SWOT Type Considerations of Lubricant and Low GWP Refrigerant Options

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ABSTRACT

Refrigerants considered or being considered as lower GWP options in multiple types of compressor designs and system applications, cover a broad range of chemistries. With every refrigerant chemistry difference, there is most likely going to be different lubricant chemistries, viscosities and formulations required to meet demand for reliable and efficient operation. Looking at a Strengths, Weaknesses, Opportunities and Threats (SWOT) type of approach, typically used to understand business practices, can be helpful in defining combinations and eliminating unlikely candidates.
Market changes in refrigerant candidates has created gaps in maintaining success with some current lubricants used with current higher GWP refrigerants. In addition, demand for more applications, such as high temperature heat pumps or operation in higher or lower ambient environments, call for investigation of thresholds in some combinations or options. Numerous refrigerant manufacturers and suppliers can have different approaches to what products they want to offer which increases the number of candidates to evaluate and can strain evaluation timetables and cost by all the groups involved in the testing and approval process.
This paper approaches some refrigerants and lubricants with a modified SWOT tactic for design, picking candidates and initiating screening processes which utilizes several techniques to understand acceptability. Both synthetic and natural refrigerants will be discussed along with evaluating some applications that are current topics of interest. Some lubricants used with current refrigerants are not the best candidates and, in some cases, not suitable with certain lower GWP refrigerants, resulting in needed changes or variations to lubricant chemistries. The lower stability of some newer refrigerants along with some applications looking to minimize carbon footprint by utilizing electrification and higher temperature limits creates issues with lubricant and refrigerant stability, compatibility, lubrication, and proper interaction that impacts compressor and system reliability and efficiency.

1. INTRODUCTION

Refrigeration and air conditioning has existed for almost a century using refrigerants based on chlorinated molecules in CFC and HCFC chemistry. During this time there has only been a few lubricant options that have been used with these refrigerants. These refrigerants are in the process of being totally phased out but since the early 1990s there have been several iterations for alternate no ozone depletion potential and low global warming potential options. This includes HFC, new refrigerants based on HFO and HFCO chemistries and revival or increased use of more natural based refrigerants. During these last 35 years, lubricant options have been increased with the need to make numerous evaluations for acceptable candidates. It is easy to first emphasize the lubricating potential of various lubricants in multiple compressor designs and bearings. But the interaction and need for evaluation goes well beyond lubrication into several other parameters. Given the amount of development needed, it is important to create screening and evaluation methods to understand strengths, weaknesses, opportunities, and threats critical to establishing combinations. Maintaining this type of property evaluation is vital to efficiency and reliability considerations within the system.

Compressor and system engineers and designers benefit from effective and time efficient methods to help screen potential options, because longer term studies are usually needed for approval, so minimizing options is helpful in time and cost. Some methods and techniques can be simple to make evaluations but most needs in this industry call for more specialized equipment and techniques along with personnel having critical understanding of these concepts. Since industry direction on refrigerants is still somewhat uncertain, use of these methods are vital.

2. NAVIGATING THE OPTIONS - REFRIGERANTS

Refrigerants are the start of the process of effective operation in refrigeration and air conditioning systems. Over the years, significant effort has been made in development, testing, approval, and manufacture of various refrigerant chemistries to meet needs. After determining that some refrigerant chemistries have various levels of negative environmental impact, significant time and money has been spent finding solutions. Several testing programs have been used to identify candidates, like various Alternative Refrigerant Evaluation Program (AREP) through ARI/AHRI when CFC/HFC refrigerants transitioned to no ODP HFC refrigerants and more recently during the transition of HFC to lower GWP refrigerants like HFO and natural refrigerants (Rohatgi 2012). During these transitions certain aspects of the refrigerant properties are evaluated for acceptability.

2.1 Strengths

There are several viable refrigerant candidates that have the potential to meet current requirements for lower GWP options. Changes to HFO refrigerants offer easier transition compared to when CFC/HCFC transitioned to HFC refrigerants especially with lubricant options. The use of natural refrigerants based on hydrocarbon chemistry, carbon dioxide and ammonia have already been established for years with certain limitations.

