Identifying lubricant options for compressor bearing designs

J Karnaz\textsuperscript{1}, C Seeton\textsuperscript{1} and L Dixon\textsuperscript{2}

\textsuperscript{1}Shrieve Chemical Products, Inc. USA
\textsuperscript{2}Shrieve Products International Ltd UK

E-mail: jkarnaz@shrieve.com
E-mail: cseeton@shrieve.com
E-mail: ldixon@shrieve.com

Abstract. Today’s refrigeration and air conditioning market is not only driven by the environmental aspects of the refrigerants, but also by the energy efficiency and reliability of system operation. Numerous types of compressor designs are used in refrigeration and air conditioning applications which means that different bearings are used; and in some cases, multiple bearing types within a single compressor. Since only one lubricant is used, it is important to try to optimize the lubricant to meet the various demands and requirements for operation. This optimization entails investigating different types of lubricant chemistries, viscosities, and various formulation options. What makes evaluating these options more challenging is the refrigerant which changes the properties of the lubricant delivered to the bearing. Once the lubricant and refrigerant interaction are understood, through various test methods, then work can start on collaborating with compressor engineers on identifying the lubricant chemistry and formulation options. These interaction properties are important to the design engineer to make decisions on the adequacy of the lubricant before compressor tests are started. This paper will discuss the process to evaluate lubricants for various types of compressors and bearing design with focus on what’s needed for current refrigerant trends. In addition, the paper will show how the lubricant chemistry choice can be manipulated through understanding of the bearing design and knowledge of interaction with the refrigerant to maximize performance. Emphasis will be placed on evaluation of synthetic lubricants for both natural and synthetic low GWP refrigerants.

1. Introduction
The world sits at a crossroads. Challenges like climate change try to focus on reducing the impact that refrigerants have on the environment while still balancing this with indirect emissions though energy consumption by equipment. As the world grows more accustomed to comfort cooling, domestic refrigeration, food preservation, etc., refrigeration and air-conditioning has become an integral part of how we go about our day. Residential, commercial, and industrial equipment used in refrigeration and air-conditioning products can account for 20-30\% of the electrical energy consumption in most regions. In the US three quarters of the homes have some form of air conditioning accounting for 6-8\% of energy consumption.
consumption [1]. Keeping this equipment reliable and energy efficient results in better preservation and comfort, cost savings and environmental benefits. The compressor in these systems is an essential component for performing the required work but it also consumes energy. For example, in restaurants, the electrical energy consumption associated to refrigeration is about 10-16% and for supermarkets 44-60%. In each case, the compressor is accounting for 75-80% of the consumption [2]. These types of values make operation of the compressor critical for maintaining adequate food preservation and distribution along with establishing appropriate levels of energy efficiency.

Today we are facing the additional complexity of evaluating alternate refrigerants that have less impact on environmental concerns like global climate change. As refrigerants are being evaluated, it is important that levels of reliability and performance are maintained or strengthened in systems when compared to refrigerants they are replacing. For the most part, compressors used in applications utilize a lubricant to help protect the bearings and perform other desirable tasks. These lubricants are always interacting with the refrigerant so understanding the impact of this interaction is essential to understanding the impact of performance. Evaluating interaction of the lubricant within compressors is a multistep task starting with the chemistry and property of the lubricant, the type of refrigerant being used, the compressor design, and system operation. Choosing the right lubricant can provide compressor operation that is reliable and efficient in combination with the refrigerant being used [3].

2. Refrigerant Direction
The world is becoming integrated by way of communication, trade, and other activities but there is still a difference when it comes to the use of refrigerants. Countries are not moving at the same pace or in the same direction when it comes to determining what they will chose as a viable refrigerant moving forward. Some developing countries still using R-22 appear to be considering other options instead of R-410A. The Kagali Amendment to the Montreal Protocol will minimize the use of HFC refrigerants in the future but is a phase down not a phase out so numerous refrigerant chemistries could be in play for several years [4]. Natural refrigerant options such as carbon dioxide, ammonia, and propane, though not new, are finding more acceptability and use for their low GWP values and availability. Countries where higher ambient temperature conditions exist are finding it difficult to move away from HCFC refrigerants to HFC refrigerants or to next generation lower GWP refrigerants due to higher operating temperatures and pressures that are generated. Other solutions might be needed for these situations.

