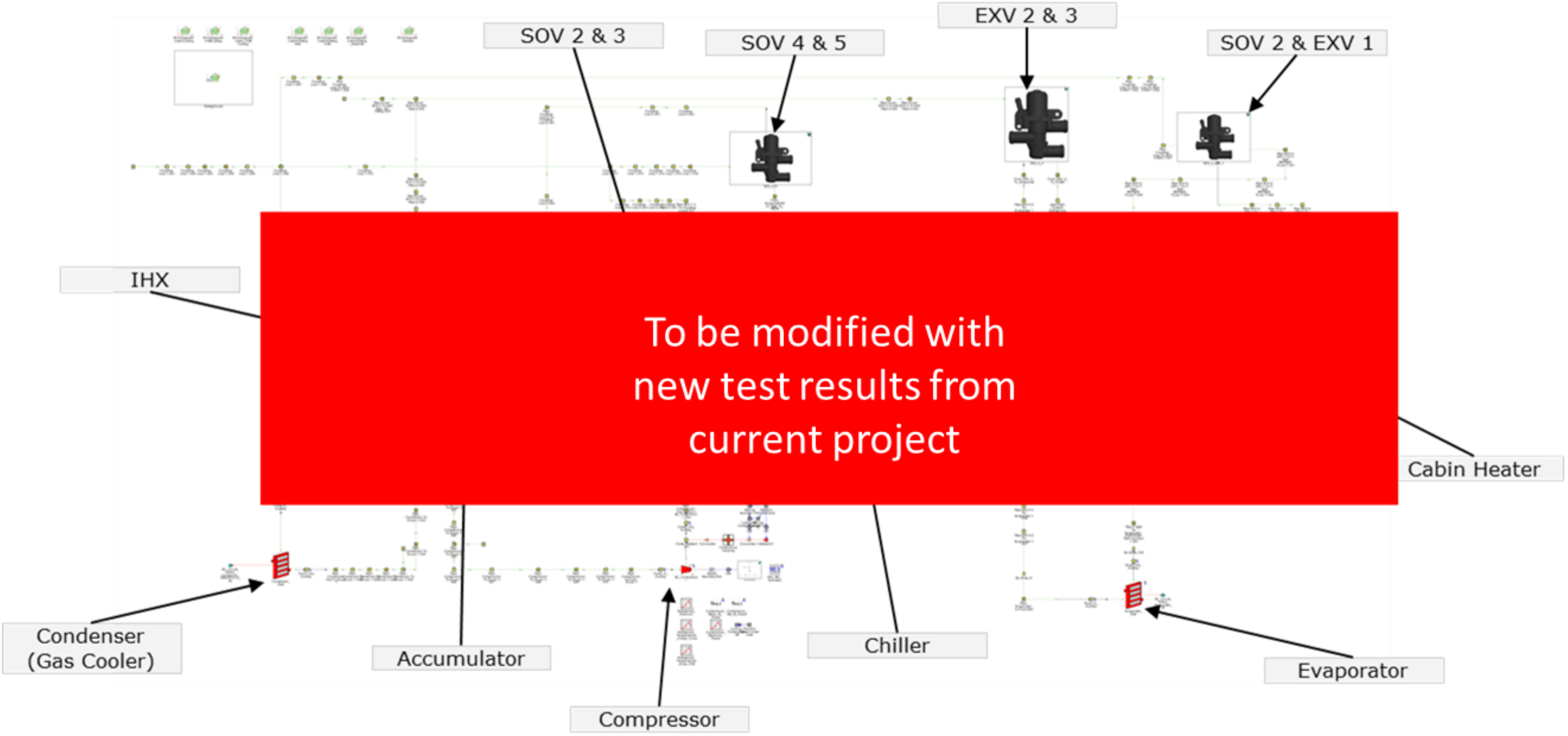
5 x Pressure and temperature sensor
P,T
8 electric valves: shut-off and expansion functions. Apparently same hardware.
Thick pipes – low density fluid
Thin pipes – high density fluid
SOV
Valve with shut-off function
EXV
Expansion valve
HP filling port
LP filling port
Accumulator with additional internal heat exchange function
Outer condenser (gas cooler) for A/C cooling and heat pump with ambient source
SOV 1
SOV 3
SOV 4
SOV 5
EXV 3
EXV 2
SOV 2
EXV 1
Accumulator
Chiller
Chiller for battery cooling and heat pump with powertrain waste heat
Ambient Air
Radiator
Outer Condenser
Grill shutter
HV compressor (up to 6.5 kW power)
Refrigerant R-744
Electric cabin heater
CH
PTC
EVAP
Blower
HVAC
to cabin
Direct condenser for cabin heating

