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## Testing of HFO Refrigerant With Less Than 150 GWP in a Commercial Freezer

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### ABSTRACT

R-404A has been the global industry standard HFC refrigerant for commercial refrigeration in both small and large systems. However, due to its high global warming potential (AR4 100 year GWP = 3922), lower GWP alternatives to R-404A are urgently needed. In particular, the recently enacted European F-Gas regulation requires commercial hermetically sealed systems to use refrigerants with <150 GWP by January 1, 2022. Regulations on high GWP HFCs in other regions are also being proposed. To address this need, a hydrofluoroolefin (HFO) refrigerant mixture with <150 GWP named XL20 (R-454C) has been developed. XL20 is a mixture of HFO-1234yf and HFC-32. HFO-1234yf is in the formulation to dramatically reduce the GWP and HFC-32 has been added to increase the cooling capacity and provide performance close to R-404A. Though XL20 is mildly flammable, the small charge sizes found in self-contained systems are able to accommodate refrigerants with some degree of flammability. This paper will present results from experimental testing of XL20 in a self-contained freezer originally designed to use R-404A. Standard performance parameters will be measured and compared to the R-404A baseline, including energy consumption, pressures and temperatures and mass flow rate. Compatibility of XL20 with lubricants and other system materials will also be presented.

### 1. INTRODUCTION

Finding low GWP alternatives in commercial refrigeration continues to be a need because the leading HFC refrigerant in use is R-404A with a 100 year GWP of 3922 (IPCC, 2007), among the highest of the HFC refrigerants. Though non-flammable alternatives have been developed such as XP40 (R-449A) (Minor, 2015) and XP44 (Minor, 2014), there is need for lower GWP options to meet recently enacted regulations under European F-Gas (EU F-Gas, 2014). Specifically, the F-Gas regulation requires refrigerants with GWP less than 150 in commercial refrigerators and freezers that are hermetically sealed (self-contained) by 2022.

A new refrigerant, XL20 (formerly XL20) has been developed with performance similar to R-404A. It has received a safety classification of A2L and provisional name of R-454C under ASHRAE SSPC 34 (ASHRAE, 2013). It is a mixture containing 21.5 weight% R-32 and 78.5 weight% HFO-1234yf. Its GWP is 148 based on IPCC Fourth

Assessment Report (Jallow *et. al.*, 2007) and 146 based on IPCC Fifth Assessment Report (Myhre *et. al.*, 2013). Since XL20 is mildly flammable (ASTM, 2009), its use will likely be limited to small charge direct systems. Drop-in performance of XL20 has been evaluated in a reach-in freezer originally designed for R-404A. Lubricant miscibility, thermal stability and materials compatibility have also been assessed.

## 2. THERMODYNAMIC PROPERTIES AND PERFORMANCE

A comparison of thermophysical properties of XL20 compared to R-404A are shown in Table 1. The boiling points are very similar with the critical point about 10K (18F) higher than R-404A. Vapor pressures and liquid densities are slightly lower. The vapor densities of XL20 is slightly lower than R-404A which will reduce mass flow rate.

**Table 1:** Thermophysical Properties

	<b>R-404A</b>	<b>XL20</b>
Boiling Point °C (°F)	-47 (-53)	-46 (-51)
Critical Point °C (°F)	72 (162)	82 (180)
Vapor Pressure at 25°C, 77°F in kPa (psia)	1254 (181)	1169 (170)
Liquid Density at 25°C, 77°F in kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	1044 (65.2)	984 (61.4)
Vapor Density at 25°C, 77°F in kg/m <sup>3</sup> (lb/ft <sup>3</sup> )	65.3 (4.07)	44.3 (2.77)

To evaluate the thermodynamic cooling performance, cycle modeling was performed for XL20 versus R-404A under low temperature refrigeration conditions: Evaporator temperature = -35°C (-31°F), Condenser temperature = 40°C (104°F), Subcool amount = 0K (0F), Suction temperature = -15°C (5°F) and compressor isentropic efficiency = 70%. Results are shown in Table 2.

