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Evaluating Lubricants For Lower GWP Refrigerant Compressor Operations

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ABSTRACT

Refrigerant Lubricants are an essential component to refrigerant and air conditioning compressor operation regardless of the refrigerant used. But to maintain reliable and efficient operation, the choice of lubricant can vary depending on the type of compressor, design of the system and especially the kind of refrigerant.
Historically, refrigerants used in applications have changed over the period of time since the invention of refrigeration due to various reasons. Today the global warming potential (GWP) value that exists for each refrigerant are being scrutinized if the GWP value is deemed too high which could result in a negative environmental impact. One of the so called high GWP refrigerants is R-404A which is on the fast track to be minimized through regional and global phase downs and potential phase outs. Various replacement/substitute refrigerants exist today that have been evaluated or are currently being evaluated as lower GWP choices in place of R-404A refrigerant. For R-404A the typical lubricant of choice has been a synthetic lubricant such as a polyol ester (POE) which meets certain criteria for refrigerant and lubricant interaction. Replacement/substitute lower GWP refrigerants for R-404A will vary in the type of lubricant chemistry that is satisfactory for effective operation resulting in numerous lubricant selections.
This paper will evaluate lower GWP refrigerant options and what lubricant chemistry is best suited. Various rules that apply to what testing is needed to make the appropriate conclusions will be outlined and results of refrigerant and lubricant interaction will be presented. This data will then be used to determine how the changes in lower GWP refrigerant properties will dictate these lubricant options. This type of information will allow for maintaining the required compressor performance parameters associated with the industry.

1. INTRODUCTION

Since the beginning of the use of some type of mechanical refrigeration and air conditioning, the working fluid (refrigerant) used has taken center stage in not only the performance of the system but also how the various properties these refrigerant possess will affect the areas it is used in. Early refrigerants used in the late 1800’s and early to mid-1900’s like Methyl Chloride, Sulphur Dioxide, Carbon Dioxide, Ammonia and Hydrocarbons carried properties like toxicity, flammability and high pressure that brought about safety concerns evolved to ChloroFluoroCarbon (CFC) and HydroChloroFluoroCarbon (HCFC) synthetic refrigerants with less safety concerns. With the industrial revolution came the apprehension of how the environment was being effected by emissions which led to the investigation of CFC and HCFC refrigerants effect on the ozone. These refrigerants deemed as having some level of Ozone Depletion Potential (ODP) were soon mandated by protocols and laws to be phased out or phased down during a certain time period over the course of the late 1980’s until today. Once again, despite the benefits of performance properties, these refrigerants displayed the external environmental concerns require other options. Thus HydroFluoroCarbon (HFC) refrigerants which met safety concerns and ODP environmental concerns were developed along with expanded development on so called natural refrigerants (carbon dioxide, ammonia and hydrocarbons) to try to identify refrigerants that would maintain some level of performance while having no ODP. Systems in which these refrigerants are used will have varying levels of refrigerant leaking into the environment which can have a direct effect on the environmental response. Over time studies have claimed that the HFC refrigerants that migrate into the atmosphere have a relationship to the climate change due to the Global Warming Potential (GWP). This now has implemented another change to refrigerants that have a lower GWP which once again include natural refrigerants but also new synthetic refrigerants based on HydroFluoroOlefin (HFO) chemistry. Table 1 shows some of the history of refrigerants based on safety, environmental concerns and other observations.

Table 1: Refrigerant history information

Refrigerant	ODP	GWP	Safety and Other Considerations	Misc.
Methyl Chloride	0.02	9	Toxicity and Flammability concerns.	More recently this refrigerant designated as R-40 has caused some issues due to reactivity.
Carbon Dioxide	0	1	Non-toxic and high pressure gas.	Lower energy efficiency when used at higher ambient temperatures has been a limitation.
HC R290	0	~20	Non-toxic and highly flammable.	The flammability has led to maximum charge limits be set for use in various types of equipment.
CFC R12	0.82	10,900	Non-toxic and non-flammable.	Effect refrigerant based on system operation but ozone depletion potential has led to its removal.
HFC 134a	0	1430	Non-toxic and non-flammable.	Stable refrigerant chemistries but this stability results in too long of atmospheric life.
HFO 1234yf	0	<1	Non-toxic and mild flammability.	Lower GWP values sacrifice some stability when compared to HFC refrigerants.

In addition to the changes in refrigerants over the years, the mechanical mechanism mainly a compressor, has also evolved and expanded to meet certain requirements. Typically these compressors require some type of lubrication to maintain bearing integrity and efficient operation, so various types of lubricants are employed. Designing a lubricant for a particular compressor design and application is basically set by the design and application and may not vary significantly as the same type of compressor changes in size. This cannot be said though for changes to the refrigerant, over the years as we have seen changes to the refrigerants used we have also seen changes to the lubricants required. Lubricant and refrigerant properties like miscibility, solubility, stability are key to the successful and efficient operation of the compressor and system. Some of these lubricant changes over the years caused by refrigerant changes have been small but some have been very significant with an exhaustive amount of evaluation needed. Regardless of the level of change, it is important to understand the requirements needed for each refrigerant to be able to recommend the appropriate lubricants. This concept is no different today with some of the lower GWP refrigerants that are currently being targeted for use.

