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International Institute of Ammonia Refrigeration  
1001 North Fairfax Street, Suite 503  
Alexandria, VA 22314

703-312-4200 • [info@iiar.org](mailto:info@iiar.org) • [www.iiar.org](http://www.iiar.org)

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## Technical Paper #11

# CO<sub>2</sub> systems: Lubricants and Oil Management Strategies

Giacomo Pisano, M.Sc. Engineering,  
DORIN USA

### Abstract

*The use of carbon dioxide (CO<sub>2</sub>), especially in industrial refrigeration systems, has received a lot of attention in the last decades. As for any equipment, a correct lubricant choice and a proper oil management strategy are key for the safe, reliable, and efficient operation of refrigeration systems. This paper describes how to select the most appropriate lubricant, both from a compressor and a systems perspective. The lubrication properties, Daniel plots, viscosity drops, and system oil management of the most common lubricants used in CO<sub>2</sub> refrigeration systems—polyolester (POE) and polyalkylene glycol (PAG)—are described. Oil management design features and guidelines are provided for the most common system configurations, including DX and pumped and overfed (ejector) executions, to select the optimal lubricant and oil management strategy for any application involving CO<sub>2</sub> as the refrigerant.*



## **Introduction**

Selecting the most appropriate lubricant and its associated oil management strategy is key for a safe and reliable system operation.

Transcritical carbon dioxide (CO<sub>2</sub>) applications are associated with large differential pressures, which induce specific loads in the compressor drive gear up to five times higher than those of HFCs, HFOs, and ammonia [1]. From a compressor perspective, the selected oil should provide effective lubrication to prevent premature compressor wear and failure.

Furthermore, lubricant dilution into the refrigerant is a key parameter to be considered when designing CO<sub>2</sub> systems. The specific behavior of oil-to-refrigerant miscibility curves should also be considered, noting that CO<sub>2</sub> solubility in the lubricant is higher than that of other refrigerants [1]. From a systems perspective, the selected oil management strategy should ensure that the oil carried over into the system is properly fed back to the compressor's suction groups.

## **Lubricant selection from a compressor perspective**

The most widely used lubricants in CO<sub>2</sub> applications are polyolester (POE) and polyalkylene glycol (PAG) [2]. From a compressor perspective, both lubricants should be evaluated using Daniel plots that describe the pressure-viscosity-temperature (PVT) behavior of CO<sub>2</sub> and the given lubricant. These plots allow for visually checking the amount of refrigerant dissolved into the lubricant and the viscosity drop experienced by the lubricant during its actual operation in the compressor sump.

The figure below shows the residual visual viscosity for both PAG68 and POE85 at an oil temperature of 60 °C (140°F) and 32°F SST. The plots reveal that the resulting mixture of oil and refrigerant indicates residual viscosities of 15 cSt and 10 cSt when

using PAG68 and POE85, respectively. This outcome suggests that both lubricants can be considered valid options under these operating conditions but PAG68 performs better than POE85.

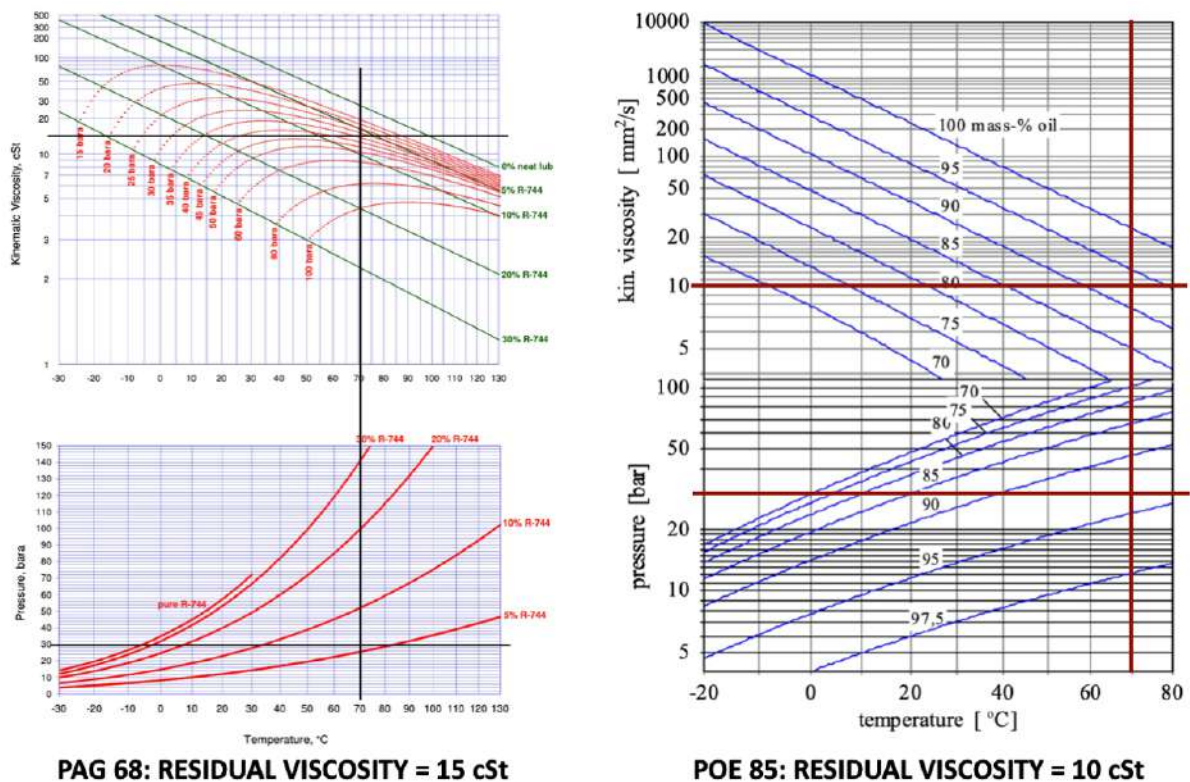


Figure 1. PVT diagrams (Daniel plots) for PAG68 and POE85 in a CO<sub>2</sub> gaseous environment.