2.2 Weaknesses

HFO refrigerant's chemical structure allows for lower GWP values but also creates reduced stability when compared to HFC refrigerants which for years represented highly stable products. This creates the need to evaluate limitations when compared to using current options. This can require a significant amount of testing given the matrix of candidates being evaluated. Other critical factors such as flammability, toxicity and higher-pressure operation are concerns when transitioning away from HFC refrigerants to other synthetics and natural refrigerants, with varying levels of concern. Evaluating new options requires testing which involves time, cost, and justification.

2.3 Opportunities

An advantage of evaluating new refrigerants is the benefit when testing is being done that other modifications and improvements can also be studied. The flammability of some alternate refrigerants generated a variety of testing to determine severity of events (Gradient 2015). This allowed for modifications of standards and in some cases expanding refrigerant charge limits in various types of equipment and use scenarios. Containment criteria was also investigated with development of methods to help minimize leaks through better joining techniques and other advancements. Probably the most important outcome was optimization of compressors, components, and systems to improve energy efficiency gains.

2.4 Threats

Nothing is perfect so there is also downsides to some changes, in the case of refrigerants it could require additional changes to system design and not be effective as a drop-in replacement. Operation at certain conditions might degrade stability, as seen in some lower GWP options, be difficult to find acceptable compatibility with lubricants in compressor operation and lack efficiency equivalency. There are still potential environmental surface impacts, such as PFAS, associated with some synthetic refrigerants that are still being discussed on their future.

3. NAVIGATING THE OPTIONS - LUBRICANTS

3.1 Strengths

Given the chemistry variation of lower GWP refrigerant options, there are several lubricant chemistry options used throughout the years with different grades within these selections. This allows for choices based on performance, reliability, and cost to meet most needs. Optimization can still be achieved through lubricant and refrigerant interaction properties and viscosity choices. Several formulations have been used through the years that already have some understanding and can potentially translate to use with lower GWP refrigerant candidates.

3.2 Weaknesses

It has become more difficult to develop new chemistries due to global regulations which can affect the benefits that lubricants provide for refrigerant operation in systems. The potential magnitude of testing needed to qualify options can also restrict evaluation and slow down the transition.

3.3 Opportunities
Like with refrigerants, once changes are needed this allows for investigation of new lubricants and formulations that might not have been considered with status quo refrigerant options. Cost implications such as researching cost reductions can happen when change occurs.

3.4 Threats
Given the number of refrigerant chemistries differences, there are needs to identify different types of lubricant chemistries to meet the need of lubricant and refrigerant properties in order to maintain the quality of operation, reliability, and performance. This can not only require an investment in cost but also time and maybe equipment.

4. NAVIGATING THE OPTIONS – INTERACTIONS

Studies outside of testing refrigerants and lubricants in compressors and systems has become critical to navigating the magnitude of options and various designs to help in the screening process. These tests help form the SWOT type of evaluation important to not only transitioning to new refrigerant options but also investigating changes to existing options that could provide benefits. Three of the most important criteria for initial understanding of options are:

- Miscibility data – the separation point of various concentrations of lubricant and refrigerant, benefits understanding of lubricant movement within a system that affects oil return and heat transfer properties (Standard 218 2019).
- Pressure-Viscosity-Temperature data (Daniel Plots) – compilation of data representing the viscosity of a combination of lubricant and refrigerant at various conditions of temperature and pressure. Benefits understanding of viscosity provided to bearing surfaces and dilution of refrigerant in lubricant at various locations within a system (Seeton 2006).
- Chemical Stability data – screening technique to qualify the potential acceptability of lubricant, refrigerants, and materials within a system. Benefits understanding of a lifetime of operation within a system at certain conditions condensed to a very short period of testing time based on accelerated methods (Standard 97 2017).