This paper will investigate some key lower GWP refrigerants either in the market today or being evaluated for future use to identify potential lubricant candidates. Lubricant and refrigerant properties will be discussed and compared to baseline refrigerants and lubricants used today. Other industry work on compressors and systems using some of these lower GWP candidates will also be discussed. The focus will be on alternate lower GWP refrigerants as substitutes/alternatives for HFC refrigerant R-404A.

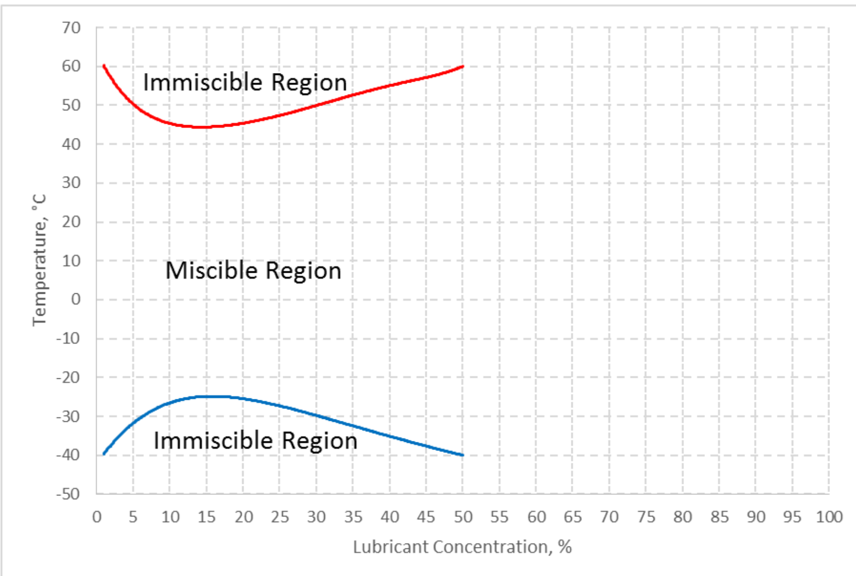
2. LUBRICANT AND REFRIGERANT INTERACTIONS

Understanding of the lubricant and refrigerant interaction is needed to create an operating system that is both reliable and has maximum energy efficiency. When refrigerants change, a bench study of the interaction is the first start to matching the right lubricant to the refrigerant. The interaction studies can be broken down into various areas of interest each providing both a first look approach and potential final approach to making a lubricant choice. These tests can provide a significant amount of information in a relatively short period of time which will benefit the lubricant supplier along with the compressor and system manufacturer. After bench studies, it is sometimes helpful to obtain other information based on initial compressor or system testing to help decide on direction.

2.1 Lubricant and Refrigerant Interaction - Miscibility

Typically without proper oil separation devices or techniques, lubricants used inside of a compressor sump will migrate into the system by way of the refrigerant or movement (velocity). Once out into the system, it is imperative that the oil move back to the compressor to eliminate any potential bearing lubricant starvation issues and minimizing of heat transfer degradation on the heat exchange surfaces. A quick screening tests can be performed either in sealed glass tubes or windowed cells, for higher pressure situations, to evaluate the interaction of the lubricant with the refrigerant. Lubricants at various concentrations can be viewed over specified temperature ranges to see when the mixture separates into two phases which is considered immiscible or stays one phase which is considered miscible. Figure 1 is a rendering of a typical miscible curve. These evaluations can be made quickly to understand if a current lubricant is going to be acceptable with a new refrigerant or if lubricant modifications are required.

Figure 1: Miscibility of lubricant and refrigerant



2.2 Lubricant and Refrigerant Interaction - Solubility

Whereas miscibility measurements are usually more of a concern for operations inside the system, solubility is usually a measurement valued inside the compressor or where the oil is being distributed. Concentration levels of refrigerant in the lubricant are measured and then the resulting pressure at varying temperature is measured and plotted. Figure 2 is a representation of a typical pressure vs temperature solubility plot. With this data and knowing operating conditions within a compressor system, the resulting dilution factor the refrigerant will have on the lubricant can be calculated. This dilution factor is important in determining proper lubrication properties that a bearing will experience at conditions. Other dilution information is also important to compressor system design and operation.