Munoz et al. [3] performed a detailed investigation using the same lubricants at different oil temperatures and varying operating conditions, as shown in the figures below.

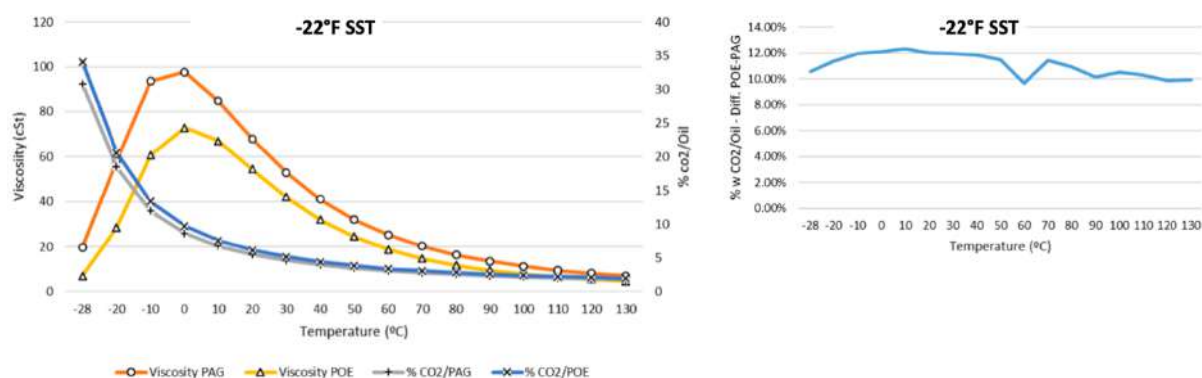


Figure 2. Residual viscosity and solubility of PAG68 and POE85 in a CO<sub>2</sub> gaseous environment at -22°F SST.

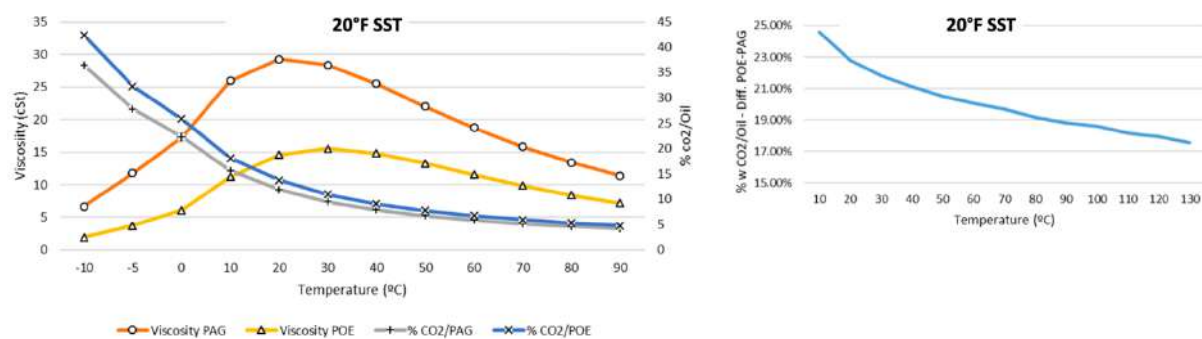


Figure 3. Residual viscosity and solubility of PAG68 and POE85 in a CO<sub>2</sub> gaseous environment at 20°F SST.

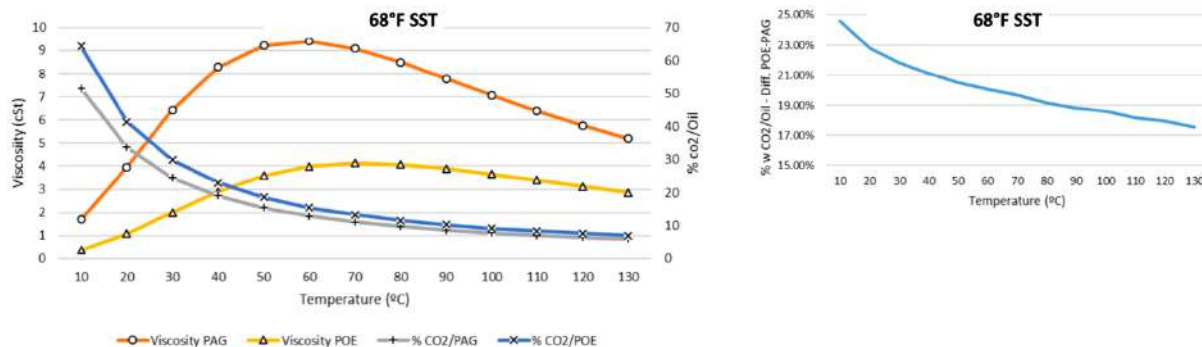


Figure 4. Residual viscosity and solubility of PAG68 and POE85 in a CO<sub>2</sub> gaseous environment at 68°F SST.