Coolant circuit

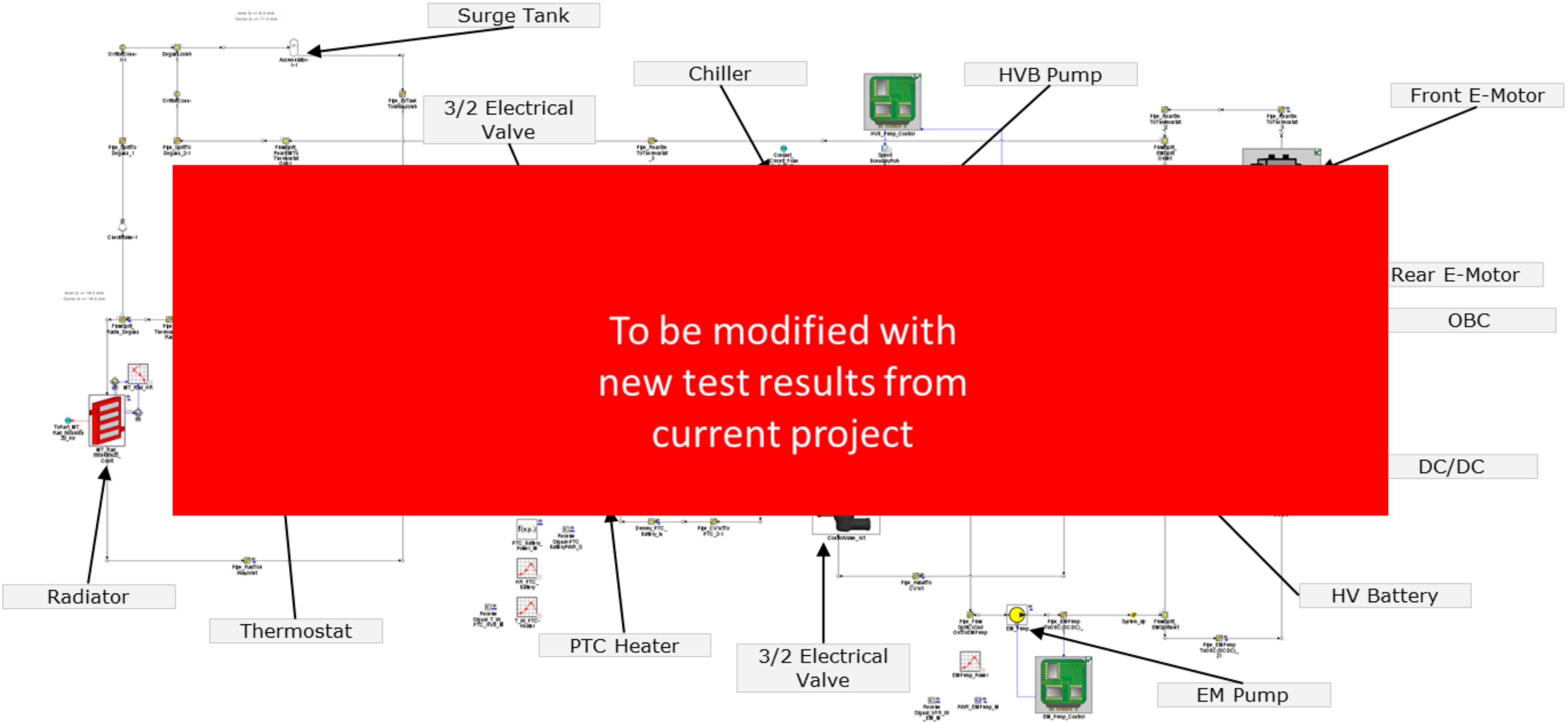
- ✓ 1 circuit, 1 surge tank, 1 radiator
- ✓ Can be split into 2 separate circuits for battery and e-drive via 2 electrically driven valves
- ✓ 1 chiller can be used either for heat pump or battery cooling