Once the solubility is determined, then this will translate into a viscosity of the combination of lubricant and refrigerant sometimes referred to as the "working viscosity". Figure 3 is a typical representation of a plot relating solubility of the refrigerant in the lubricant to working viscosity. The data plotted this way is sometime referred to as a pressure-viscosity-temperature plot or "Daniel Plot". These types of plots are essential to compressor design engineers to get a quick look at what value of film thickness that might be seen at a bearing with a particular lubricant and refrigerant to provide a screen before compressor testing is done. Today sophisticated equipment is used to make measurement of lubricant and refrigerant solubility and working viscosity values from which models can be developed to solve for different operating conditions. Figure 4 shows a picture of the environmental chamber and schematic of the equipment used to measure solubility and working viscosity of refrigerant and lubricant mixtures.

2.3 Lubricant and Refrigerant Interaction – Compressor and System Studies

Screening tests and system tests lasting 2-4 weeks can be used to help make intial studies of not only the candidate refrigerant but also a quick evaluation study of the lubricant. Compressor calorimeter and endurance testing can predict the effective capacity and efficiency that the new refrigerant provides along with expected durability. The lubricant choice can also affect the compressor efficiency and the endurance tests are the best way to identify the optimized lubricant formulation. System testing evaluates the overall benefits or deficiencies that refrigerant testing shows. System testing can also assess how the lubricant is affecting performance based on parameters like oil circulation rates and lubricant-refrigerant interaciton.

Figure 2: Solubility

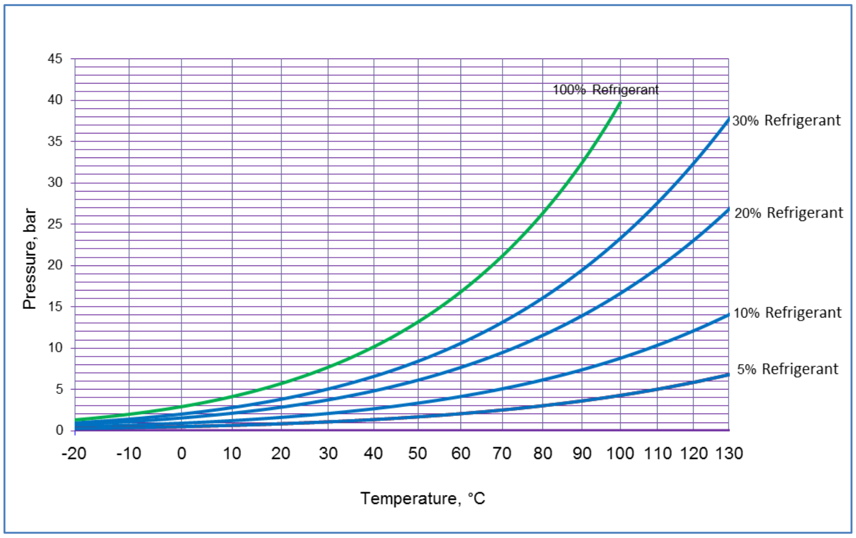


Figure 3: Pressure-Viscosity-Temperature (PVT) curve

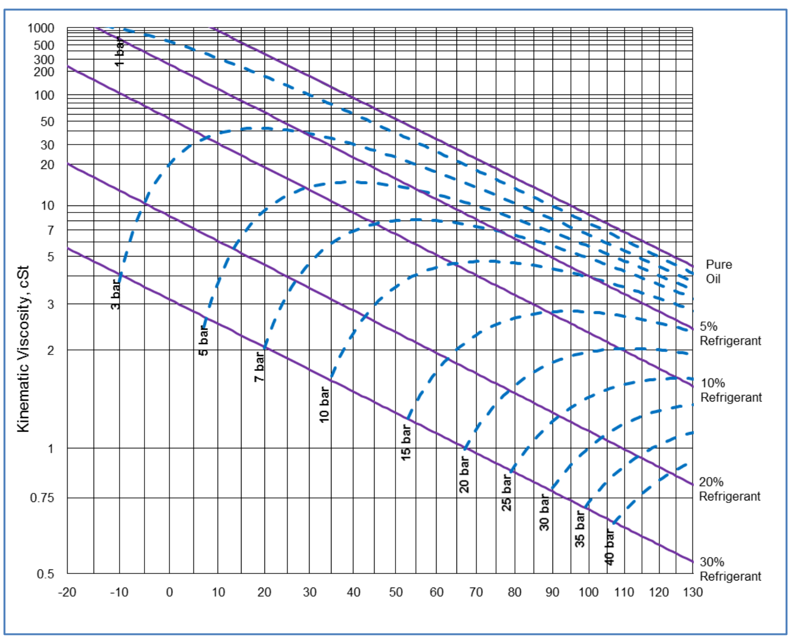
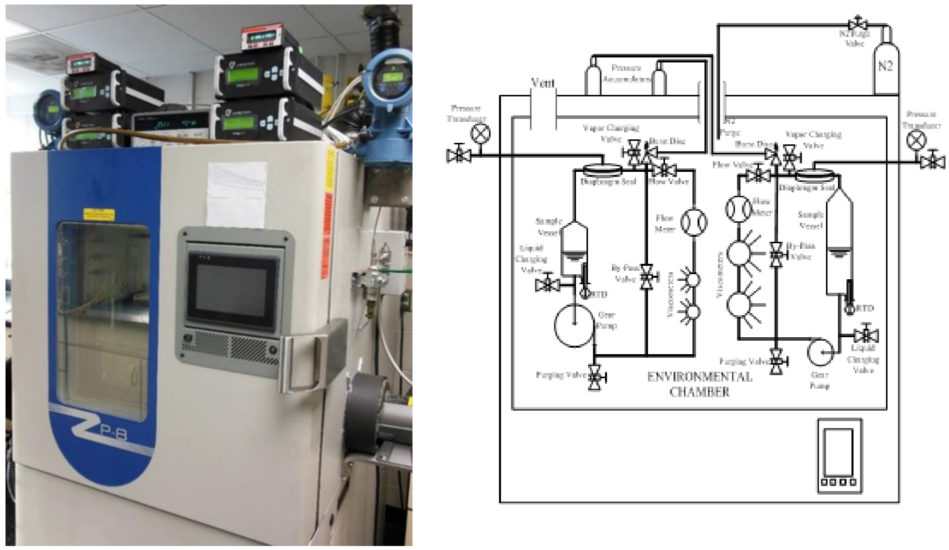