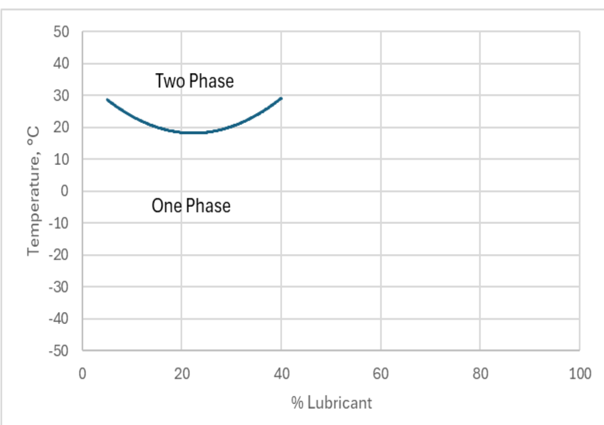


Figure 1: Phase Separation POE/HFC

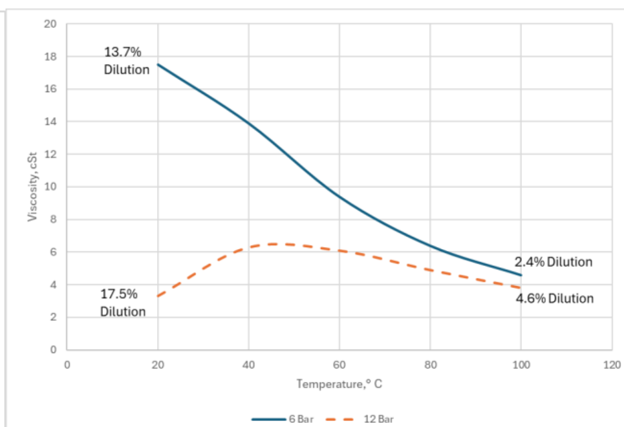


Figure 2: Working Viscosity POE/HFC

Table 1: Sealed Tube Stability Work

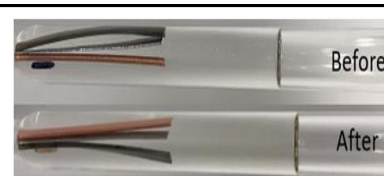
		Before	After	
POE and HFC Refrigerant 14 Days @ 175°C Low Moisture and No Air	TAN mg KOH/g Oil	0.01	0.02	
	Fluoride ppm	0	0	

Figure 1 is an example of miscibility where in this case the lubricant and refrigerant combination has a significant low temperature miscibility, referred to as Upper Critical Solution Temperature (UCST) but separation at a fairly low Lower Critical Solution Temperature (LCST). This type of data can help define acceptability in particular types of systems providing proper oil circulation, return and enhance system heat transfer properties. Figure 2 is an example of information that can be gathered from the PVT plots, in this case looking at a POE lubricant with an HFC refrigerant. The lines on the graph show how working viscosity changes with temperature and pressure, and a few dilution points are outlined at the extremes. This information can show how dilution can have a significant effect on the working viscosity as seen at 20°C and how increasing temperature can reduce this affect, as shown at 100°C. Table 1 is an example of data generated from evaluating the stability of lubricants and refrigerants at accelerated conditions to help identify potential shortcomings of these combinations in compressor and system operations. For this example showing results of testing a POE lubricant and HFC refrigerant, these combinations have shown to have acceptable thermal stability as indicated by the good results.

5. LOW GWP OPTIONS

Several refrigerant options are available today based on lower GWP values that are dedicated to various applications. Each of these selections can be evaluated with a SWOT approach to provide a better understanding of suitability and what is needed to move towards acceptability. In general, each SWOT can be broken down as follows regarding the refrigerant and lubricant.