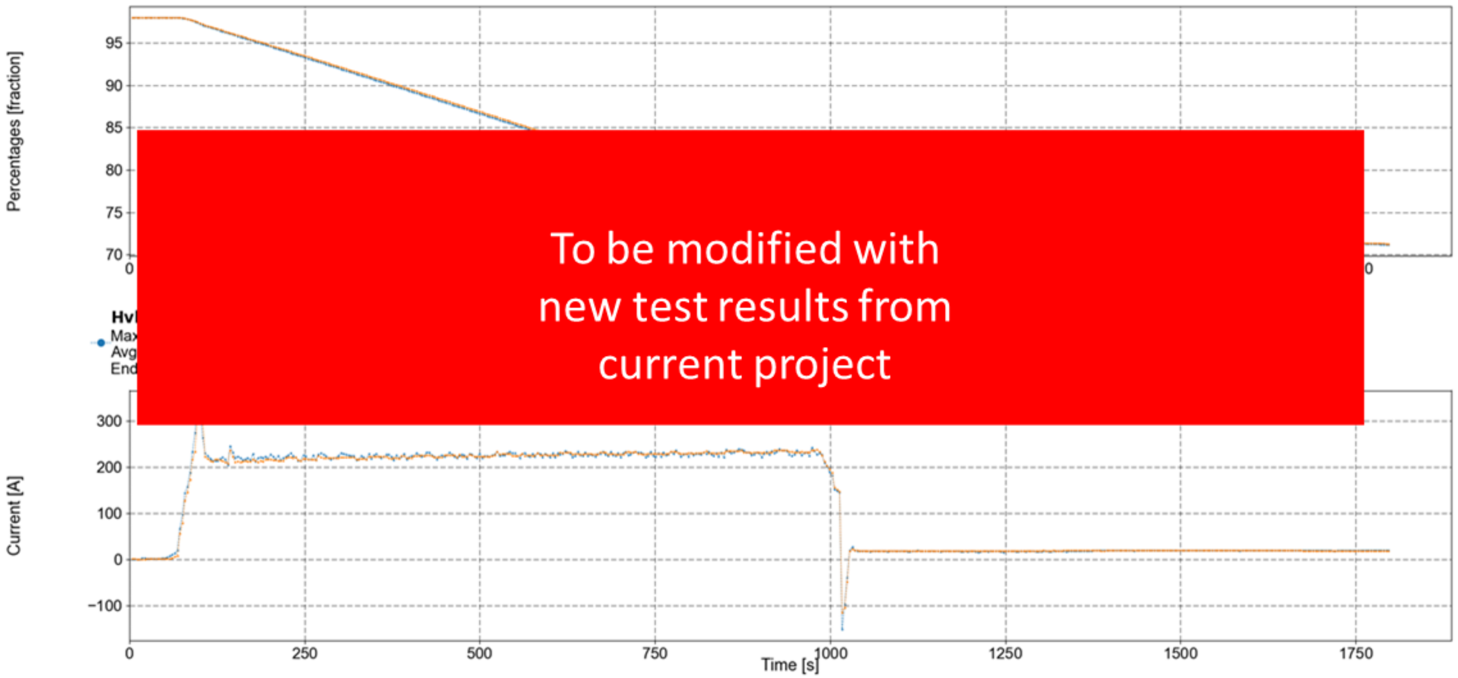
Overall Simulation Model **Refrigerant** Circuit