Overall refrigerant use on a global outlook still has some uncertainty, but regardless of the refrigerant used the implications this introduces to operation of a compressor and lubricant should be investigated. Refrigerant and lubricant interactions will vary and sometimes significantly based on the chemistry of both parties and therefore must be evaluated on more of a case by case basis. Due to refrigerant properties, it takes advanced knowledge and special equipment/instrumentation to accomplish the tasks.

3. Lubricant and Refrigerant Interaction
Many papers, including those by these authors, describe the various things that should be evaluated for lubricant and refrigerant interaction. Probably the three most critical are: 1) stability; 2) miscibility and 3) working viscosity. Stability is handled by testing per ASHRAE Standard 97 or testing in pressure metal vessels [5]. Miscibility is the ability of the lubricant and refrigerant to maintain a single phase over a range of temperatures and concentrations. Typical miscibility curve is a measurement over a range of lubricant to refrigerant concentrations (1 to 50%) and temperatures that are representative of the system application, for example 50°C to -40°C [6]. When the solution indicates two phase separation, or in some cases a level of cloudiness, this temperature is recorded as the phase separation temperature. When measured over a range of concentrations, the curves that are drawn represent the maximum lower critical solution temperature (LCST) and the minimum upper critical solution temperature (UCST). Determining the working viscosity is more complicated of a procedure and to be done accurately needs special designed equipment to handle the range of operating temperature and pressure while simultaneously measuring the desired parameters. Seeton introduced this approach and
equipment which has been implemented by others over the years [7]. Most effective approaches to these measurements require analysis over a range of refrigerant concentrations and temperatures representative of system operation. Once measurements are made, modelling of the results provide coefficients that can be used to input into equations to calculate dilution, density, and viscosity. These coefficients and equations can be incorporated into a solver program that can output values with inputs of temperature and pressure. Figure 1 below is an example of coefficients derived from a test and equations for calculating the required values. This type of information has been an essential tool to assist compressor and bearing design engineers.

| coeff | Pressure | Density | Kin. Visc. |
|-------|----------|---------|------------|
| a1    | 6.5942E+00 | 1.2884E+00 | 1.6174E+01 |
| a2    | -2.0840E+03 | -1.1726E+03 | -2.5479E+00 |
| a3    | 1.1019E+05 | 6.4681E+07 | 0.0000E+00 |
| a4    | 4.9823E+00 | 1.9433E+01 | 2.4105E+01 |
| a5    | -2.4298E+03 | 7.3487E+04 | -4.4680E+00 |
| a6    | 2.0527E+05 | -2.1003E+06 | 0.0000E+00 |
| a7    | 5.9950E+01 | 1.3269E+00 | -4.0466E+01 |
| a8    | -4.2760E+02 | -6.7821E+03 | 6.7974E+00 |
| a9    | 5.4673E+04 | 8.2914E+06 | 0.0000E+00 |
| a10   | 0.999891  | 0.9996   | 0.9936     |

Vapor Pressure:
\[ \log_{10}(P) = a_1 + \frac{a_2}{T} + \frac{a_3}{T^2} + \log_{10}(\omega) \left( a_4 + \frac{a_5}{T} \right) + \log_{10}(T) \left( a_6 + \frac{a_7}{T} \right) \]

Density:
\[ \rho = a_1 + a_2 T + a_3 T^2 + a_4 \left( a_5 + a_6 T + a_7 T^2 \right) + a_8 \left( a_9 + a_{10} T + a_{11} T^2 \right) \]