Strength The ability of the refrigerant and lubricant to provide a required capacity and energy efficiency target based on each type of application. Stability and chemical compatibility also need to be addressed and approved.	**Weakness** Selecting industry and environmental requirements for GWP values. Reduced stability of new refrigerants over existing options. Too many options requires significant amount of testing.
Opportunity Allows for testing new combinations that might be restricted due to historical stability of legacy products used and time constraints.	**Threat** Availability and cost of alternate product options along with time and cost to evaluation that make implementation more challenging.

5.1 HFO/HFC Manipulation

Looking back at Section 4 the examples of miscibility and working viscosity were of current POE lubricant and R-404A HFC refrigerant. There are several alternate lower GWP options being considered using HFO refrigerants like R-1234yf or R-1234ze(E) in combination with HFC refrigerants to create commercial and residential refrigerant options for R-404A and R-134a in various compressors used in refrigeration. Figure 3 shows some of these options with capacity comparison and GWP value to R-404A.

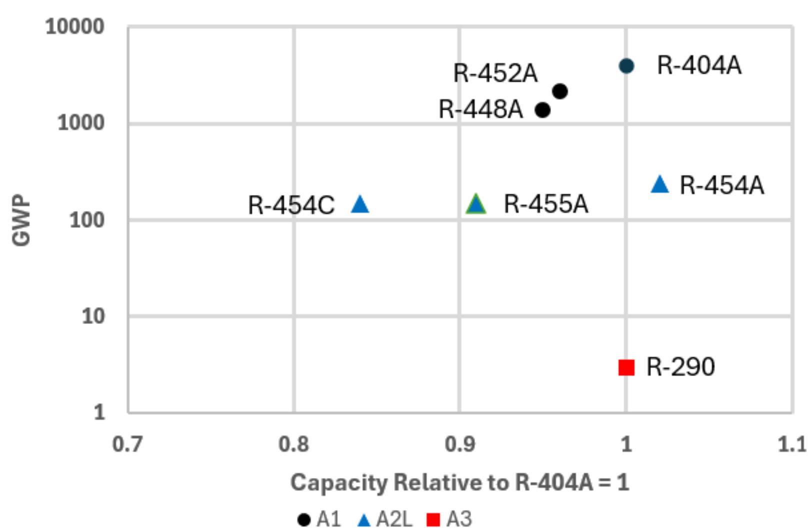


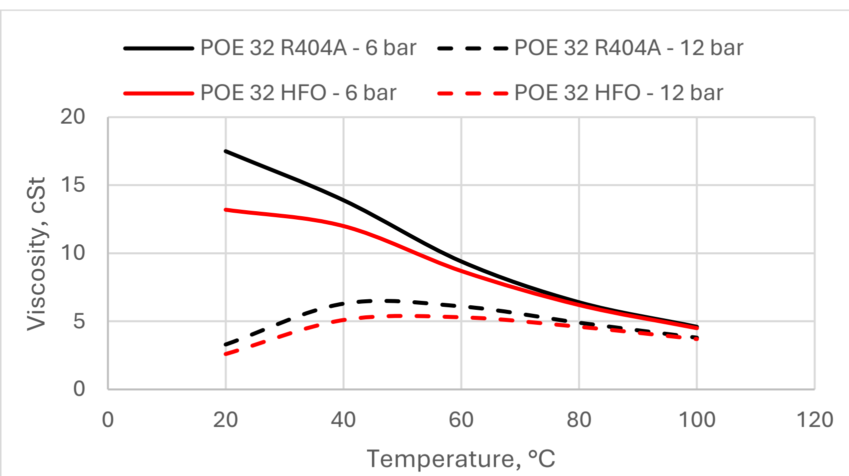
Figure 3: Low GWP Refrigerant Comparison to R-404A

The advantage these refrigerants bring is the ability to provide an expanded range of miscibility to traditionally used lubricants and new options. This allows the investigation of other lubricant options that might not be ideal for use with HFC type systems. Table 2 shows the changes in miscibility ranges when different lubricant options are used with transitioning low GWP HFO refrigerants. Various ISO 32 lubricant options are shown comparing to current lubricant used with HFC refrigerants shown in Figure 1. First observation is that using the current lubricant with an HFO based refrigerant creates a broader miscibility range that could benefit expanded use in other applications. Moving to other options generates opportunities to maintain miscibility or move to options that could be better cost based or benefit performance within a compressor or system. Miscibility manipulation can also be used to change the dynamic of bearing lubrication as will be shown in the next section.