Figure 4: PVT Apparatus



3. Lubricant Studies for Lower GWP R-404A Substitutes

R-404A refrigerant is used in a number of low and medium temperature refrigeration applications ranging from commercial systems using smaller capacity reciprocating compressors to larger semi-hermetic compressors and scrolls used in supermarket rack systems. Since the GWP value of R-404A is one of the largest amongst HFC refrigerants used today, there is pressure to reduce the use of this refrigerant (phase down) to potential phase outs. The European Union has restricted use of refrigerants in certain applications having GWP values above 2500 starting in 2020, the so called F-gas Regulation. The U.S. EPA has also followed similar actions to de-list R-404A as an acceptable refrigerant for certain commercial applications. Given the recent pressure to control the use of R-404A, many compressor and system manufacturers are moving ahead with trying to identify solutions ahead on any phase-down or phase-out schedule. Even though some HFC refrigerants like R-407A and R-407F can meet the anticipated GWP level and R-744 (CO_2) has found more and more use in supermarket applications as a transcritical fluid, this paper will focus on other lower GWP candidates. The refrigerants I have chosen to discuss are three HFO/HFC that are non-flammable, a slightly flammable HFO/HFC candidate and a flammable HC candidate. Investigation will be made on how these refrigerants interact with lubricants and if current marketed lubricants used with R-404A are still good candidates to use with these particular lower GWP candidates.

4. HFO/HFC Blended Refrigerants

4.1 R-448A

This refrigerant is a blend of R32/R125/R134a/R1234yf/R1234zeE at percent concentrations of 26/26/21/20/7 and has an ASHRAE safety designation A1 with a GWP value of 1390. As a first look and comparison, the refrigerant was evaluated for miscibility with a number of lubricant candidates based on polyol ester (POE) chemistry that are used today with R-404A refrigerant. Table 2 is a snapshot of miscibility at 10 and 20 percent lubricant concentration in R-448A. OP in the table designates one phase or miscible and TP designates two phases or when the mixture became immiscible. As a comparative, the POE32 reference in the table has a 10 and 20 percent miscibility profile with R-404A that still maintains one phase below -60°C. Reviewing the data it shows that R-448A will have similar miscibility performance with the same lubricants used with R-404A. Given this similarity it would be predicted that based on the miscibility these lubricants could be used in the same type of applications that R-404A is used in without concern for system operating parameters that may minimize oil return and heat transfer.

Table 2: Miscibility Results of Various POE Lubricant Viscosities with R-448A

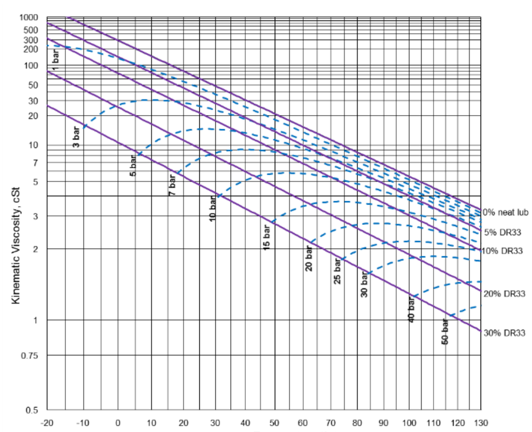
	POE 22		POE 32		POE 68A		POE 68B	
	10%	20%	10%	20%	10%	20%	10%	20%
20C	OP	OP	OP	OP	OP	OP	OP	OP
10C	OP	OP	OP	OP	OP	OP	OP	OP
0C	OP	OP	OP	OP	OP	OP	OP	OP
-10C	OP	OP	OP	OP	OP	OP	OP	OP
-20C	OP	OP	OP	OP	OP	OP	OP	TP
-30C	OP	OP	OP	OP	OP	OP	OP	TP
-40C	OP	OP	OP	OP	OP	OP	TP	TP
-50C	OP	OP	OP	OP	OP	OP	TP	TP
-60C	OP	OP	OP	OP	OP	TP	TP	TP