The previous figures show that POE85 absorbs more gaseous CO<sub>2</sub> than PAG68 under all operating conditions. This result suggests that PAG68 is a more effective lubricant, as also indicated by the residual viscosity graphs, which show that PAG68 always exhibits higher residual viscosities. However, the real, practical compressor operating conditions should be considered because such conditions result in drive gears experiencing oil temperatures between 60°C and 80°C (140–176°F). Hence, in addition to PAG68, POE85 provides an acceptable residual viscosity at low and medium SST (e.g., -22°F SST and +20°F SST). Nevertheless, if higher SST values are considered (e.g., in the case of heat pumps, with 68°F SST), POE85 is no longer an option because it results in low residual viscosity.

Notwithstanding, the PVT diagrams for PAG68 and POE85 show that both types of lubricants can be used in a wide range of applications (low temperature (LT) with SST of -22°F and medium temperature (MT) with SST of 20°F). However, this theoretical behavior should be verified through internal tests, which typically include:

- Steel ball test: This test determines the load-carrying capabilities of a lubricating grease under high-load applications.
- Compressor qualification test: This test is used to formally approve a compressor design before its commercial launch.

The figures below illustrate the results of the laboratory steel ball wear tests, using POE85 and PAG68. The figures show the wear width and sliding surface appearance obtained in the tests at pressures of 70 bar (1015 psi) and 80 bar (1160 psi).

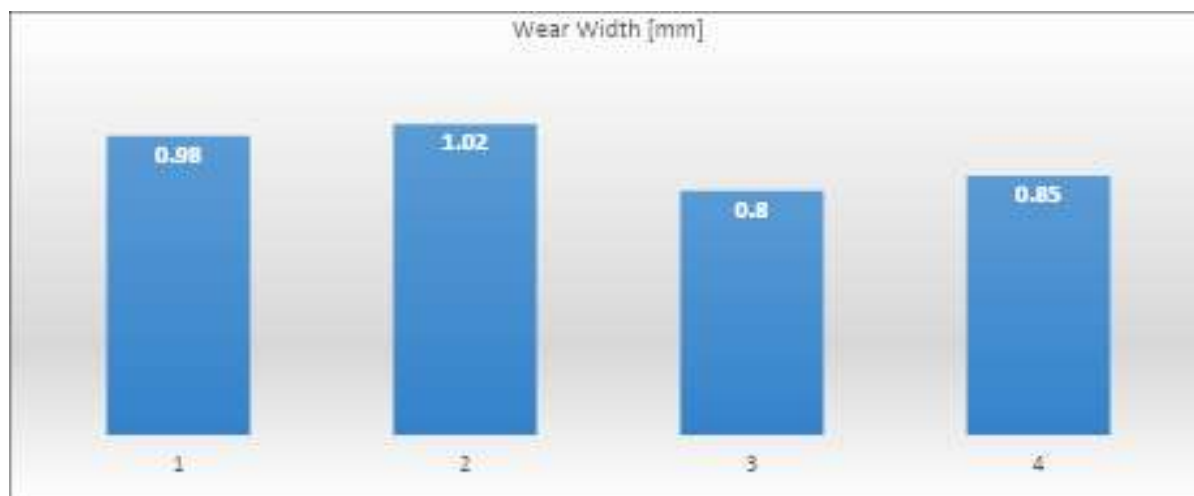


Figure 5. Wear width steel ball test.

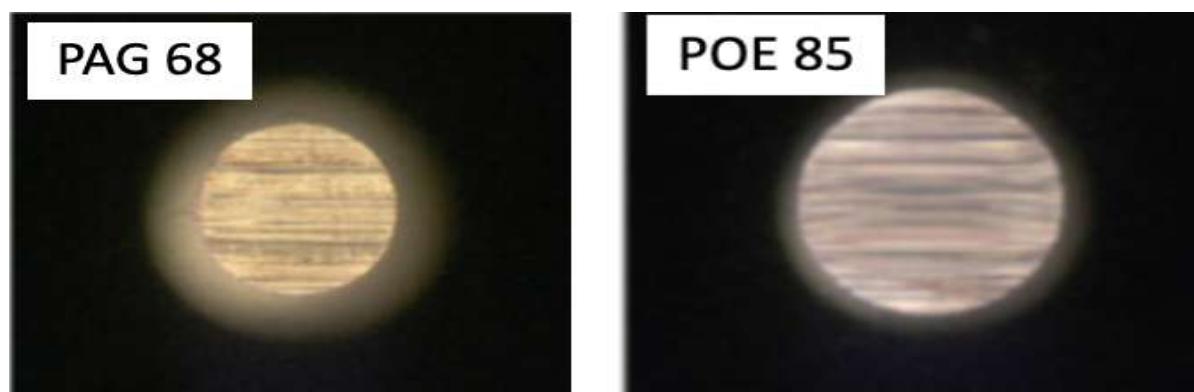


Figure 6. Sliding surface appearance.