**Table 2:** Thermodynamic Cycle Performance

	P <sub>suct</sub> kPa (psia)	P <sub>disch</sub> kPa (psia)	T <sub>disch</sub> °C (°F)	T <sub>glide</sub> °C (°F)	CAP kJ/m <sup>3</sup> (Btu/ft <sup>3</sup> )	CAP Rel to R-404A	COP	COP Rel to R-404A
R-404A	167 (24)	1833 (266)	90 (194)	0.4 (0.7)	810 (21.7)	100%	1.319	100%
XL20	124 (18)	1563 (227)	102 (216)	5.9 (10.6)	702 (18.9)	87%	1.415	107%

XL20 exhibits slightly lower pressures and capacity R-404A because it is a lower pressure refrigerant. However, the thermodynamic cycle efficiency is 7% higher than R-404A. XL20 also has a moderate temperature glide. However other refrigerants such as, R-407C, which have been used successfully for many years, have similar temperature glide of 5K (9F). Compressor discharge temperatures are also about 12K (21F) higher than R-404A, but well below temperatures which may require liquid or vapor injection, usually greater than about 135°C (275°F).

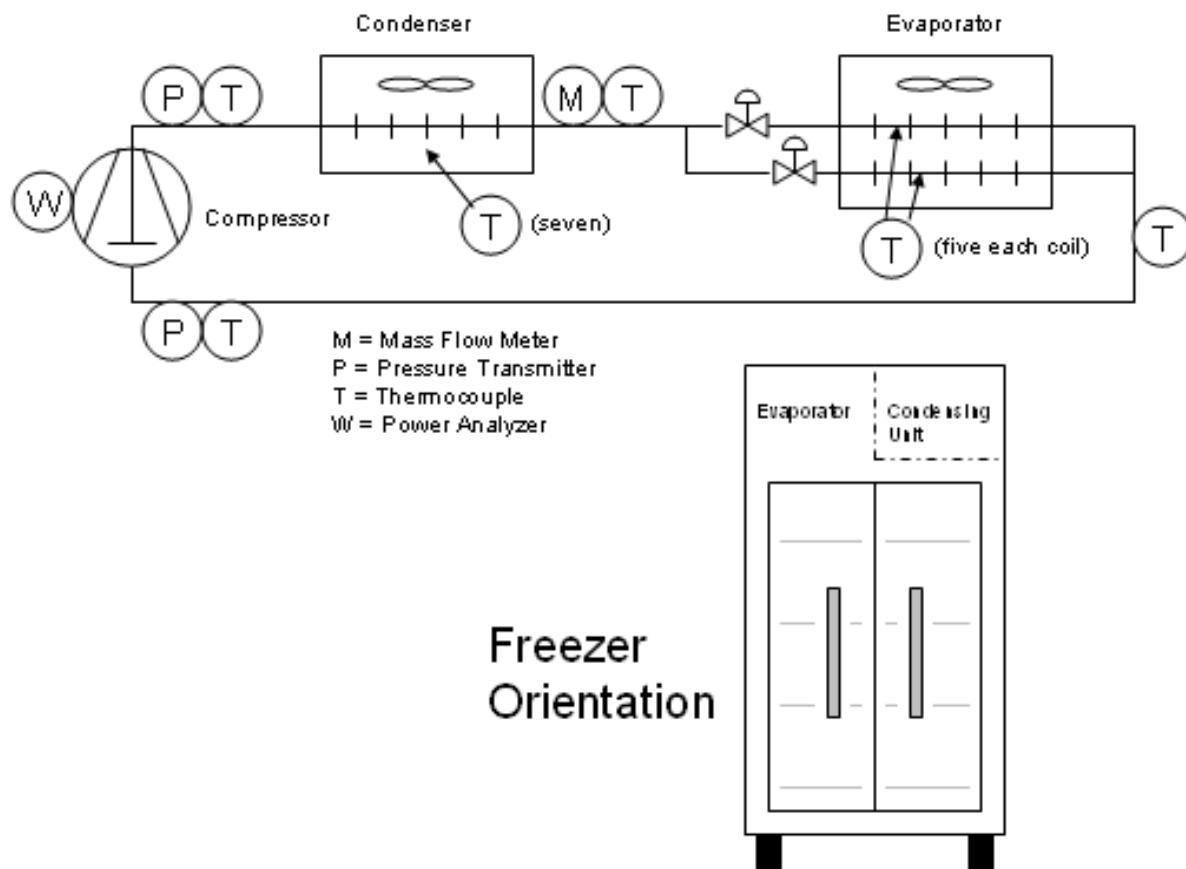
## 3. DROP-IN COMMERCIAL FREEZER TESTING

In order to measure system performance of XL20 in a system, a reach-in freezer was selected, fully instrumented and placed in a constant temperature room. The freezer is a 52 ft<sup>3</sup> (1.5 m<sup>3</sup>) double-door unit was designed for R-404A with a refrigerant charge size of 1.05 kg (2.31 lb). It has a reciprocating compressor which uses 1.15 kg (2.54 lb) polyol ester (POE) 32 centistokes lubricant. The system is controlled with a thermal expansion valve (TXV). A picture of the unit is shown in Figure 1.