Recently a number of studies have been presented on lower GWP refrigerants through the AHRI Low GWP AREP and other independent manufacturer studies. These compressor and system tests are usually done as drop-in tests or with minimal changes. Sometimes these tests can provide some insight to the potential effect the lubricant might be having with the candidate refrigerant. Recently a couple of studies have been done with R-448A refrigerant in comparison to R-404A. Rajendran (2013) showed in a supermarket mock set-up that at a low temperature application (-22°F/-30°C evap) and at a medium temperature (12°F/-11°C evap) that R-448A when compared to R-404A baseline showed a 3% and 3-8% respectably improvement in energy efficiency. This data was consistent with performance measurements made on this refrigerant in comparison to R-404A. For the system test the scroll compressor POE lubricant used with R-404A was used with the R-448A and based on the system test performance results it would appear that the lubricant had no negative effect. In a separate study by Baba and Yamaguchi (2014), carried out in an inverter controlled unit at constant capacity, R-448A was compared to R-404A at condensing temperatures of 45°C to 55°C. Improvements in volumetric capacity between 6 and 10% and in COP between 4 and 7% were measured. Once again for this test the same POE lubricant used in the standard rotary compressor was used with the R-448A test, and the fact that there was no volumetric capacity loss is a good indication that this oil will not be challenged with solubility changes that could affect performance.

4.2 R-449A

This refrigerant is a blend of R32/R125/R134a/R1234yf at percent concentrations of 24/25/26/25 and has an ASHRAE safety designation A1 with a GWP value of 1400. As a first look and comparison, the refrigerant was evaluated for solubility and working viscosity with a POE lubricant candidate and compared to solubility and working viscosity data of the same POE lubricant with R-404A. Figure 5 shows the Daniel Plot for POE32 lubricant with R-449A.

Figure 5: Pressure-Temperature and Viscosity Data for POE32 and R-448A



Using this data and Daniel Plot data from POE32 with R-404A a comparison was made at four different pressures and two different temperatures. The comparison data is tabulated in Table 3. Even though there could be some difference in operating conditions between the two refrigerants that might result in slight changes to the numbers, this is a good indication that when using the same POE lubricant for both R-404A and R-449A the working viscosities provided to the bearings will be similar.

Table 3: R-449A and R-404A comparison with same lubricant

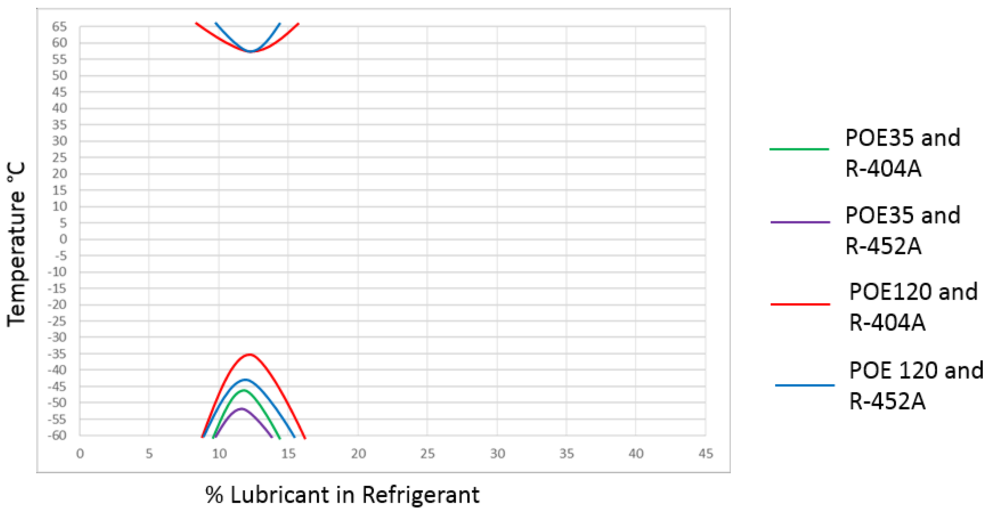
40°C	2 Bar	4 Bar	10 Bar	20 Bar	**80°C**	2 Bar	4 Bar	10 Bar	20 Bar
R-404A Dilution Viscosity	4% 24 cSt	10% 15 cSt	21% 6 cSt	NA	**R-404A** Dilution Viscosity	1.6% 8 cSt	5% 7 cSt	8% 5 cSt	20% 2.8 cSt
R-449A Dilution Viscosity	4% 23 cSt	10% 15 cSt	21% 5.5 cSt	NA	**R-449A** Dilution Viscosity	1.5% 9 cSt	4.5% 7.5 cSt	8% 4.8 cSt	20% 2.7 cSt