Kinematic Viscosity:
\[ \log_{10}\left( \nu \right) = a_1 + a_2 \log_{10}(\rho) + a_3 \log_{10}(T) \]

\[ + a_4 \left( a_5 + a_6 T + a_7 T^2 \right) + a_8 \left( a_9 + a_{10} T + a_{11} T^2 \right) \]

Figure 1: Coefficients and Equations used in Daniel Plot Graphs

4. Compressor Design and System Demand

Understanding bearing lubrication is an important core need for compressor design engineers. Calculations can be made to measure desired film thickness needed for a bearing to sustain an operational lifetime and meet efficiency constraints. Over the years, with the advancement of computer speed and capacity, modelling programs for bearings have become an important step in bearing evaluations with lubricants. Numerous bearing designers offer programs that can determine film thickness measures with inputs of certain parameters. For applications where just the lubricant is present this is usually a straightforward input of bearing sizes, surface finish and particularly the viscosity of the lubricant at conditions like temperature. Most of this information is easily accessible by the bearing design or compressor engineer. But for calculations in refrigeration and air conditioning where the refrigerant now plays a vital role in determining what these operating parameters and subsequent inputted values are, it becomes more burdensome to obtain accurate information. This makes testing as described earlier for lubricant and refrigerant interaction more valued to the designer and today has become as important as asking for information like chemistry and base oil viscosity of a lubricant.

Each compressor type is designed differently and within each design, bearing design can vary. When it comes to evaluating and choosing a refrigeration lubricant, it is essential to make the evaluation in a systematic approach considering the compressor type and internal design. The next few sections will look at various types of refrigeration and air conditioning compressor designs and account for what is important to consider when looking for the appropriate lubricant. We will assume that lubricant and refrigerant interaction has already been evaluated for stability and system compatibility.

4.1 Rotary

Many rotary compressors are used in the air conditioning market in a variety of applications. Particular lubrication challenges within rotary operation is that the lubricant operates under discharge temperature and pressure conditions and the vane-roller bearing interface is predominately in boundary lubrication. The vane-roller interface dynamic is usually not solved by the lubricant viscosity but more so with the incorporation of additives that have extreme pressure (EP) and/or antiwear (AW) functionality [8]. Usually the lubricant viscosity is raised high enough to allow for some small amount of film thickness without degrading efficiency at the other bearings. Operating at higher temperatures typically means
the dilution factor of refrigerant in the lubricant is moderate but the higher temperature also means the base oil viscosity will be lowered. For rotary compressors, it is beneficial to have a lubricant that can minimize refrigerant dilution (without sacrificing other system requirements), a base oil with a higher viscosity index, a higher pressure-viscosity coefficient (though in the presence of refrigerant, the lubricant $\alpha$ coefficients differences are minimized), and an effective formulated additive package. The other bearings in the compressor are typically journal bearings and thrust surface bearing which can be lubricated adequately with the base lubricant viscosity, but if too high, can result in some frictional drag increase. The bearing material used in most rotary compressors is some form of ferrous based material so additive selection is more straight forward if it remains compatible with the lubricant and refrigerant. The lubricant choice in these compressors is usually a factor of providing enough viscosity to maintain compressor bearing durability but compressor engineers today are trying to push the limits of the lubricant to help achieve better energy efficiency. So a combination of reducing base oil viscosity, lubricant chemistry and additive technology is being challenged to find solutions.

**Lubricant Keys:**
Rotary compressors over the years with different refrigerants have been consistent on the base oil viscosity requirements which is 68 cSt. These compressor bearing designs are typically challenged by the additive that is used and how this additive is impacted by the bearing material, base oil chemistry, refrigerant, and bearing mechanism. Rotary compressors are more suited for higher evaporator temperature application which limits the effective operating range and range of capacity. These situations usually help to define the need for a limited base oil viscosity range. Rotary compressors are always formulated with an additive package that helps to minimize bearing wear. Over the years the selection of additive chemistry has been critical to maintain levels of effectiveness and compatibility with certain lubricants and refrigerants.