**Figure 1:** R-404A Reach-in freezer used in experimental testing

The freezer was placed in a constant temperature room and fully instrumented with temperatures (T), pressures (P), mass flow rate (M) and energy measurement (W) as shown in Figure 2.



**Figure 2:** Schematic showing instrumentation of reach-in freezer

Tests were conducted at two ambient conditions 90°F (32°C), and 70°F (21°C) +/- 0.5F (0.3K). An R-404A baseline was tested first. At each condition, the evaporator exit superheat was controlled by adjusting the TXV to 6-7F (3-4K). The freezer internal average compartment temperature (average of four thermocouple readings) was controlled to 1.4°F (-17°C). After testing, R404A was replaced with XL20. A charge optimization was conducted to optimize energy consumption. A low charge was initially introduced to the systems, superheat set and energy consumption measured. Additional charge was added until the energy consumption was minimized. The refrigerant charge for XL20 was 1.00 kg (2.20 lb), about 5% lower than R-404A. A new charge of the same POE lubricant was added to the system to prevent cross-contamination from the baseline test. No other changes were made to the system except to adjust the evaporator superheat with the TXV to match R-404A superheat conditions, taking the temperature glide of XL20 into account. For XL20, the TXV was closed approximately 1 1/2 turns due to the lower mass flow rate. Results are shown in Table 3 for I-P units and in Table 4 for SI units.

**Table 3:** Reach-in Freezer Test Results – I-P Units

	EC (kWhr/day)	EC to R404A	M (lb/hr)	P <sub>suct</sub> (psia)	P <sub>disch</sub> (psia)	CR	T <sub>disch</sub> (°F)
<b>Ambient T = 90°F</b>							
R404A	34.34	100%	94	32	300	9.4	204
XL20	34.84	101%	78	25	259	10.4	217
<b>Ambient T = 70°F</b>							
R404A	23.69	100%	105	29	230	7.9	170
XL20	24.41	103%	73	24	196	8.2	179

**Table 4:** Reach-in Freezer Test Results – SI Units

	EC (kWhr/day)	EC Rel to R404A	M (kg/hr)	P <sub>suct</sub> (kPa)	P <sub>disch</sub> (kPa)	CR	T <sub>disch</sub> (°C)
<b>Ambient T = 32°C</b>							
R404A	34.34	100%	43	220	2068	9.4	96
XL20	34.84	101%	35	172	1785	10.4	103
<b>Ambient T = 21°C</b>							
R404A	23.69	100%	48	200	1585	7.9	77
XL20	24.41	103%	33	165	1351	8.2	82

Operating pressures and mass flow rate were lower for XL20, as expected from the thermodynamic analysis. XL20 compression ratio was also similar to R-404A. XL20 exhibits about 1-3% higher energy consumption than R-404A. This was not expected based on the higher COP observed in the thermodynamic analysis. However, thermodynamic analysis does not take into account system effects such as compressor efficiencies, heat transfer properties, pressure drop and other factors. There is opportunity for optimization in a new system designed for use with XL20 specific properties. Results also indicate efficiency is improved at higher ambient conditions. Although compressor discharge temperatures of XL20 were slightly higher than R-404A, they were still within a range that should not require liquid injection. Liquid injection is usually needed at discharge temperatures greater than about 265°F (130°C).