Steel ball wear tests demonstrated that PAG68 performed slightly better than POE85 in terms of wear width and surface appearance. The wear width measured using PAG68 peaked at 0.85 mm with an 80-bar load, against the 1.02 mm wear width measured with POE85. Furthermore, the surface appearance was smoother, with fewer scars per mm<sup>2</sup>, when using PAG68. Nevertheless, even if POE85 performed slightly worse than PAG68, the measured data indicate that both lubricants are suitable for CO<sub>2</sub> compressors.

However, the steel ball wear test alone is insufficient to assure reliable compressor operation throughout its lifetime. Thus, specific qualification tests are generally conducted by compressor manufacturers before commercial launch [1]. These tests were also performed in our case, with satisfactory results for both PAG68 and POE85 in low- (e.g., -22°F SST) and medium-temperature (e.g., +22°F SST) applications.

The figures below display the components of the same compressor models after being subjected to qualification tests using PAG68 and POE85.



Figure 7. Shaft journals after qualification tests – PAG68.



Figure 8. Bearings and pistons after qualification tests – PAG68.



Figure 9. Shaft journals after qualification tests – POE85.



Figure 10. Bearings and pistons after qualification tests – POE85.

The figures prove that both PAG68 and POE85 can be used with CO<sub>2</sub> in low- and medium-temperature applications. In particular, PAG provided a slightly lower surface polishing on the shaft journals and a slightly lower wear rate on the bearing surfaces.

## Lubricant selection and oil management from a systems perspective

Lubricant choice and oil management strategy are among the most important factors to be evaluated when designing a CO<sub>2</sub> refrigeration system. The choice between PAG68 and POE85 should be made keeping in mind several parameters, one of the most important being considerably different miscibility with liquid CO<sub>2</sub>.

While POE85 is fully miscible with liquid CO<sub>2</sub> in the most common evaporating temperature ranges [4], PAG68 is only partly miscible [5], as shown in the figures below.

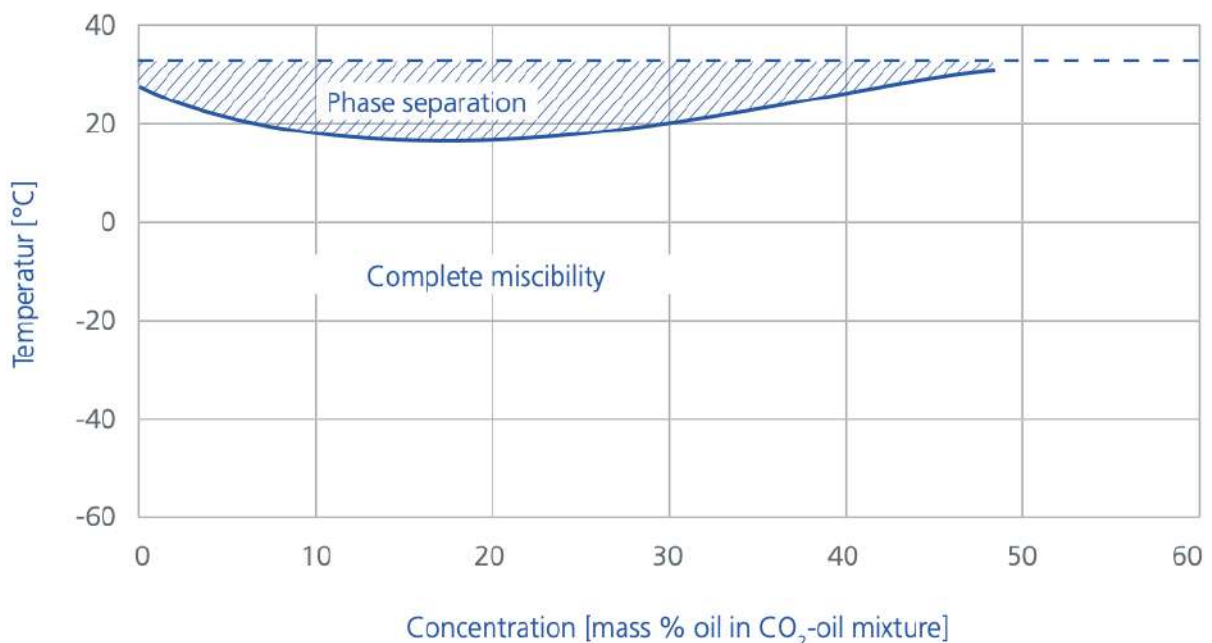


Figure 11. POE85 and liquid CO<sub>2</sub>: full miscibility.

