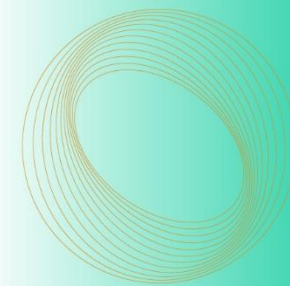




The Business Case Natural Refrigerants



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29 Sept. 2026



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Business Case for
Natural Refrigerants



**TECHNISCHE
UNIVERSITÄT
BERLIN**

Performance Evaluations with R-290

Comparison of an R-290 Mobile Refrigerant Thermal Management System with and without Vapor Injection Technology

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Testing & Development support by **IPETRONIK**

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- 01 Case Study Introduction – *Why and how was it done?*
- 02 Data Analysis and Comparison – *What did we observe?*
- 03 Lessons Learned – *What have we learned?*
- 04 Value Assessment – *How do customers benefit from the results?*
- 05 Outlook – *How can the findings improve our products?*

01

Case Study Introduction

Why and how was it done?

What is Vapor Injection (VI) Technology?

Ford Vapor Injection Heat Pump (VIHP) Technology

Global Ford
Portfolio with
VIHP-Technology
(R-1234yf & R-134a)



E-Transit Custom



E-Tourneo Custom



E-Transit



Mustang Mach-E

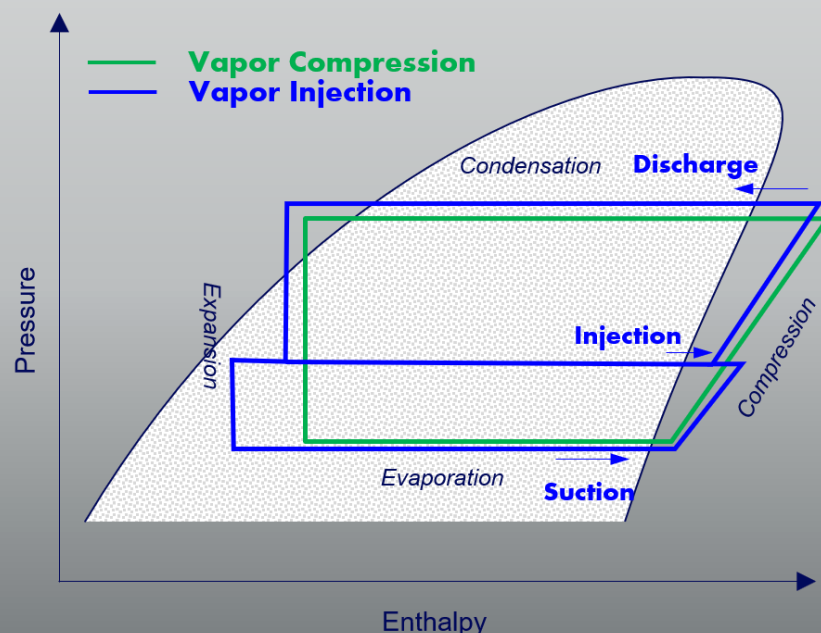


F-150 Lightning



EOP

VIHP Principle (ideal, R-1234yf)



Vapor Injection vs. Vapor Compression Heat Pump:

Advantages:

- Condensing mass flow & max. capacity @ similar efficiency
- Mechanical compressor load & discharge temperature
- Larger operating ambient temperature range (heating)
- Improved efficiency & NVH through operating range

Challenges:

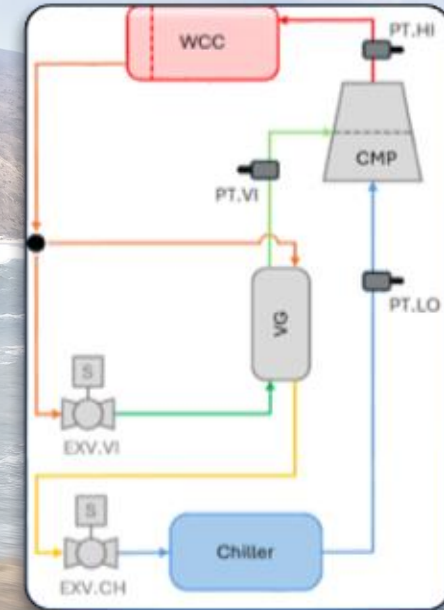
- ➡ Refrigerant charge mass
- ➡ Control system complexity – higher sensitivity

Case Study Motivation:

Does Vapor Injection (VI) Technology in an R-290 Dual Secondary Loop (Water-to-Water) Heat Pump system provide performance and/or efficiency benefits?