#### 4. THERMAL STABILITY

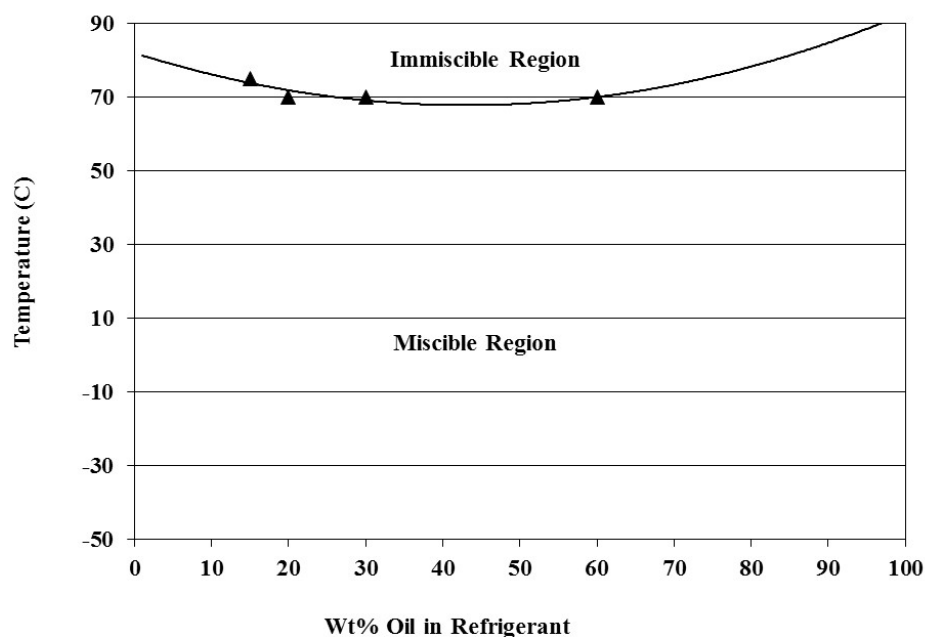
XL20 was evaluated for thermal stability in sealed glass tubes using ASHRAE Standard 97 (ASHRAE, 2007) with POE 32 centistoke as a lubricant. The glass tubes were loaded with carbon steel, copper and aluminum coupons. Refrigerant and lubricant were then added to the tubes and frozen before a vacuum was pulled to remove air. In some tubes, air (2000 ppm) contamination was added to refrigerant and moisture contamination (500 ppm) was added to the oil. The tubes were sealed and aged in a heated oven at selected temperatures 175 °C for 14 days. Tubes and coupons were visually inspected and analyzed after exposure for fluoride ion using ion chromatography. High concentrations of fluoride ion would indicate fluid decomposition. MDL (Minimum Detection Limit) indicates fluoride ion level was below the procedure detection limit of (MDL = 0.3 ppm). As shown in Table 5, XL20 was determined to be thermally stable as negligible amounts of fluoride ion were generated and metal coupons and fluids showed no visible changes.

**Table 5:** Thermal Stability Results

Aging Temp (°C)	Air (ppm)	Water (ppm)	Fluoride ion F- (ppm)	Coupon and Fluid Visual Inspection
XL20	None	None	0.31	No Change
XL20	None	500	0.51	No Change
XL20	2000	None	MDL	No Change
XL20	2000	500	MDL	No Change

## 5. LUBRICANT MISCIBILITY

The miscibility of XL20 was tested with a POE 32 centistoke lubricant. A range of refrigerant and oil mixture compositions were prepared in sealed glass tubes. The tubes were heated to 75°C (167°F) and then cooled to -50°C (-58°F) and observed in 5K (9F) increments. Results are show in Figure 3. XL20 shows excellent miscibility exhibiting complete miscibility at low temperatures and an immiscible region at temperatures 70°C (158°F) and higher. Therefore, XL20 is expected to be completely miscible in the operating ranges of commercial refrigeration systems.

**Figure 3:** Miscibility of XL20 with POE Lubricant

## 6. PLASTICS AND ELASTOMERS COMPATIBILITY

The compatibility of XL20 was evaluated with a range of typical plastics and elastomers typically used in the refrigeration industry. Samples of different plastics and elastomers were prepared and their initial weights and dimensions measured. Tubes were then placed in sealed glass tubes which were filled with either pure refrigerant or a 50/50 mixture of refrigerant and POE lubricant. The tubes were filled and placed in a 212 °F (100 °C) oven for two weeks. After heating, the plastics were removed and measured for changes in physical properties (weight, length, and hardness change) twenty four hours after removal from the tubes. The following rating system was used to characterize the compatibility of the different samples tested:

### Rating

- 0  $\leq$  10% weight gain or loss, and  $\leq$  10% linear swell and  $\leq$  10 hardness change
- 1 >10% weight gain or loss, or >10% linear swell or >10 hardness change
- 2 >10% weight gain or loss, and >10% linear swell and >10 hardness change

Results for plastics evaluations are shown in Table 6. Performance is very similar for both R-404A and XL20, indicating there are many suitable plastics and elastomers for use with XL20. Overall, the plastics showed less reactivity than the elastomers which is typical of refrigerant compatibility testing. It should be recognized that these data reflect compatibility in sealed tube tests, and that refrigerant compatibility in real systems can be influenced by the actual operating conditions, the nature of the polymers used, compounding formulations of the polymers, and the curing or vulcanization processes used to create the polymer. Specific grades, additives, etc. can also vary and potentially affect results for different polymers and other materials.