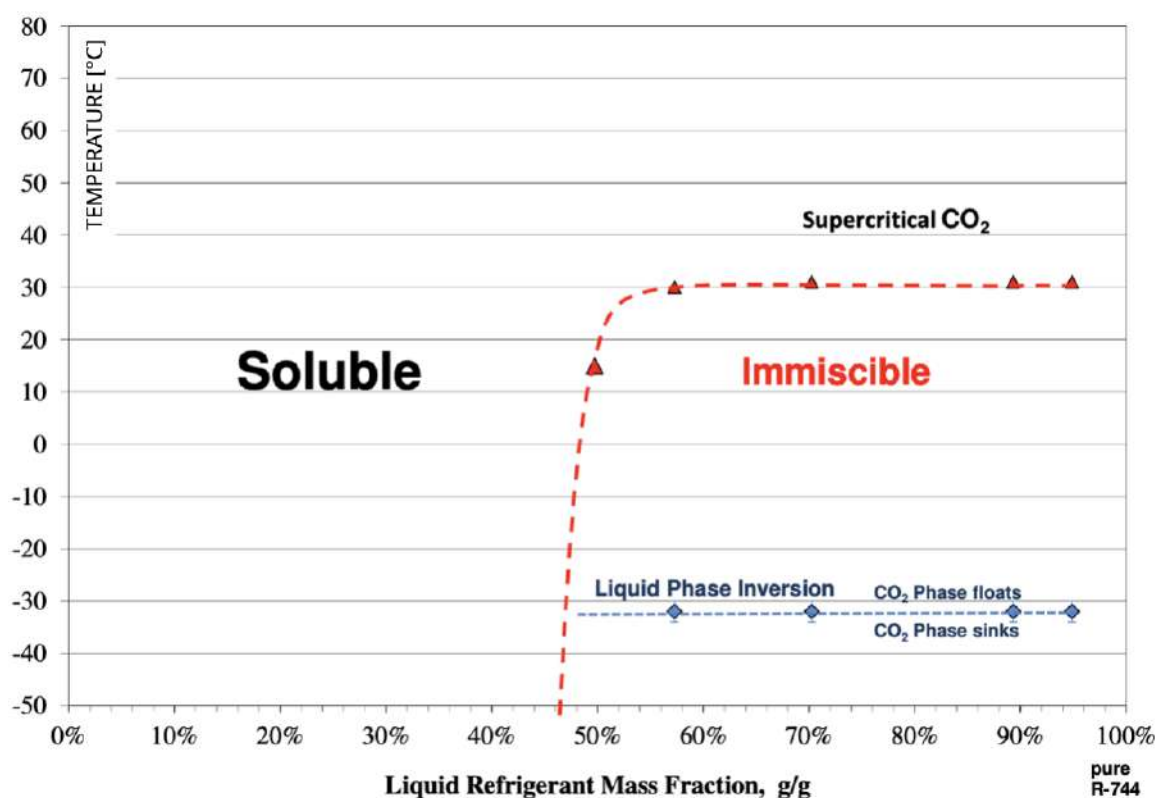


Figure 12. PAG68 and liquid CO<sub>2</sub>: partial miscibility.

The previous figure shows how PAG68 becomes less dense than liquid CO<sub>2</sub> below -32°C (-25.6°F) SST; in other words, it sinks above this temperature and floats on top of liquid CO<sub>2</sub> below this temperature.

The features of the aforementioned oils make the difference in terms of lubricant choice. No lubricant can fulfill all the needed lubricity and miscibility requirements; thus, lubricant selection and oil management are case-specific. The following chapters provide guidelines for the design of the most common refrigeration systems (dry expansion and pumped and overfed (ejector) executions of a CO<sub>2</sub> booster transcritical installation).

### Oil management - Dry expansion CO<sub>2</sub> booster system

The most typical dry expansion (DX) CO<sub>2</sub> system architecture is represented by a booster flash gas bypass execution, which can be improved from an efficiency standpoint by adding parallel compression [6]. The figure below shows a simplified sketch of a booster parallel compression system, including the oil management strategy.