### 4.2 Reciprocating
Reciprocating compressors are a piston driven compression mechanism with a large variety of sizes, design, and lubrication complexities. Since these compressor types can range from very small capacity hermetic units to large hermetic and semi-hermetic units, the lubricant selection is a broad range of viscosity and chemistry depending on the application and refrigerant type. Bearing design in reciprocating compressors are a variety of types, material, and motions of operation along with the method that lubricant is distributed to the bearing. This complexity makes lubricant recommendation a complicated effort of modelling design and compressor testing. Today with requirements to obtain energy efficiency levels or commercial competitive advantages to providing efficiency most reciprocating compressors are designed to have minimal oil film thickness. This is especially evident in small compressor designs for applications like refrigerators or light commercial applications where small changes to lubrication can influence compressor efficiency and reliability [9]. Figure 2 is a representation of what can happen when a bearing design is not maximized for working viscosity. If viewed as a modified Stribeck Curve, when the working viscosity is too low, energy efficiency is sacrificed due to potential bearing wear. If working viscosity is too high, efficiency suffers due to bearing drag. The concept of lowering the base oil viscosity to achieve better energy efficiency has been utilized for years in the refrigerator compressor design as depicted in Figure 3. As with every bearing design, there are limits to the surface finishes and oil distribution where at some point too low of viscosity results in bearing fatigue and efficiency losses.
Lubricant Keys:
The reciprocating compressor due to its diversity of sizes and applications requires a larger variation of lubricant base viscosities and additive chemistries to cover the range. Lubricant viscosity requirements can range from 3-32 centistokes in small fractional horsepower compressors up to viscosities in the range of 68 to 100 cSt in larger units operating in such applications as supermarkets. Additive chemistry can vary because the bearing material used in compressors can be made of iron, copper or aluminium substrates which will have different interaction properties and additive effectiveness. Since different bearings in reciprocating compressors can be affected by both the refrigerant pressure differential associated with an application and the compression ratio, most of the time the lubricant base oil viscosity is over engineered for larger compressors and stretched to its lower viscosity limit in smaller capacity compressors. Another difficulty with reciprocating compressor lubricant selection is that these compressors operate over a very wide range of low temperature to high temperature evaporator designs and for most cases the same lubricant is desired.

4.3 Scroll
Scroll compressors have found many uses especially in air conditioning applications because of the levels of energy efficiency and sound that can be achieved under certain conditions. Scroll designs have both compressor low side operation or high side operation so this needs to be taken into consideration for lubricant selection. The scroll wraps used in the design as the compression mechanism is a critical component for lubrication and is sometimes equipped with tip seals to enhance lubrication [10]. Other bearing lubrication needed for scroll compressors are journal or sleeve bearings, Oldham rings and sometimes roller bearings. Many scroll designs today operate with R410A refrigerant operating with an ISO 32 lubricant in low side design and up to an ISO 68 lubricant in scroll compressor operating as a high side design. Like with all applications improving energy efficiency is always an ongoing project even with current R410A designs. Today, transitioning away from higher GWP R410A has scroll compressor manufacturers looking at R32 refrigerant which brings about some lubricant selection challenges. These challenges will be discussed later under lubricant options.

Lubricant Keys:
For scroll compressors used in both air conditioning/heat pump applications and in commercial refrigeration, most designs use a lubricant with base oil viscosity of 32 cSt. The operational conditions and design of the compressor usually doesn’t call for the need of additives in the oil to enhance or protect lubrication so bearings are typically designed to be optimal with the ISO 32 base oil. The choice of lubricant for scroll compressors is more fixed on the refrigerant and maintaining optimized lubricant-refrigerant interaction properties. A lubricant challenge that sometimes can exist with scroll compressor
design is that they are capable of handling more liquid refrigerant when compared to reciprocating and rotary compressor designs. This needs to be considered when evaluating working viscosity calculations.