Overall Simulation Model **Coolant** Circuit



Case 1 MaxHVB@45°C



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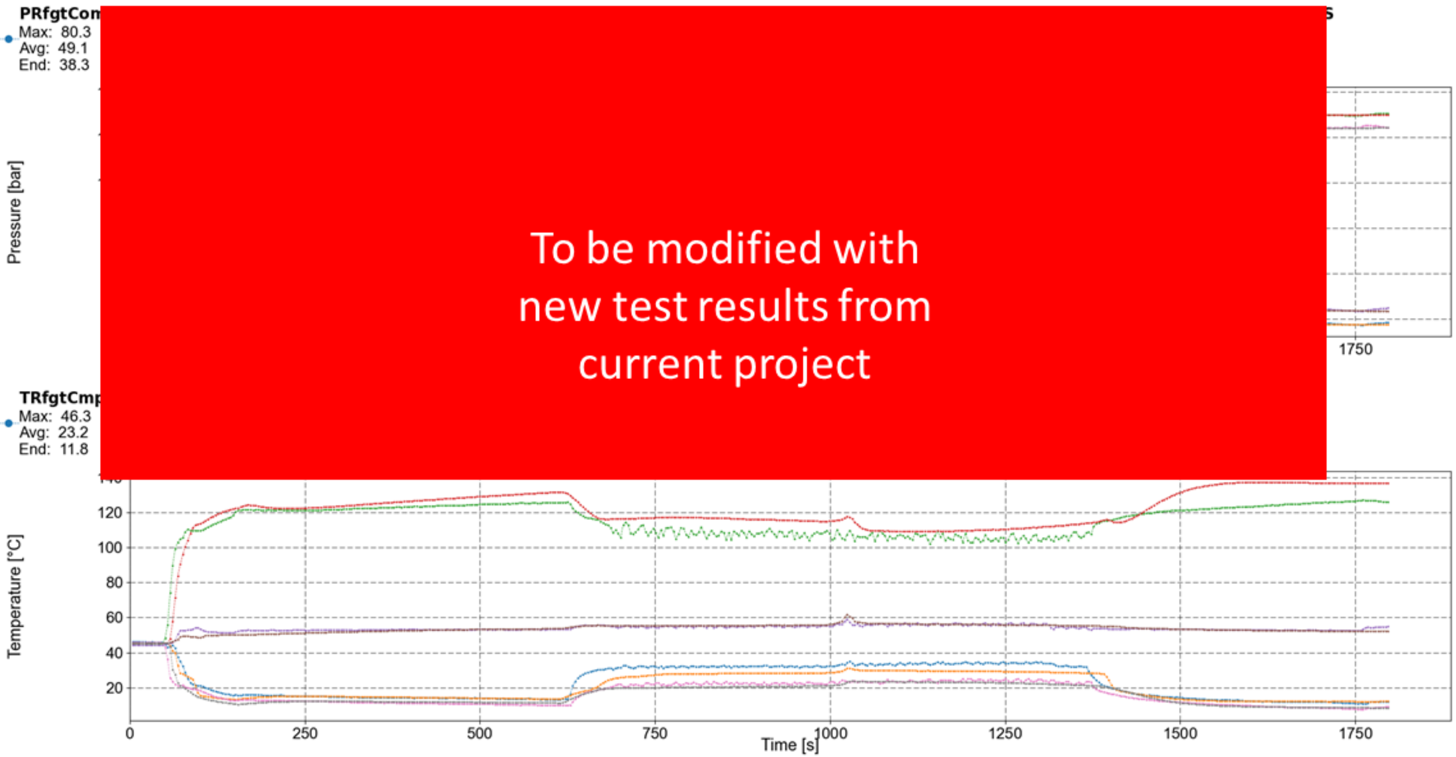


Accuracy Overview

Num.	Control unit	Criteria
2		mpared with test data
3	Cabin coo	**er time for average head**
4	Battery inl	**verage over time**
5	EDU inle	**erage over time**
6	Refrigerar o	age accuracy absolute
7	R477 side c	absolute value<**10** bar **in**
8		**oints** **nts** Refrigerant circuit: total flow rate <5% **in average over all operating points**

To be modified with
new test results from
current project

Chapter 5

Control Software: Predictive Cabin Thermal Management

Predictive Overview and Example applications

Predictive Battery preconditioning
Pre warm the battery before drive starts.
→ Store heat in the battery