R-290 Dual Secondary Loop Bench Setup

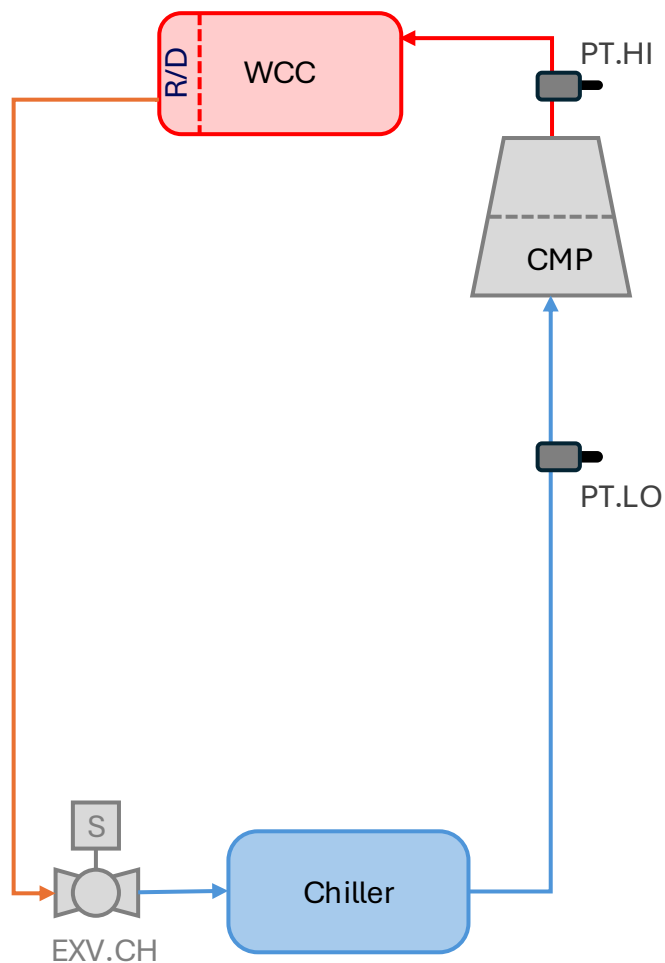
- **Natural refrigerant** thermal management system for next-gen BEVs
- **Hardware Baseline:** Integrated Dual Secondary Loop module, VI, R-1234yf (YF)
- **System hardware upgrade to R-290** as PFAS-free natural refrigerant:
 - Advantageous thermodynamic properties
 - Reuse or minor modification of YF components and control logic
 - Trend: Supplier e-compressors with common design for multiple refrigerants
- Testing timing Q1 to Q3 2025, including component & system (module) characterization
- Testing and development support by **IPETRONIK**
- Hardware supply, tuning, and development support by a Global Tier 1 supplier