### 4.4 Screw

Lubrication of screw compressor bearing designs is usually not driven by optimizing the lubricant to provide energy efficiency improvements. The lubricant supply to the screw mechanism and other bearings, usually roller bearings, is maintained at a high enough working viscosity to preserve bearing separation and provide sealing to minimize refrigerant leakage loses. Most screw compressors operate with base oil viscosity above ISO 100 and the working viscosity with some refrigerants have presented some challenges to both providing a high enough base viscosity and using the right lubricant chemistry. Lubrication for screw compressors is managed by an oil separator on the discharge side or an oil sump inside the compressor operating under suction conditions. With either mechanism the working viscosity requirements with the refrigerant is usually a wider viscosity range instead of specific values to achieve minimal bearing film thickness like in other compressor types. Challenges exist with trying to find high enough lubricant viscosity for certain lubricant chemistries. For example, when operating with R22 refrigerant many screw compressors designs had to move from mineral oil type lubricants to synthetic chemistries to obtain a high enough lubricant viscosity. These challenges were easily met but today with refrigerants like R1234zeE another challenge exists because of the high dilution potential that this refrigerant has with numerous types of lubricants. For example, many screw compressors operating with R134a use POE lubricants with viscosities in the range of 100 to 220 cSt, and when evaluated at discharge conditions, give adequate working viscosity. But when the working viscosity of these same lubricants are measured with R1234zeE, the values fall short of what is desired. Other lubricant chemistry options are needed to solve this issue. Table 1 is a comparison of lubricant chemistries with R134a and R1234zeE at operating conditions showing how alternate lubricant chemistries like polyalkylene glycols (PAG) can match current operation.

| Lubricant / Refrigerant | Dilution, % | Viscosity, cSt |
|-------------------------|-------------|---------------|
| ISO 170 POE / R134a     | 15          | 13            |
| ISO 170 POE / R1234zeE  | 32          | 3.5           |
| ISO 100 PAG / R1234zeE  | 23          | 12            |

**Lubricant Keys:**

Screw compressors fall in-line somewhat with reciprocating compressors when it comes to the range of lubricant viscosities required for various applications. Typically, base oil viscosity range from 68 cSt up to 400 cSt depending on refrigerant, OEM viscosity requirements and application. Since the screw bearings are designed to operate on a large amount of working viscosity, most lubricant recommendations are in the range of 5 to 20 cSt working viscosity for lubrication via the compressor sump and some oil separation on the discharge side. Most screw compressors that are operating with oil supply from the discharge oil separator are aiming for working viscosity in the range of 15 to 50 cSt. Usually these compressors operate with very high viscosity lubricants in the 220 to 400 cSt range or work with oil cooling after the separator to increase working viscosity at refrigerant dilution. Lubricants for screw compressors usually work without the use of additives for wear and friction reduction.

### 5. Lubricant Options for Low GWP Refrigerants

Based on all the discussions we have had on lubricant-refrigerant interaction and compressor bearing operation, it is valuable to look at what lubricants are best suited to meet these demands. Usually for this exercise it is best to break out by refrigerant type to determine measured interaction properties, then evaluate based on compressor type and specified needs within a system.
5.1 Hydrocarbon Refrigerants

As the chemistry changes, so does the amount of dilution and the working viscosity. For the AB example, the dilution is around 10% with a viscosity of 5 cSt; for POE dilution at 7.5% and viscosity at 8 cSt and for PAG the dilution is reduced to 5% and viscosity increased to 15 cSt. In some applications, the values associated with the AB or POE might be adequate for the bearing design but there may be instances that this is still too low. The PAG provides the advantage of having a higher viscosity but also lower dilution which can help in applications that are restricted today by charge limitation of flammable refrigerants. It is also easy to adjust the viscosity of the PAG without changing the chemistry since it is a polymer. This can be an advantage when moving to lower starting base oil viscosity which can benefit compressor efficiency.