Table 2: Miscibility Comparison Studies Transitioning to HFO Based Refrigerants

Option (ISO 32)	Refrigerant	20% Lubricant UCST	20% Lubricant LCST
Current	HFC	<-60°C	18°C
Current	HFO/HFC	<-60°C	40°C
Option 1	HFO/HFC	<-60°C	40°C
Option 2	HFO/HFC	-45°C	40°C
Option 3	HFO/HFC	-20°C	>60°C
Option 4	HFO/HFC	5°C	>60°C

Looking back at Figure 2, as with the miscibility example, the PVT data is shown as an example for an ISO 32 POE lubricant typically used with R-404A. Moving to low GWP refrigerant options for R-404A shows how these types of refrigerants compare in regard to working viscosity and refrigerant dilution. Expanding upon Figure 2, shows how the same lubricant behaves with an HFO/HFC blend. Figure 4 compares the same ISO 32 POE lubricant with R-404A and HFO based refrigerant. We see moving to the HFO based refrigerant creates more solubility. This can sometimes be predicted from the miscibility which in this case showed an expanded miscibility range which can be directly proportional to increased solubility. We see in the lower temperatures and particularly the higher pressure the significant drop in viscosity due to the higher solubility. Moving to higher temperatures, the change is not as prevalent since the temperature tends to drive the refrigerant off. Determining the acceptability of the POE 32 chemistry for HFO based on this chart shows little working viscosity differences at the higher temperatures for various pressures. Mid-point temperatures viscosity differences would need to be evaluated based on the bearing type and compressor design. Lower temperature differences as already discussed are reduced but this doesn't always eliminate use but might actually provide a benefit. Considering the Stribeck Curve in Figure 5 we see that if providing too high of viscosity to a bearing, can cause visco-drag resulting in loss of energy efficiency. It is important to maintain bearing viscosity optimization for compressor reliability and performance.



POE 32 R-404A	% Dilution 6 bar	% Dilution 12 bar
20°C	13.7	38.7
40°C	7.8	18.4
60°C	5.2	11.0
80°C	3.7	7.5
100°C	2.9	5.5

POE 32 HFO	% Dilution 6 bar	% Dilution 12 bar
20°C	15.8	41.4
40°C	9.1	20.6
60°C	6.0	12.6
80°C	4.3	8.7
100°C	3.3	6.4