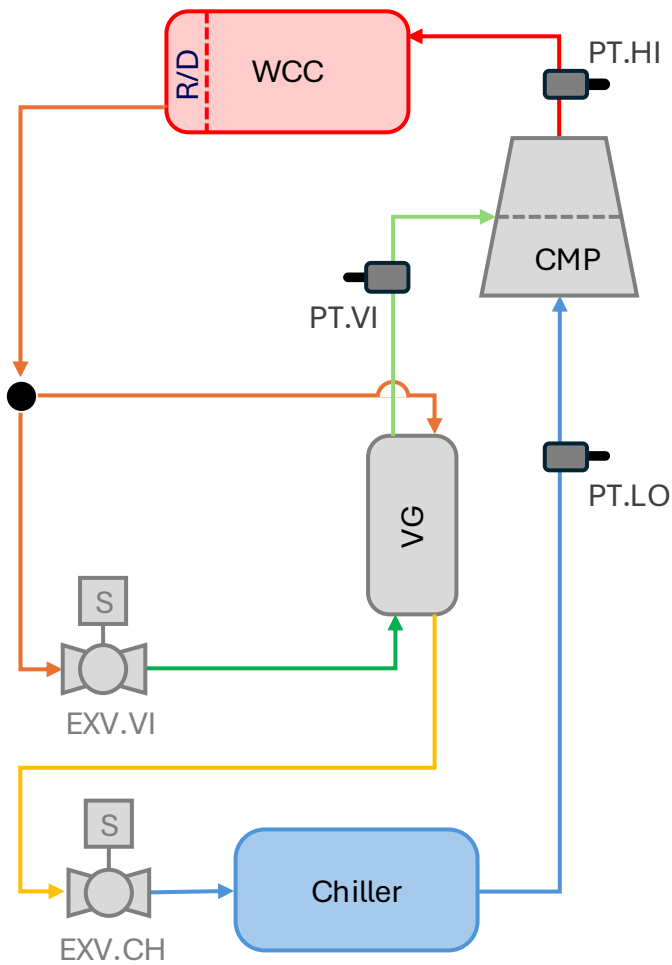
Baseline Hardware Schematic

R-290 Dual Secondary Loop System Schematic

Vapor Compression Cycle



Vapor Injection Cycle



Abbreviations:

CMP = Compressor
 WCC = Water Cooled Condenser
 R/D = Receiver/Dryer
 VG = Vapor Generator
 EXV.CH = Electronic Expansion Valve (Chiller)
 EXV.VI = Electronic Expansion Valve (VI path)
 PT.HI = Pressure & Temperature Sensor (compressor discharge)
 PT.LO = Pressure & Temperature Sensor (compressor suction)
 PT.VI = Pressure & Temperature Sensor (VI path)

02

Data Analysis and Comparison

What did we observe?

Bench Test Boundary Conditions

R-290 Dual Secondary Loop Bench Test Boundary Conditions

Data Point ID	Operating Mode	Ambient Temperature	Relative Humidity	WCC Coolant Inlet	Chiller Coolant Inlet	Target Q Chiller (cooling) / WCC (heating)	VI Status
		[°C]	[%RH]	[°C]	[°C]	[kW]	[ON/OFF]
		Target	Target	Target	Target	Target	Actual
C.1	Cooling Mode	43	40	60	15	7.0, 7.5, 8.0	ON, OFF
C.2				55	5	5.5, 6.0, 6.5	ON, OFF
C.3				65		5.5, 6.0, 6.5	ON, OFF
C.4				55		3.5, 4.0, 4.5	ON, OFF
C.5		35		43		3.5, 4.0, 4.5	ON, OFF
C.6		43		60	8	7.5, 8.0, 8.5	ON, OFF
C.7				65		7.0, 7.5, 8.0	ON, OFF
H.1	Heating Mode	-18	5	43	-20	6.5, 7.0, 7.5	ON, OFF
H.2				55		8.5, 9.0, 9.5	ON, OFF
H.3						8.0, 8.5, 9.0	ON, OFF
H.4		-7			-10	5.0, 5.5, 6.0	ON, OFF
H.5				48		3.0, 3.5, 4.0	ON, OFF
H.6						9.0, 9.5, 10.0	ON, OFF
H.7		7			3	5.0, 5.5, 6.0	ON, OFF

~ SC03

Maximum A/C

Maximum Heater

~ Cold CO / Type 6

Dehumidify / Reheat

Measurements done in steady-state condition, averaged over time, with defined target tolerances.