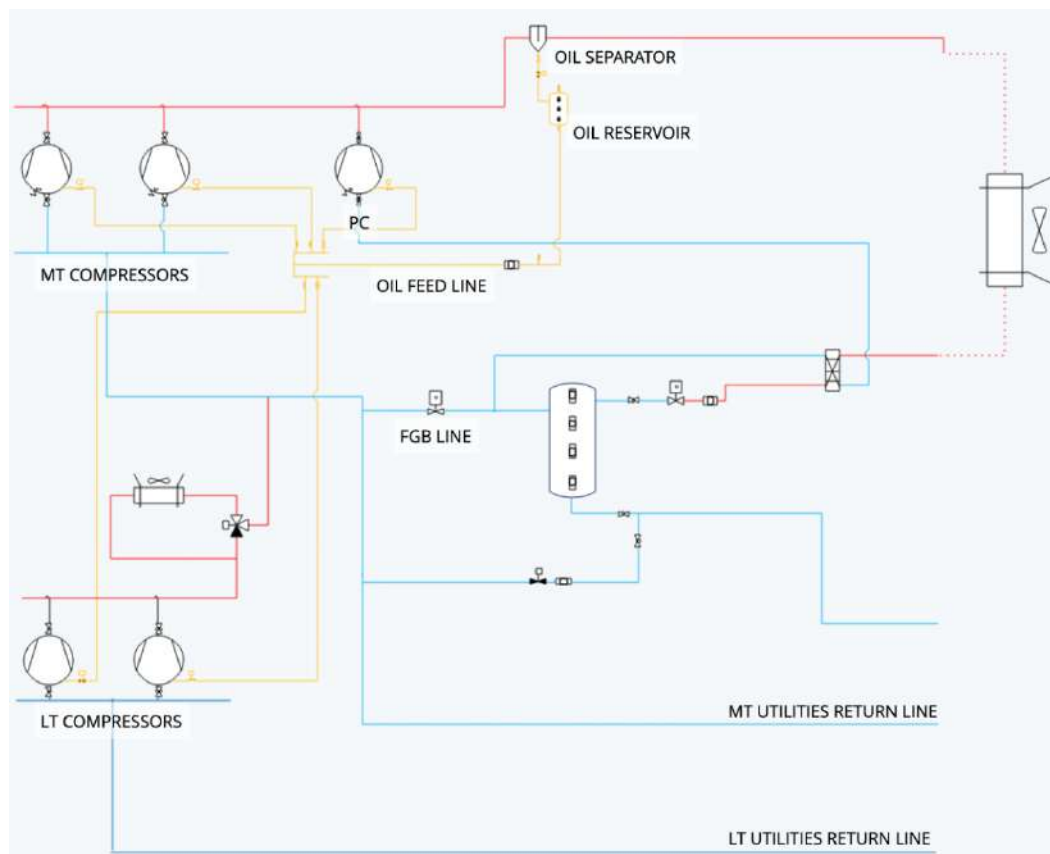


Figure 13. Sketch of a CO<sub>2</sub> booster dry expansion system with parallel compression.

Three compressor suction groups can be identified in this figure: the low temperature (LT), medium temperature (MT), and parallel compression suction groups. The LT

suction group compresses the gas stream coming from LT utilities. When parallel compressors are not engaged, three contributions make up the MT suction stream: LT compressor discharge, MT utilities return line, and flash gas bypass line. The MT compressors discharge the stream; therefore, this group contains the total system's CO<sub>2</sub> mass flow but also contains the oil entrained from both MT and LT compressors. If parallel compressors are engaged, their execution follows the MT suction group.

Therefore, an oil separator is placed after the MT and parallel compressors' discharge to separate the lubricant from the refrigerant. This arrangement allows almost pure CO<sub>2</sub> to move toward the gas cooler. The oil being separated accumulates in the separator's bottom and is then fed toward the LT, MT, and parallel compression suction groups. The lubricant is normally fed back to compressors, using oil floats and controllers. When the oil level is below a certain threshold in a given compressor sump, a solenoid valve opens its specific return line, allowing the oil level to be replenished in the compressor.

However, oil separator efficiency is not 100%. Various oil separators are available in the market, with manufacturers declaring separation efficiency up to 98% [7]. Thus, although a substantial part of the oil entrained by the LT, MT, and parallel compressors is effectively separated, a small mass fraction of the lubricant keeps moving toward the gas cooler and through the utilities. This small amount of lubricant should be recovered in a timely manner to avoid a lack of lubrication in the compressors. POE85 and PAG68 perform well in typical booster DX systems; both lubricants exhibit adequate oil return properties once the refrigerant is fully evaporated. There are more than 35,000 CO<sub>2</sub> DX systems running worldwide, either with POE85 or PAG68, evidencing these lubricants' effectiveness [8].

In addition, pipe runs should be properly executed to ensure that oil returns from the gas and utilities to the rack. The following figure provides some indications in this sense.

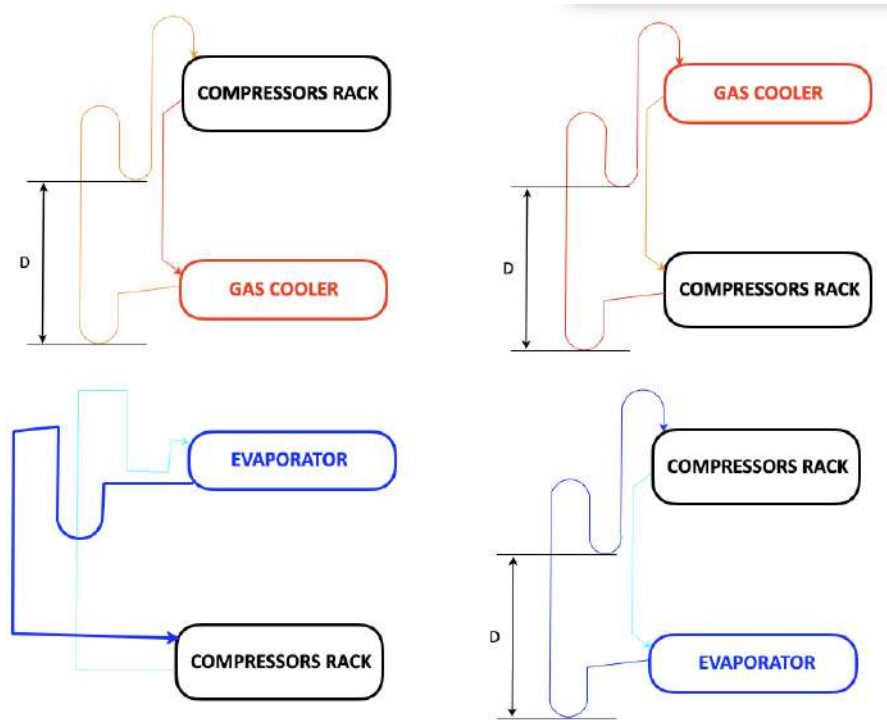


Figure 14. Pipe routing: simplified sketch.

This figure's main takeaways relate to the distance between raisers, which should be around 6 ft., and the slope of the horizontal pipes, which should trend downward, following the direction of the flow, descending 1" for every 20 ft.

CO<sub>2</sub> systems are often questioned regarding their energy efficiency because of their power consumption in warmer climates, where coefficient of performance (COP) values are normally penalized when no technical solutions aiming at lower power consumption are introduced. Flooded and overfed configurations, such as pumped systems and ejector technology, help improve performance [6]. However, these implementations bring new challenges from a lubricant choice and oil management perspective. These challenges are described in the next sections.