Figure 4: HFC and HFO Comparison with Traditional POE 32 Lubricant

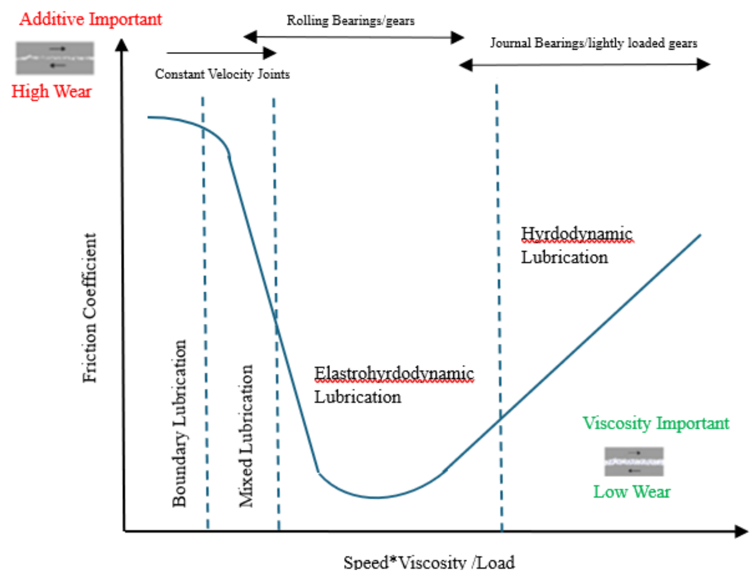


Figure 5: Stribeck Curve Example of Bearing Lubrication and Viscosity

We can see the potential strength of using the same lubricant which provides history in compressor use with similar performance. But can also take advantage of testing new refrigerants as an opportunity to look at alternate lubricants for additional optimization benefits. Figure 6 shows comparisons with traditional lubricants and new lubricant options when transitioning to low GWP refrigerants.

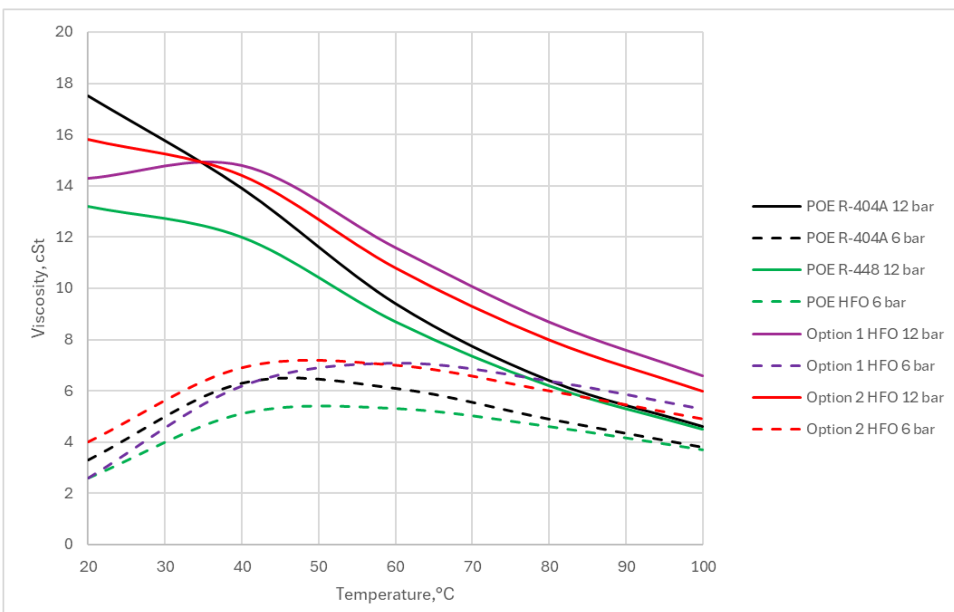


Figure 6: Creating lubricant options to benefit system operation and performance with low GWP Refrigerants

Figure 6 shows two lubricant options for HFO refrigerant compared to both the POE 32 used with HFC and HFO. Option 1 can be a performance benefit and more similar to what was experienced with R-404A. This option has the advantage of creating more working viscosity at higher operating temperatures. This is important given that HFO replacement refrigerant chemistries for R-404A also create higher discharge temperatures which could minimize bearing viscosity with traditional HFC lubricant chemistries. This may offset the need to change bearing design and still allow for operation in the typical working ranges associated with applications. Option 2 is more of a lubricant cost reduction approach which still can maintain effective bearing operation and also has better stability at the higher operating conditions. Having to test the new refrigerants creates an opportunity to evaluate cost reductions.