Results Overview – Deltas VI ON vs. VI OFF



	Ambient Temperature	Q̇ WCC/Chiller	Compressor RPM	Compressor Input Power	Compressor Discharge Pressure	Compressor Discharge Temperature
	[°C]	[kW]	Avg. Delta %	Avg. Delta %	Avg. Delta %	Avg. Delta [K]
	Control Target	Control Target	Measurement	Measurement	Measurement	Measurement
C.1	43	7.0, 7.5, 8.0*	-26%	-12%	-1,1%	-0,5
C.2		5.5, 6.0, 6.5	-27%	-15%	-1,1%	-3,3
C.3		5.5, 6.0*, 6.5*	-33%	-17%	-1,5%	-3,2
C.4		3.5, 4.0, 4.5	-21%	-6%	-0,5%	0,1
C.5	35	3.5, 4.0, 4,5	-12%	0%	0,1%	-0,7
C.6	43	7.5, 8.0*, 8.5*	-30%	-15%	-0,5%	-7,0
C.7		7.0*, 7.5*, 8.0*	-23%	-3%	1,5%	-1,5
H.1	-18	6.5, 7.0*, 7.5*	-13%	-5%	1,2%	-9,6
H.2	-7	8.5, 9.0*, 9.5*	-28%	-10%	0,5%	-9,0
H.3		8.0, 8.5, 9.0	-24%	-10%	0,6%	-8,7
H.4		5.0, 5.5, 6.0	-21%	-9%	0,3%	-4,2
H.5		3.0**, 3.5**, 4.0	-18%	-5%	0,1%	-0,4
H.6	7	9.0, 9.5, 10.0	-19%	-6%	0,2%	-1,5
H.7		5.0, 5.5, 6.0	-15%	-3%	-0,1%	-0,3



* Capacity targets not met with VI OFF

** Control instability with VI ON



Significant reduction of **compressor speeds, input power, and discharge temperatures** with VI active.
 Capacity short-fall for **VI OFF** operation in heating and cooling modes.
 Minimum impact on discharge pressure with VI ON.

03

Lessons Learned

What have we learned?

Observations & Lessons Learned from Bench Testing

		VI ON 	VI OFF 	
High Load 		Capacity  Efficiency 	Capacity 	VI ON meeting capacity targets with improved efficiency VI OFF <u>not</u> meeting all targets
Part Load 		Efficiency 	Efficiency 	VI ON did not achieve all efficiency targets » VG, EXV, Chiller tuning
Low Load 		Stability 	Efficiency 	Superheat stability issues in VI mode » VG, EXV, Chiller tuning
Oil Selection & Compressor Durability 		Initial VI testing with YF PAG oil » accelerated compressor wear  Development of R-290 specific PAG oil with unique properties required		
EXV Tuning 		YF EXVs » coarse superheat control & over-sized at highest loads  R-290 tuned with reduced orifice & flow control curve optimization		

04

Value Assessment

How do customers benefit from these results?

System Impact vs. Customer Benefit



Technology Drivers

- Switch to R-290:
 - Improved properties for heat pump applications
- Dual Secondary Loop:
 - Elimination of cabin heat exchangers
 - Reduced refrigerant charge
- VI Technology:
 - Increased capacity, efficiency & ambient temperature range



Vapor Injection Benefits

- Leverage higher capacity or higher efficiency
 - Reduced thermal system energy consumption >>> Enhanced driving range
- NVH & durability benefit due to reduced operating speeds & internal stress



Trade-Offs for Vapor Injection implementation

- Hardware: Additional VI content (BOM & mass), increased refrigerant charge
- Control Logic: Added complexity for control logic & hardware protection themes

05

Outlook

How can the findings improve our products?

Future Plan and Outlook

R-290 Dual Secondary Loop Heat Pump with VI - Next Steps



Bench Testing Activities

- Control strategy & calibration optimization
- Component tuning for efficiency gain



Partial Load



Minimum Load



Mule Vehicle Integration & Testing



2026

Integration

Demonstrator



2026 / 27

Evaluation



Wind Tunnel



Road



Market & Regulatory Environment

- Supporting Global Standardization Committees (SAE, ISO)
- Monitoring **Market Trends** and **Regulatory Environment** (PFAS restrictions)
- Assessing **New Vehicle Model** options and **Market Entry Timing** for R-290

R-290 provides substantial benefits for future thermal management systems.