A system study was done with R-449A in comparison to R-404A baseline by Leck and Minor (2014) in a split condensing unit open display food case. A reciprocating compressor using a 32 centistoke POE lubricant was used for both tests changing only to fresh lubricant for the second test after the baseline test. Tests were conducted at a couple different ambient temperatures at both low and medium temperature conditions. The results indicated that R-449A showed 3-4% less energy consumption at low temperature and 8-12% less energy consumption at medium temperature over R-404A tests. These results along with the dilution and viscosity results in Table 3 would suggest that the lubricant has no negative affect on performance when operated with R-449A.

4.3 R-452A

This refrigerant is a blend of R32/R125/R1234yf at percent concentrations of 11/59/30 and has an ASHRAE safety designation A1 with a GWP value of 1945. Initial miscibility and solubility studies were done with the refrigerant and compared to R-404A/Lubricant studies. Current POE chemistry at various viscosities was compared by a manufacturer with R-404A and R-452A to see if the current POE lubricant could be used without complications. Figure 6 is a comparison study with two lubricants and the results indicate that miscibility differences between R-404A and R-452A are small and should not be an issue.

Figure 6: Miscibility study commercial comparison of R-404A and R-452A



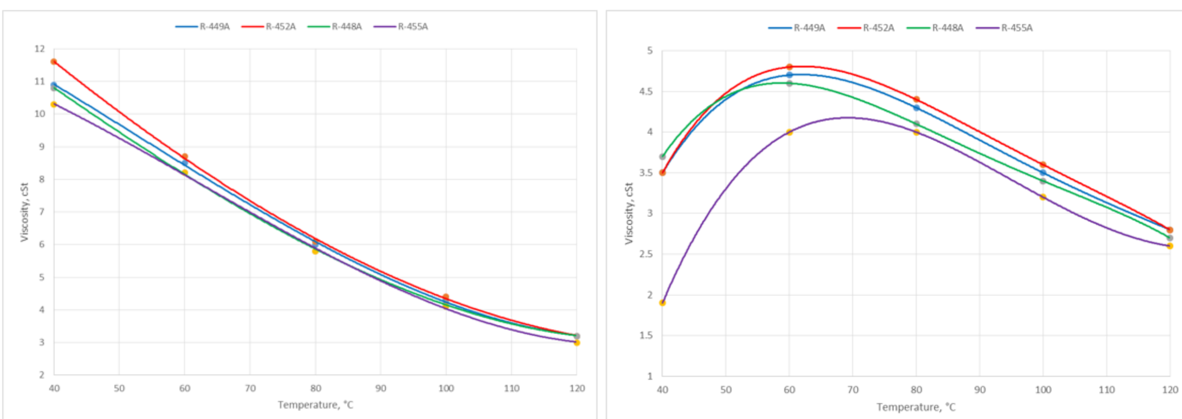
PVT data generated for the two POE lubricants listed in the miscibility tests indicated that these lubricants have similar profiles with the two refrigerants and would be considered similar enough that differences seen in compressor lubrication should also be minimal. Actually, compressor testing was done to confirm what was measured in the PVT data and no issues were reported.

As with the other R-404A substitute refrigerants discussed earlier some studies have been done with R-452A in compressors and systems and reference in literature data. A paper by Kujak *et al.* (2015) showed a system study that was done with a trailer transport refrigeration unit which commercially operates with R-404A. Baseline testing was done with R-404A and after measurements the system was operated with R-452A using the same POE lubricant. Results compared to the baseline study indicate that the volumetric efficiency at higher rpm speed was 2% lower while at lower rpm speed was 0.5% lower. The authors commented that these differences would be considered small enough to say that R-452A has similar performance to R-404A and these results would also indicate that the POE lubricant did not have a negative effect and is an effective product for R-452A.

4.4 R-455A

This refrigerant is a blend of R32/R1234yf/R744 at percent concentrations of 21.5/75.5/3 and has an ASHRAE safety designation A2L with a GWP value of <150. Since this refrigerant has some mild flammability compared to the previous three candidates it is more uncertain at this time about the potential commercialization but most likely will not be an issue. Miscibility tests with R-455A and the same POE32 lubricant mentioned in the previous studies indicates that the combination is fully miscible from 0 to 40% lubricant concentration at temperature measurements from 65°C to -60°C. From experience, lower temperature miscibility usually relates to the refrigerant having an increased level of solubility/dilution, therefore, it was valuable to make comparisons of the solubility/working viscosity of R-455A and the other HFO/HFC blends that were rated A1. Figure 7 are plots showing the working viscosity comparison of R-455A; R-448A; R-449A and R-452A over a range of temperatures at two different pressures with the same POE32 lubricant. The results do indicate that R-455A shows lower working viscosity at some conditions, this does seem to relate to the difference in lower temperature miscibility. There is not enough information to determine if these difference are significant.