5.2 R-290 Hydrocarbon

Hydrocarbon refrigerants like R-290 can have several advantages in system operation, as shown in Figure 3 it can be a good match for HFC refrigerants like R-404A (Leer Engineering 2023). The advantages also extend to the ability to use propane with several lubricant chemistry candidates, in several types of commercial and residential applications using reciprocating, scroll and rotary compressors. Using R-290 offers the strength of using multiple lubricants, weakness of high flammability, opportunity to test multiple lubricant candidates and the threat of trying to navigate refrigerant charge limits. Table 3 evaluates using R-290 in smaller compressors usually associated with light commercial applications. Mineral oils can be acceptable with hydrocarbon refrigerants with the strength of cost, but they bring weakness of reduction in operational performance and stability. POE and AB are options for use in R-290 applications, with POE providing a reduction in refrigerant dilution with increased working viscosity and AB a cost benefit but providing greater stability and flash point over mineral oil. The table shows that an AB 32 has equivalent bearing viscosity to POE 22 with an experimental lubricant product, SHR 3025, also showing comparable viscosity but is also the same base viscosity as the POE 22. This lubricant chemistry could potentially be manipulated to also match a POE 32 viscosity result.

Table 3: Comparison of various lubricant chemistry options for use with R-290

Properties		POE 22	AB 22	POE 32	AB 32	SHR 3025
Viscosity @ 40°C, cSt		21.8	22.0	32.5	30.0	18.4
Flash Point, °C		200	175	210	184	200
45 °C and 6 Bara	Dilution, %	7.0	9.6	7.0	9.6	9.6
	Viscosity, cSt	5.4	4.2	6.9	5.2	5.3

Making a comparison for a commercial type of system operating at 50°F (10°C) saturated suction temperature and oil supply temperature of 122°F (50°C), we see for R-404A and a particular POE ISO 22 chemistry achieves a working viscosity of 5.2 cSt. R-290 can still use a POE 22 lubricant but with slightly modified chemistry to obtain a similar working viscosity of 5.0 cSt. Table 3 shows choosing to use an AB 32 (alkylbenzene) lubricant for cost reduction will still maintain adequate bearing viscosity. R-290 refrigerant also allows for investigation of new lubricant chemistries, as shown with SHR 3025 which can match the POE 22 while maintaining a lower initial base oil viscosity.

As mentioned above, using R-290 offers the opportunity to investigate multiple types of lubricant chemistries to help customize the performance. R-290 has found use in small light commercial applications but also in larger commercial applications such as supermarket rack systems as a lower GWP option. Considering Table 4 and an operating condition of 70°C (158°F) and 6 bara (87 psia) we can make comparison to a number of lubricant chemistries with viscosity around ISO 68. Mineral oil and Alkylbenzene can provide similar results but as mentioned early the AB has stability advantages. POE, as shown earlier, begins to provide higher working viscosity with reduced solubility which can be used as an advantage. The Polyalkylene Glycol (PAG) chemistry is where we can really start to manipulate chemistry to try to take advantage of reducing solubility which can be very important when considering the amount of system refrigerant charge. Given standards that limit the amount of a hydrocarbon refrigerant charge, using lubricants, like the PAGs, can provide benefit to creating similar or better performance with reduced amount of refrigerant without any other compressor/system changes is an important investigation.

Table 4: Lubricant Options for R-290 Commercial Refrigeration Applications

Chemistry	Dilution, %	Working Viscosity, cSt	V40 Viscosity, cSt
Mineral Oil	5.5	6.0	65
Alkylbenzene	5.7	5.8	61
Polyolester 1	4.1	10.2	63
Polyolester 2	3.7	14.0	64
Polyalkylene Glycol A	2.9	14.0	68
Polyalkylene Glycol B	4.0	18.7	68
Polyalkylene Glycol C	2.5	15.2	65
Polyalkylene Glycol D	3.5	17.4	69
Polyalkylene Glycol E	3.7	17.5	68
Polyalkylene Glycol F	3.1	17.5	68

5.3 Low GWP Refrigerant and Lubricant Stability

As mentioned earlier, many years were spent using HFC refrigerants that were highly stable due to their structure. Additionally, many years were spent using CFC and HCFC refrigerants which were not as stable and still were successfully used. Today's option for low GWP refrigerants brings once again a variety of stability scenarios, hydrocarbons are considered thermally stable and as mentioned the use of certain lubricants like mineral oils can be the challenge. HFO based lubricants tend to fall back to the days of less stable chlorinated refrigerants but now in this case the structure has an unsaturated bond which brings instability to the molecule.