### *Oil management – Pumped CO<sub>2</sub> booster systems*

Pumped CO<sub>2</sub> execution is quite popular in industrial refrigeration systems or winter sports venues, such as ice-skating rinks. In such systems, liquid CO<sub>2</sub> circulates into the evaporators and accumulates in a low-pressure drum. When the drum pressure increases, compressors are engaged to maintain the drum pressure at the desired level. The figure below presents a simplified sketch of a low-temperature, transcritical CO<sub>2</sub> pumped system.

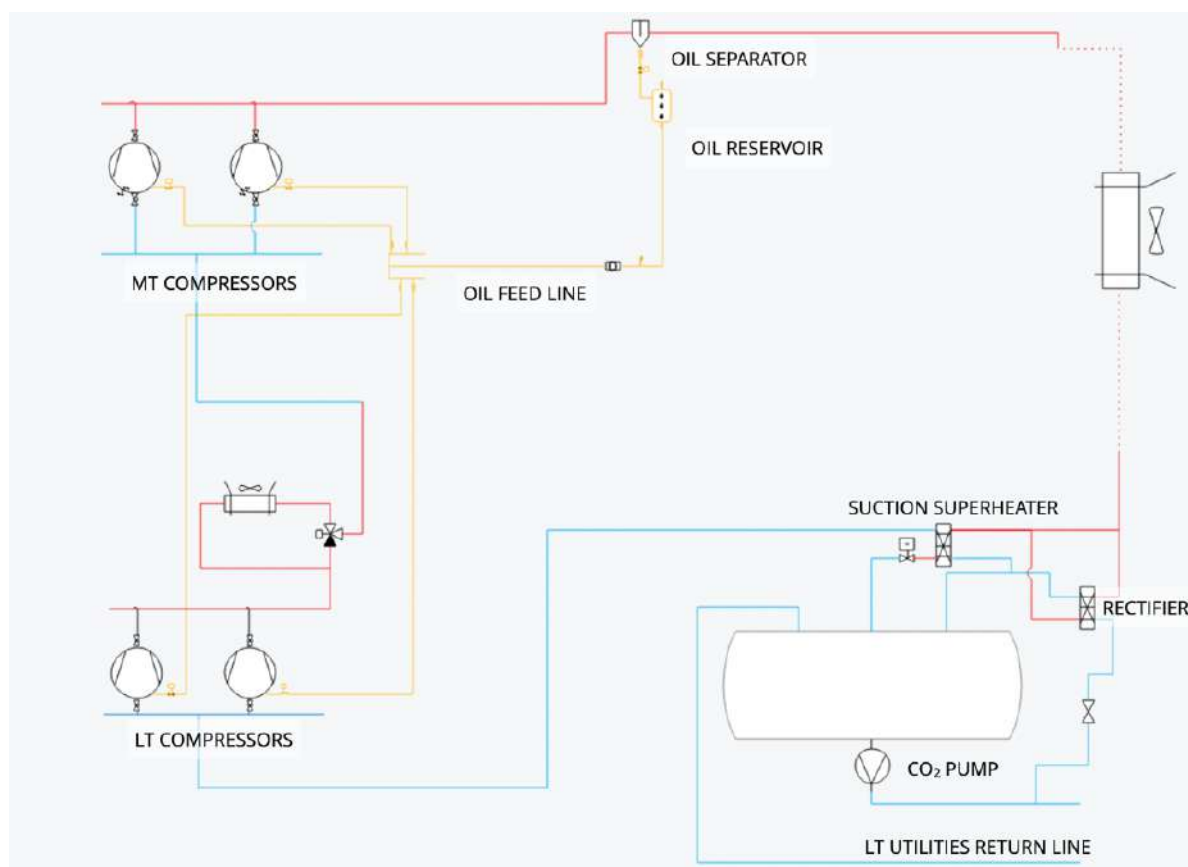


Figure 15. Low-temperature, transcritical CO<sub>2</sub> pumped system.

Oil separators do not attain 100% efficiency; thus, a certain amount of oil ends up flowing into the low-pressure drum, together with liquid CO<sub>2</sub>. This oil is normally recovered using a rectifier, which evaporates an oil-rich CO<sub>2</sub> flow bringing the lubricant toward the compressor suction line.

However, as mentioned in Section 4, care should be taken regarding lubricant selection: POE85 is fully miscible with liquid CO<sub>2</sub>, whereas PAG68 is partly miscible with liquid CO<sub>2</sub> and features density inversion below -32 °C (-25.6°F) SST.

Hence, when a CO<sub>2</sub> pumped system for typical MT operation (-10°C/14°F SST) is considered, both POE85 and PAG68 can be recovered via a rectifier. However, when it comes to an LT system, typically operating at -40 °C (-40°F) SST, POE85 becomes the preferred solution. At such a low saturation temperature, PAG68 floats on top of the CO<sub>2</sub>, complicating its recovery using a standard rectifier.

Therefore, both POE85 and PAG68 are valid options for typical MT pumped systems, whereas POE85 is the preferred solution for LT operations.

### *Overfed CO<sub>2</sub> booster systems*

The performance penalties of using CO<sub>2</sub> have been questioned in the case of high ambient temperature operations. This is especially concerning regarding the overall COP of the system. Therefore, this issue has been tackled with the implementation of numerous technical solutions, such as ejectors, since 2013 [6]. A typical CO<sub>2</sub> booster system layout, including ejectors, is shown in the figure below.