Adding VI technology further improves efficiency, performance, and operating capability, offering a robust and PFAS-free solution for next-generation electric vehicles.

THANK YOU!

Questions?



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Backup

Test Setup and Boundary Conditions

- **Tests Location:** Climatic test chamber at IPETRONIK Baden Baden, Germany
- **R-290 safety measurements:**
 - Running the tests under negative chamber pressure
 - Monitoring of test bench gas concentration sensors => coupled with air exchange system to outside ambient
 - Chamber lockout while system is under operation
- **Performance measurement settings:**
 - Test machine constants:
 - Coolant flow rates & inlet temperatures @ Chiller & Water Cooled Condenser
 - Ambient exposure (temperature & relative humidity) surrounding test module
 - Coolant inlet temperatures reflecting system operation mode & vehicle use case
 - Laboratory heat sources & sinks for coolant temperature control
 - Replaces all air-side load devices & vehicle coolant load devices
 - EXV and compressor actuated with commercial closed-loop controllers & protection logic thresholds
 - Module internal losses & natural convective losses included; Solar radiation effects and forced convective losses excluded

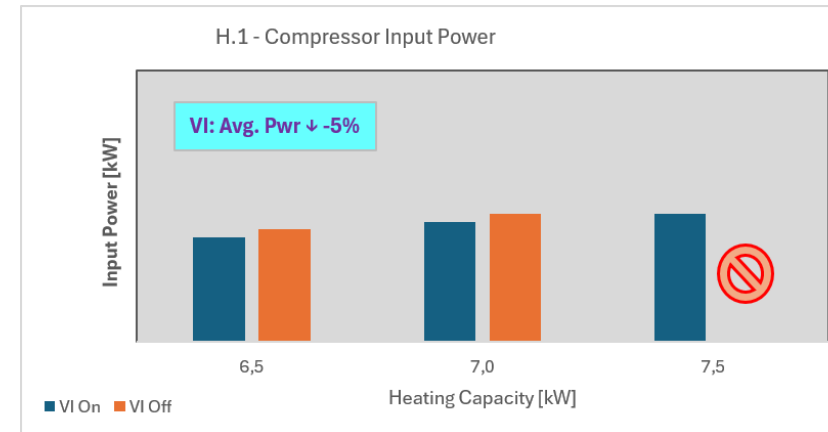
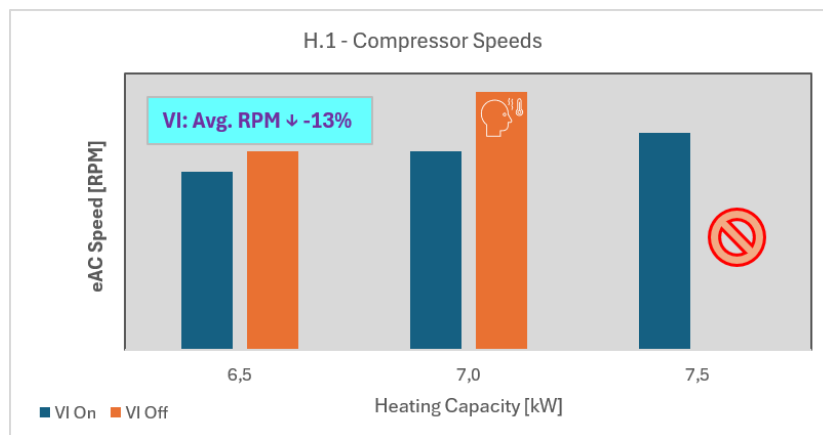
H.1 Max. Heater Performance (Defrost, Warmup, or Pre-Condition)