Numerous industry and individual company testing has been done on a variety of HFO based refrigerants with R-1234yf and R-1234ze(E) being the most used options in combination with either high levels of HFC refrigerants to negate flammability or with lower levels of HFC to promote reduced GWP levels. Table 5 is a look at stability testing of some refrigerants tested based on ASHRAE 97 sealed tube testing (14 days at 175°C) and evaluation of the lubricant, refrigerant and metals after the test (Kujak 2021).

Table 5: Glass Sealed Tube Testing of Various HFO Based Refrigerant Candidates

		TAN	Fluoride Ion	Dissolved Metals, ppm			
Refrigerant	Lubricant*	mgKOH/g	ppm	Si	Fe	Cu	Al
R-1234yf	POE	<0.05	<10	<3	<1	<1	<3
	PVE	0.07	60	14	<1	<1	<3
R-1234ze(E)	POE	<0.05	<10	<3	<1	<1	<3
	PVE	<0.05	<10	8	<1	<1	<3
R-454C	POE	<0.05	<10	<3	<1	<1	<3
	PVE	<0.05	15	17	<1	<1	<3
R-454B	POE	<0.08	<10	<3	<1	<1	<3
	PVE	0.05	29	6	<1	<1	<3

* Lubricant starting TAN <0.05. R-454C (78.5% R-1234yf/21.5% R-32); R-454B (31.1% R-1234yf/68.9% R-32)
Note: When testing was done with zinc metal with POE lubricant and the refrigerants listed above there was a significant reaction resulting in TAN increase and large amount of dissolved zinc in the lubricant.

Typical stability trending for HFO refrigerant and lubricant interaction are that R-1234yf and R-1234yf based refrigerants are more reactive than R-1234ze(E) and based refrigerants. Refrigerants with higher R-1234yf compared to the HFC amount are slightly more reactive than the opposite combination of lower R-1234yf and higher HFC refrigerants. When tested at conditions of low moisture and no air, as what was done in the Table 5 results, POE lubricant shows good stability with HFO while Polyvinyl Ether (PVE) lubricant has various levels of instability resulting in refrigerant breakdown represented by TAN increase and fluoride ion detection.

6. CONCLUSIONS

The refrigeration and air conditioning industry is challenged today with evaluating the significant amount of refrigerant options. Add to this the need to also evaluate products at significant temperature extremes and this leads to a need to find ways to screen refrigerant and lubricant candidates that can reduce the options moving onto the next stages of compressor and system studies.

- This paper has provided a simple SWOT evaluation approach to minimizing the workload of refrigerant and lubricant investigation while understanding the benefits and challenges with each scenario.
- Key aspects to bench scale evaluation are presented that assist in the screening process.
- Strengths, Weakness, Opportunities, and Threats are outlined for low GWP refrigerants, lubricants for use with low GWP refrigerants and their interaction.
- Strategies to investigate options for R-404A replacements are presented based on HFO and Hydrocarbon refrigerants.
- Manipulation of miscibility for HFO based refrigerants to replace R-404A are outlined and examples of performance and cost benefit options are presented.
- Similar approach is shown for R-290 refrigerant with emphasis on reduced dilution for charge reduction.
- Stability results for various HFO based refrigerants are presented that show were challenges exist.

NOMENCLATURE

CFC	ChloroFluoroCarbon	ODP	Ozone Depletion Potential
HCFC	HydroChloroFluoroCarbon	GWP	Global Warming Potential
HFC	HydroFluoroCarbon	PFAS	Per Fluoro Alkylated Substance
HFO	HydroFluoroOlefin	cSt	Centistoke
HFCO	HydroFluoroChloroOlefin	PVT	Pressure-Viscosity-Temperature
PAG	Polyalkylene Glycol	AB	Alkylbenzene
PVE	Polyvinyl Ether	POE	Polyol Ester

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