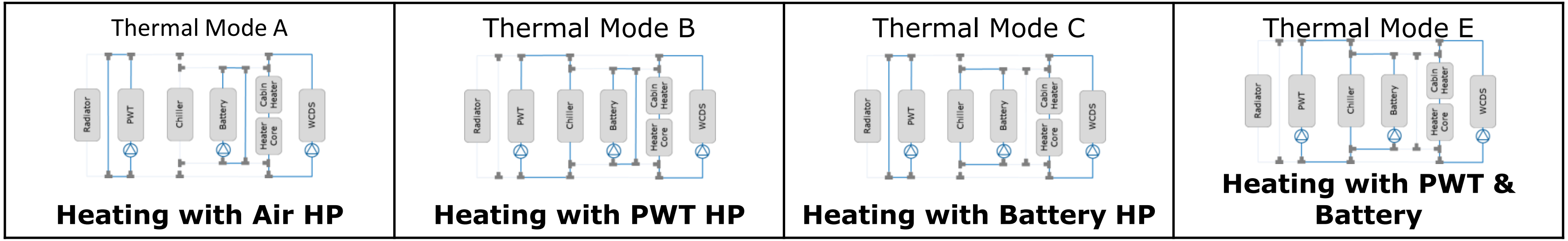
"Predictive cabin heating mode selection":
1) Use battery as heat source
2) Use powertrain as heat source
3) In City: Use ambient as heat source

0°C

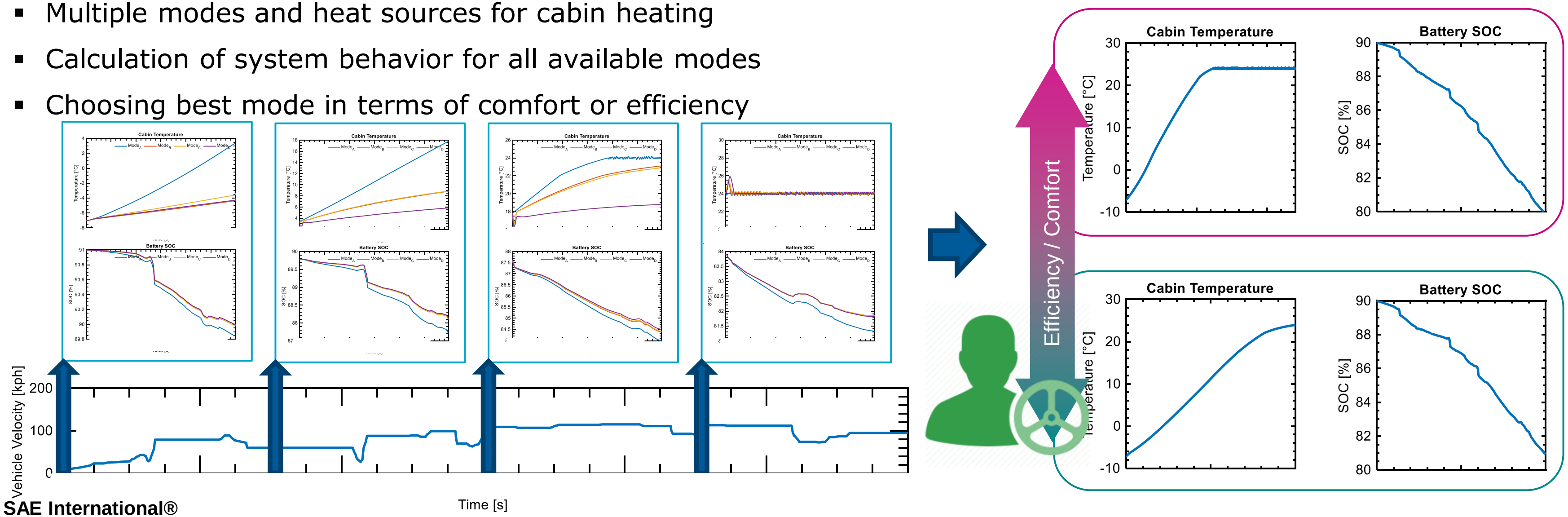
Predictive HV battery heating/cooling
Heating or cooling depending on battery temperature and predicted load
→ Reduce energy demand for heating and cooling