**Table 6:** Plastics and Elastomers Compatibility for XL20 and R-404A

Material Tested	R-404A Rating	% Wt Change	% Length Change	Delta Hardness	XL20 Rating	% Wt Change	% Length Change	Delta Hardness
neoprene 1	0	3%	1%	1	0	2%	2%	3
epichlorohydrin	0	9%	3%	-9	0	9%	3%	-6
butyl rubber	1	13%	4%	-8	1	13%	5%	-10
EPDM	0	7%	2%	-8	0	7%	3%	-9
fluorosilicone	1	6%	3%	-14	0	6%	3%	-8
HNBR	1	16%	5%	-6	1	16%	4%	-7
NBR	1	12%	4%	-10	1	11%	5%	-9
fluorocarbon FKM	1	18%	10%	-12	1	19%	9%	-11
neoprene 2	0	9%	4%	-6	0	9%	4%	-4
Viton A	1	17%	8%	-12	1	18%	9%	-10
Viton GF	0	10%	5%	-10	1	9%	4%	-13
polyester	0	9%	3%	-3	0	9%	2%	-5
nylon resin	0	-1%	1%	-1	0	0%	-1%	0
polyamide-imide	0	0%	0%	0	0	0%	0%	-1
polyphenylene sulfide	0	0%	0%	-2	0	0%	0%	0
PEEK	0	0%	0%	-1	0	0%	0%	0
nylon 6.6 polymer plastic	0	-1%	0%	0	0	0%	0%	0
PTFE	0	2%	1%	-1	0	2%	2%	-3

## 7. WATER SOLUBILITY

Water solubility of XL20 was determined by measuring the vapor-liquid-liquid equilibrium (VLLE) of XL20 with water. Measuring VLLE allows determination of the amounts of refrigerant and water present in a mixture vapor phase, refrigerant liquid phase and water liquid phase. The VLLE data are used to create an equation of state to determine saturated concentration of water in liquid refrigerant over a range of conditions. Results are shown in



Figure 4. The saturated water solubility of XL20 is slightly higher than R-404A. This means a larger amount of water will dissolve in liquid XL20 before saturation and therefore a separate water or free water phase could exist. Results demonstrate there is no increased concern for free water to be present with XL20 if there is water contamination of a refrigeration system.