Ambient  : -18 °C / -0.4 °F

Chiller coolant inlet: -20 °C

WCC $\dot{Q}^*$ & SH** controlled

Heating Mode



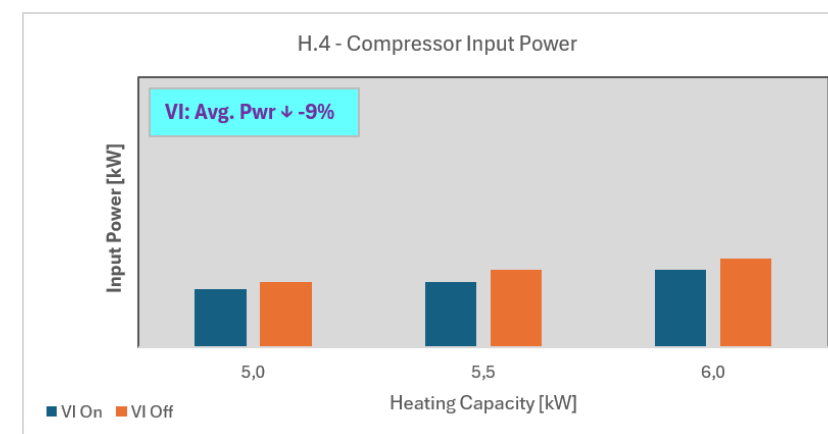
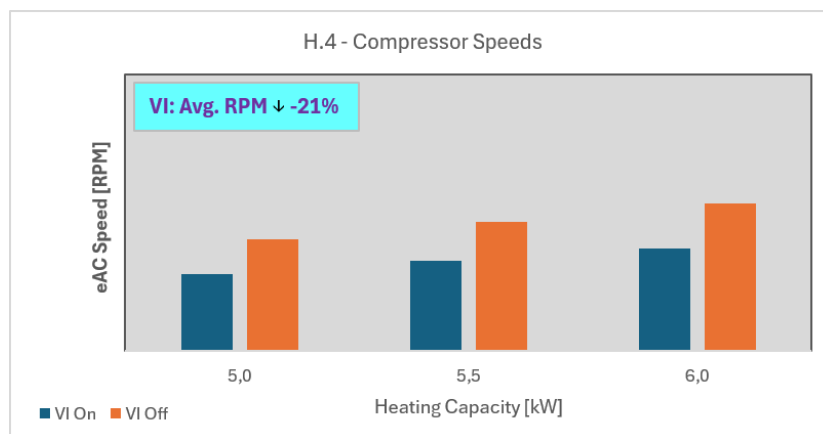
H.4 Heater Efficiency for Label (2-Cycle/5-Cycle Cold CO/WLTP Type 6)

Ambient  : -7 °C / 19.4 °F

Chiller coolant inlet: -10 °C

WCC $\dot{Q}^*$ & SH** controlled

Heating Mode



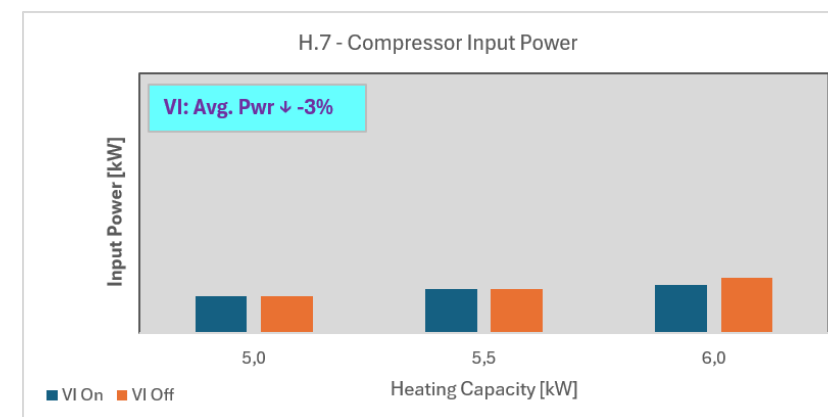
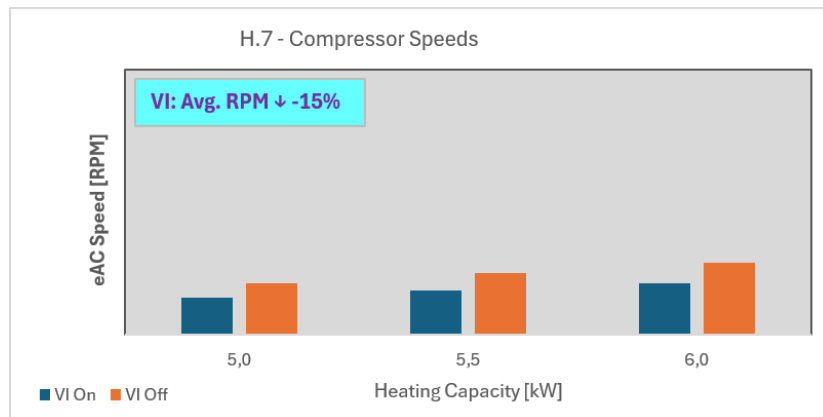
H.7 Dehumidify/Reheat