Predictive HV battery heating/cooling before fast charging
Heating or cooling depending on battery temperature and predicted load and charging power
→ Reduce charge time
→ Prevent overheating

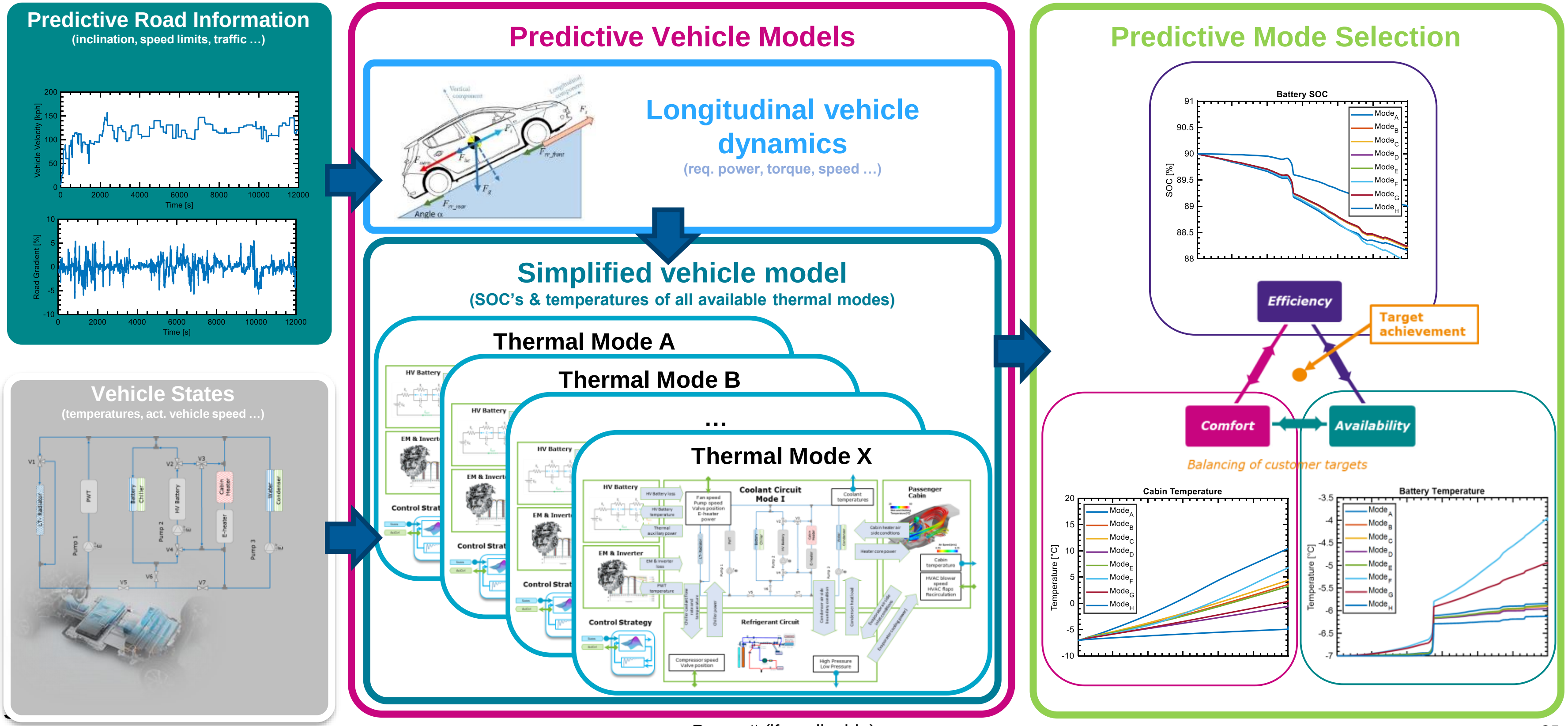
Predictive Cabin Objective



- Multiple modes and heat sources for cabin heating
- Calculation of system behavior for all available modes
- Choosing best mode in terms of comfort or efficiency



Predictive Cabin Methodology



Contact Info

Thank you for your Attention!

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