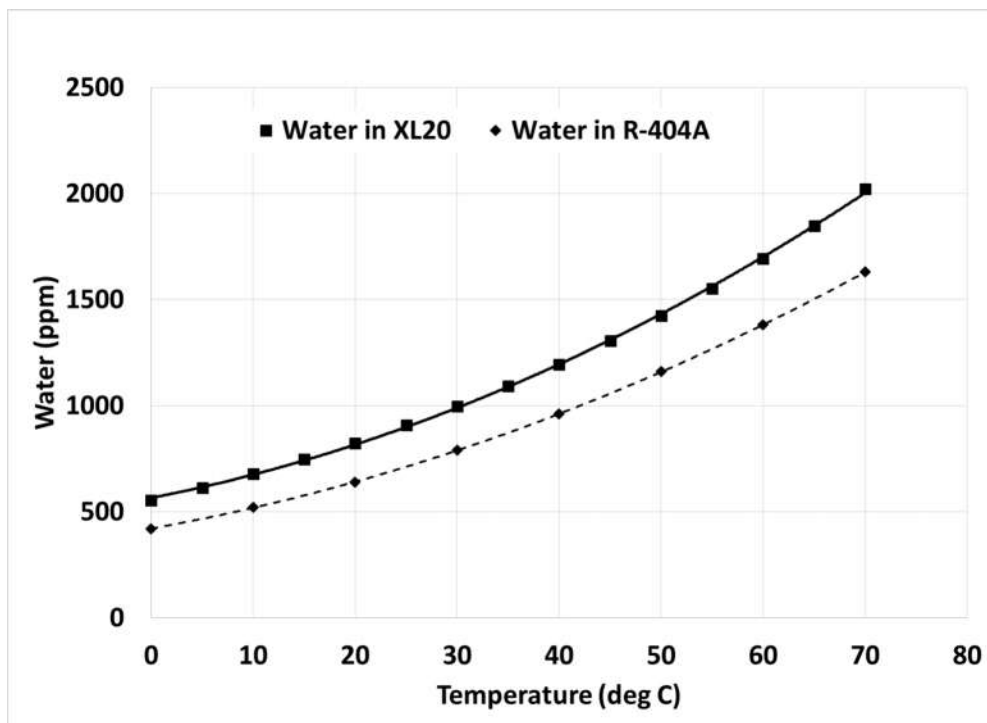


Figure 4: Saturated solubility of water in liquid refrigerant XL20

## 8. DIELECTRIC PROPERTIES

Dielectric properties are important to understand for refrigeration systems using hermetic motors. The dielectric constant of XL20 was calculated using experimental values for HFC-32 (Gbur, 2005) and HFO-1234yf (Sedrez and Barbosa, 2014). For fluid mixtures where the components are of comparable volatility, Oster's rule (Wang and Anderko, 2001) provides adequate mixture polarizations, assuming that the excess volume of the mixture is zero. The dielectric constant was then calculated using Kirkwood theory for polar components (Wang and Anderko, 2001). Results are shown in Table 7. The R-404A experimental data from Gbur, 2005 is very close to the calculated value based on Kirkwood theory which gives good confidence in the XL20 results.

Table 7: Dielectric Constants at 25°C

Refrigerant	Determination	Dielectric Constant Saturated Liquid	Dielectric Constant Saturated Vapor
R-404A	Experimental	8.1	1.18
R-404A	Calculated	8.3	1.19
HFC-32	Experimental	14.7	1.19
XL20	Calculated	10.5	1.11
HFO-1234yf	Experimental	7.6	1.07

## 9. CONCLUSIONS

A new HFO-based refrigerant XL20 (R-454C) with a GWP of <150 has been developed as a potential replacement for R-404A in commercial refrigeration. XL20 has a GWP of about 146 which is 96% lower than R-404A. It is mildly flammable (2L) and therefore may have some limitations for use in larger refrigerant charge systems such as supermarket racks. However, it is suitable for single condensing unit systems and stand-alone coolers and freezers. Drop-in performance of XL20 has been evaluated in a reach-in freezer originally designed for R-404A. The only change made to the system was a TXV adjustment. Overall, energy consumption of XL20 is comparable to R-404A. Efficiency is improved at higher ambient conditions. Plastics and elastomers compatibility, water solubility and dielectric properties of XL20 are also similar to R-404A. Suitable for use with POE lubricants has also been demonstrated. Use of XL20 can dramatically reduce the environmental impact of refrigeration systems by allowing transition away from R-404A with a refrigerant with similar performance and properties.

## NOMENCLATURE

ASHRAE	American Society of Heating Refrigerating and Air Conditioning Engineers	
CAP	volumetric cooling capacity	(Btu/ft <sup>3</sup> , kJ/m <sup>3</sup> )
COP	coefficient of performance	
CR	compression ratio	( $P_{\text{disch}}/P_{\text{suct}}$ )
EC	energy consumption	(kWhr/day)
EPDM	ethylene propylene diene terpolymer	
GWP	global warming potential	
HNBR	hydrogenated nitrile butadiene rubber	
IPCC	Intergovernmental Panel on Climate Change	
M	mass flow rate	(lb/hr, kg/hr)
MDL	minimum detection limit	(ppm)
NBR	nitrile butadiene rubber	
$P_{\text{disch}}$	compressor discharge pressure	(psia, kPa)
PEEK	polyether ether ketone	
POE	polyol ester lubricant	
P	pressure	(psia, kPa)
$P_{\text{suct}}$	compressor suction pressure	(psia, kPa)
PTFE	polytetrafluoroethylene	
T	temperature	(°F, °C)
$T_{\text{disch}}$	compressor discharge temperature	(°F, °C)
$T_{\text{glide}}$	average temperature glide of cond and evap	(F, K)
TXV	thermal expansion valve	
W	watts	(W)

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