Figure 7: Working viscosity differences of various R-404A substitute refrigerants



System tests have been conducted with R-455A in a commercial refrigeration unit and in a hermetic compressor. Yana Motta and Spatz (2014) showed test results of a ¾ HP single door reach-in freezer using a reciprocating compressor. No changes were made to the lubricant between tests with only slight changes to the evaporator flow, TXV and charge optimization. Results showed a 6% improvement in compressor efficiency and 3% system efficiency improvement and a 4% capacity loss was measured. These results appear to show no significant effect of the lubricant on performance with R-455A. A slight capacity difference could be from the thermodynamic differences of the refrigerant with possible minor changes related to the solubility factor difference. Zgliczynski and Sedliak (2016) showed results from compressor calorimeter studies on R-455A with a 1900 BTU/hr reciprocating hermetic compressor designed for R-404A. The same ISO 22 POE lubricant was used in both the baseline and alternate refrigerant study at varying evaporator temperatures (-40 to -10°C) and condensing temperatures (30 to 60°C). At the midpoint rating condition, the average capacity loss for R-455A was approximately 2% while the efficiency measured an average gain of approximately 6%. The authors commented that R-455A appears as a reasonable candidate for an R-404A replacement in lower temperature systems. Once again lubricant performance does not seem to be an issue. As an aside for discussion that will take place in the next section, comparison testing was also done in this study with R-290 refrigerant. Once again using the same ISO 22 POE lubricant, the results showed approximately 10% capacity loss and 11% efficiency gain. Solubility of R-290 will be discussed later.

5. HC Refrigerant

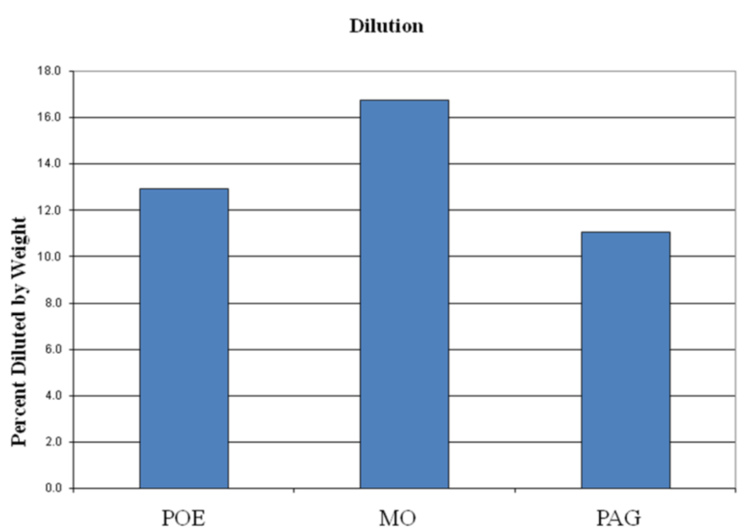
R-290 (propane) refrigerant is a single component refrigerant with an ASHRAE safety designation of A3 with a GWP value of <20. R-290 is not really a new refrigerant being investigated since it is already in use in many regions in various applications. Typically in light commercial types of systems, there is a limit to how much R-290 can be used due to the highly flammable nature of the refrigerant which can limit the size of the system in operation. In the previous section, some information was provided which compared the effectiveness of R-290 when compared to R-404A which showed better efficiency but some capacity loss. This loss in capacity could be mainly from the thermodynamics, but since R-290 has a high solubility level in most lubricants, this could also be playing a role. Unlike HFC refrigerants and the HFO/HFC refrigerants discussed earlier, R-290 can be used with mineral type oils but this brings about even higher dilution of refrigerant into the lubricant. Many compressor manufacturers have commercialized R-290 compressors using POE lubricants to help minimize the higher dilution factors that exist with mineral oils that may degrade volumetric capacity. Table 4 is a comparison of R-290 dilution in a mineral oil and a POE lubricant. The results show how dilution increases in the mineral oil.

Table 4: MO and POE dilution comparison of R-290

	4 Bar		8 Bar	
	MO	POE	MO	POE
20C	9.8%	7.5%	47.0%	35.0%
40C	5.4%	4.1%	14.2%	12.1%
60C	3.6%	3.0%	8.2%	6.9%
80C	2.6%	2.3%	5.5%	4.9%

The charge restriction in place for R-290 refrigerant usage minimizes the application and locations that this refrigerant can be used. Since the charge is limited to a certain amount, it is beneficial to understand the regions of a system that the refrigerant resides in to be able to potentially maximize charge usage. Fuentes and Hrnjak (2015) tried to measure and predict the distribution of the R-290 refrigerant in a typical light commercial unit like a beverage cooler. The results indicate that the majority of the charge was found in the condenser concluding the condenser redesign could be beneficial. Also the second highest location of the refrigerant was in the lubricant, attempting to minimize this level would also be helpful to not only charge maximization but also system performance. Lubricant chemistry as seen in Table 4 can play a role in this minimization and further optimization can be done with lubricant change. Figure 8 shows the dilution factor of three different lubricant chemistries.