The same concepts and principles can be used for rotary compressor operation where lower solubility and higher viscosity can be an advantage especially at the vane and roller interface. Typically, these applications will be compared with lubricants with starting viscosities closer to 68 cSt, but once again the advantage the PAG chemistry brings might result in the ability to lower the starting viscosity [12].

5.2 R-32
R-32 refrigerant has emerged as a lower GWP alternative to switching away from R-22 or as a substitute to R-410A. Even though R-32 is 50% of R-410A it has significant differences regarding miscibility and working viscosity compared to R-410A and current lubricants. This has required evaluating different lubricants to meet the desired miscibility and working viscosity for both scroll and rotary compressor
A novel lubricant chemistry has been developed to try to answer some of the need. A typical lubricant used with R-410 in a scroll compressor will have a miscibility range at around 20% lubricant of 40°C to -25°C. The new lubricant will show similar miscibility with a range of 30°C to -20°C at the 20% lubricant concentration. The working viscosity is another challenge because trying to maintain an equivalent R-410A miscibility with some lubricants has resulted in a working viscosity reduction that is not adequate for effective compressor bearing operation. This new lubricant can answer this problem by matching what is typically measured with R-410A and current lubricant at operational conditions.

Table 2 below shows measured PVT data for miscibility, solubility, and working viscosity for:

1) R-410A and a 32 cSt POE lubricant (baseline current market product)
2) R-32 and 32 cSt POE lubricant
3) R-32 and a POE lubricant developed for R-32
4) R-32 and 56 cSt POE lubricant developed for R-32
5) R-32 and new lubricant chemistry
6) R-410A and new lubricant chemistry

Table 2: Lubricant Development for R-32 Refrigerant; Comparison to R-410A Products

| Conditions used for R-410A: 39°C and 12.5 bara | Conditions used for R-32: 41°C and 13 bara |
|-----------------------------------------------|---------------------------------------------|
| Above Combinations | Dilution, % | Viscosity, cSt | Miscibility at 20%, °C |
| #1                | 18          | 7.2            | -25            |
| #2                | 13          | 6.8            | 10             |
| #3                | 14          | 5.8            | -20            |
| #4                | 15          | 9.1            | -15            |
| #5                | 15          | 9.4            | -25            |
| #6                | 20          | 8.7            | -50            |

The new lubricant chemistry for R-32 shows working viscosity and miscibility that matches or exceeds the standard associated with R-410A. The working viscosity of this product is more equivalent to a higher viscosity POE designated for R-32 and an additional benefit of this product is that it should be effective as an R-410A lubricant.

6. Conclusion

Numerous examples have been presented on compressor type and bearing design associated with the HVAC&R market regarding lubrication. There is much complexity that should be understood when developing and recommending lubricant options for compressor design and system application. This requires experts in the field and specialized equipment to make accurate evaluation and analysis. The refrigerant market is evolving and this requires stability, miscibility, and working viscosity data on each refrigerant and lubricant combination to advance this development and provide the compressor and system engineer the data they require. Some examples were given of current day needs for lubricants for some lower GWP refrigerants that are being evaluated for various markets using different compressor types and the benefits these lubricant options can present. In summary, for certain lower GWP refrigerant options the following lubricant needs are recommended. Lubricants for R-32 refrigerant will require enhancing the miscibility while maintaining the required working viscosity. This will require some lubricant base chemistry changes. Lubricants for HFO-1234zeE will require a lubricant that reduces the high solubility effect produced by this refrigerant and the lubricant should have an increased viscosity index. Lubricants for hydrocarbon refrigerants like R-290 will require reducing the solubility factor of this refrigerant to help maintain working viscosity and this should also help benefit in situations of charge limitation requirements/restrictions.
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