Ambient 🌡️ : +7 °C / 44.6 °F

Chiller coolant inlet: 3 °C

WCC $\dot{Q}^*$ & SH** controlled

Reheat Mode



C.5 A/C Efficiency for Label (2-Cycle/5-Cycle SC03)

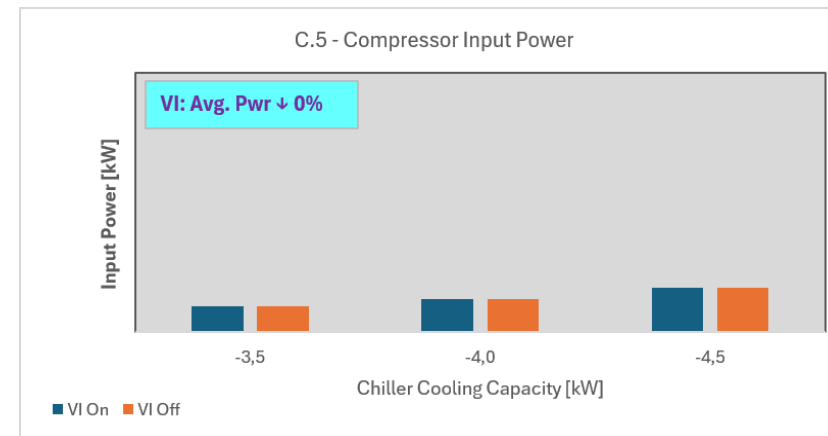
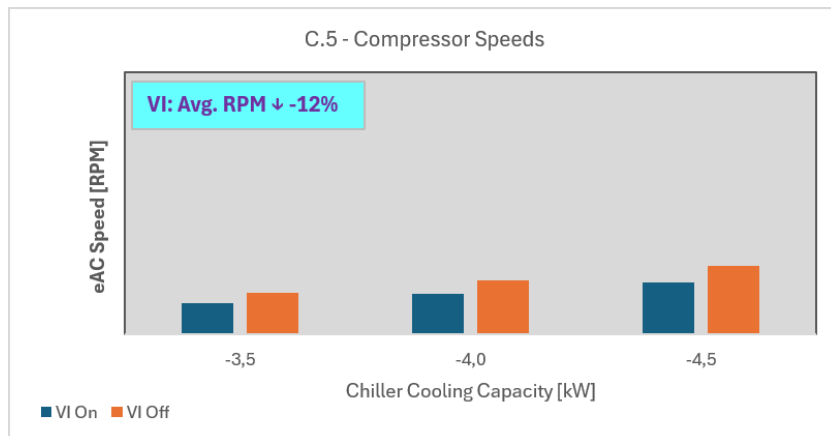
Ambient : 35 °C / 95 °F

WCC coolant inlet: 43 °C

Chiller $\dot{Q}^*$ & SH** controlled



A/C Mode



C.6 Max. A/C Performance (Pulldown, Towing, or DCFC)

Ambient : 43 °C / 109.4 °F

WCC coolant inlet: 60 °C

Chiller $\dot{Q}^*$ & SH** controlled



A/C Mode