Figure 8: Dilution factors for various lubricant chemistries at the same condition



5. CONCLUSIONS

Environmental concerns have moved the HVAC&R industry to evaluate other refrigerant options that have lower GWP values. These refrigerants still need to exhibit adequate to potential better performance because any gains made by the direct environmental effect of a low GWP refrigerant can be lost by the indirect effect of poor performance and reliability. R-404A refrigerant, due to its higher GWP value, is a target that many regions and manufacturers are looking to find alternate replacement refrigerants. Part of this performance and reliability evaluation of the system requires finding the appropriate lubricant which may or may not be the same as what was used with the refrigerant being replaced. This paper evaluated five potential candidates as substitutes for R-404A and the potential impact of lubricant chemistry. For the most part, certain lubricant chemistry currently used with R-404A in compressor operation is found to be satisfactory for use with all the refrigerants investigated by way of evaluating lubricant-refrigerant interaction or system performance studies. Lubricants like mineral oils which typically have been unacceptable for use with R-404A, due to miscibility concerns, are also not miscible with the HFO/HFC refrigerants studied. Since most of the tests outlined in this paper involved either drop-in scenarios or soft optimization techniques, it is always beneficial to determine ways to optimize the performance of the new refrigerant and this can include looking at ways to potentially optimize the lubricant.

REFERENCES

American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc, 2013 Fundamentals Handbook. Section 29 Refrigerants.

Baba, A., Yamaguchi, H., 2014, Performance evaluation of condensing unit using low GWP refrigerants, *The International Symposium on New Refrigerants and Environmental Technology,* Kobe, p. 269-273.

EPA, Final Rule, Federal Register Vol, 80 No. 138, July 20, 2015 Rules and Regulations 42870-42959, Significant New Alternatives Policy (SNAP) Program.

F-gas Regulation (EU) No 517/2014 of the European Parliament Fluorinated Greenhouse Gases.

Fidler, J., 1979, A History of Refrigeration Throughout the World, *International Institute of Refrigeration*.

Fuentes Y., Hrnjak, P., Elbel, S., 2015, Low-Charge Propane Refrigeration Systems Technology for Single and Multi-Door Bottle Coolers, *The 24th IIR International Congress of Refrigeration ICR 2015*, Yokohama, Paper ID 303.

Karnaz, J., 2013, Compressor and System Energy Efficiency Improvements through Lubricant Optimization, *8th International Conference on Compressors and Their Systems,* London, p. 163-171.

Karnaz, J., 2016, Lubricants for Low GWP Refrigerants, Seminar 16 Making the Commercialization of Low-GWP Refrigerants a Reality, *ASHRAE 2016 Winter Conference*, Orlando.

Karnaz, J., Kultgen, D., 2015, Making the Right Lubricant Choices, *The 24th IIR International Congress of Refrigeration ICR 2015*, Yokohama, Paper ID 338.

Karnaz, J., Liu, K., 2013, Lubricant and Refrigerant Properties – The Need for Lubricant Optimization with Various Type of Alternative Refrigerants, *The 5th International Conference on Cryogenics and Refrigerants*, Hangzhou, p. 116.

Kujak, S., Berge, J., Majurin, J., Kolda, M., Crombie, D., 2015, Assessment of Next Generation Refrigerant R452A to Replace R404A for Transport Refrigeration Products, *The 24th IIR International Congress of Refrigeration ICR 2015*, Yokohama, Paper ID 59.

Leck, T., Minor, B., 2014, Experience with Reduced GWP Refrigerants for Commercial Refrigeration and Air Conditioning, *International Symposium on New Refrigerants and Environmental Technology,* Kobe, p. 287-291.

Pottker, G., Yana Mota, S., Spatz M., Becerra, E., Smith, G., 2014, Refrigerants with Low Environmental Impact for Refrigeration Applications, *International Refrigeration and Air Conditioning Conference*, Purdue, Paper 1554.

Rajendran, R., 2013, Promising Lower GWP Refrigerants in Air Conditioning and Refrigeration Systems, *Advancing Ozone & Climate Protection Technologies, Bangkok*.

Yana Mota, S., Spatz M., 2014, Low Environmental Impact Refrigerants for AC and Refrigeration Systems, *The International Symposium on New Refrigerants and Environmental Technology,* Kobe, p. 282-286.

Zgliczynski, M., Sedliak, J., 2016, Compressor Calorimeter Performance Evaluation of Low GWP Alternatives top R404A in Low Temperature Applications, *AHRI Low GWP AREP*, Orlando.