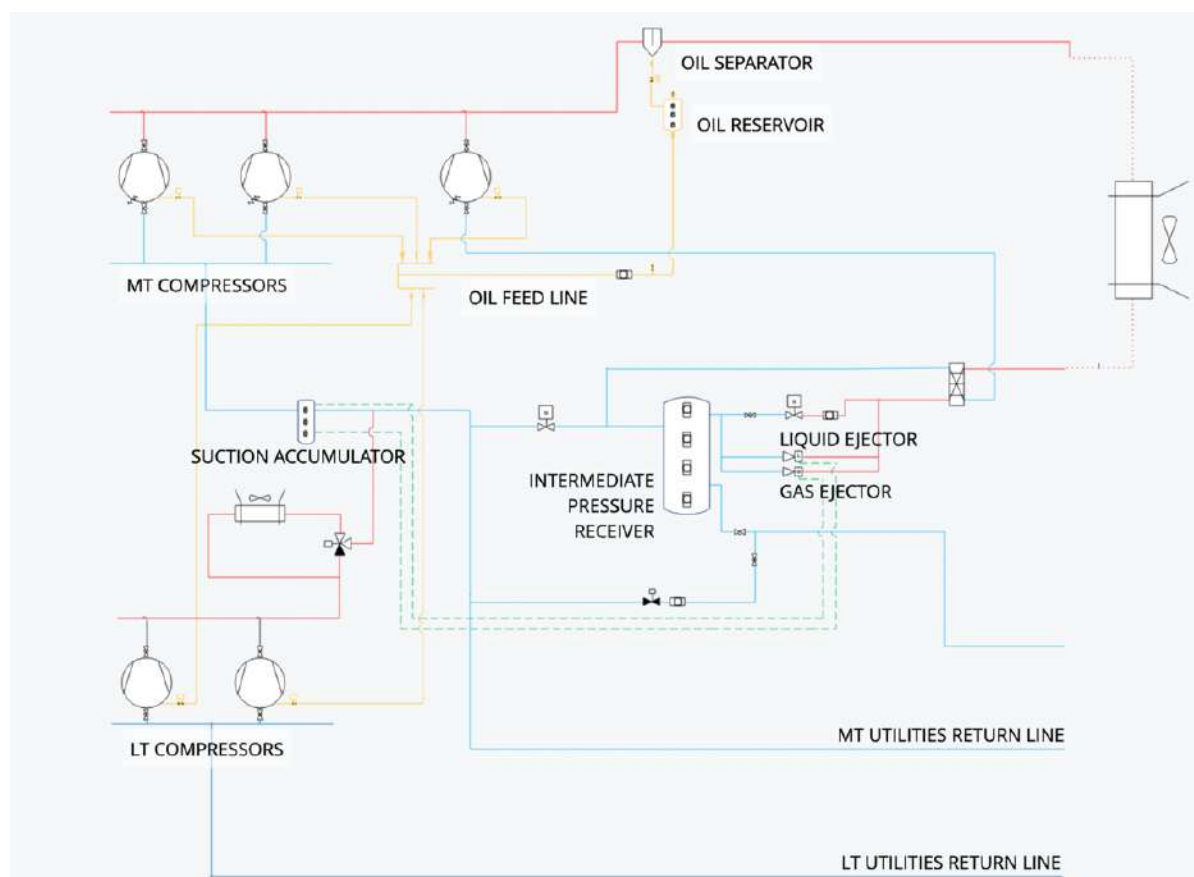


Figure 16. A CO<sub>2</sub> booster system featuring ejector technology.

Ejectors help improve the system's efficiency. In particular, liquid ejectors allow to run utilities overfed, with no superheat, thus optimizing heat transfer and minimizing the evaporator's  $\Delta T$  [6]. However, this means that a portion of the liquid refrigerant is likely to come back to compressor suction with time, necessitating the use of a generously sized suction accumulator to avoid compressor damage and premature failure.

From an oil management perspective, an ejector-based overfed system is associated with several considerations. As mentioned, oil separators do not achieve 100% efficiency; thus, some of the oil will find its way toward the gas cooler, the intermediate pressure receiver, and the utilities and suction accumulator. Therefore, a reliable oil management strategy should be in place to periodically recover this

lubricant. The parts of the system where this oil recovery could be most easily attempted are within the system receivers (e.g., the intermediate pressure receiver (IPR) and/or the suction accumulator).

However, because POE85 is completely miscible with liquid CO<sub>2</sub>, removing it from the refrigerant is challenging unless rectifiers are used. Nevertheless, doing so would partly void the zero-superheat efficiency gain introduced with the ejector technology.

Therefore, PAG68 is a simpler, more efficient, and safer lubricant solution for CO<sub>2</sub> refrigeration systems including ejector-based overfed systems. When considering the saturated conditions in the suction accumulator (-6°C/22 °F) and the intermediate pressure receiver (5°C/41°F), it is evident that PAG68 will always be denser than liquid CO<sub>2</sub>, thus sinking in the vessel's bottom and making it easier to recover.

The figure below summarizes how PAG68 stratifies and creates oil-rich zones in a vessel where liquid CO<sub>2</sub> accumulates, depending on the vessel's saturated conditions.

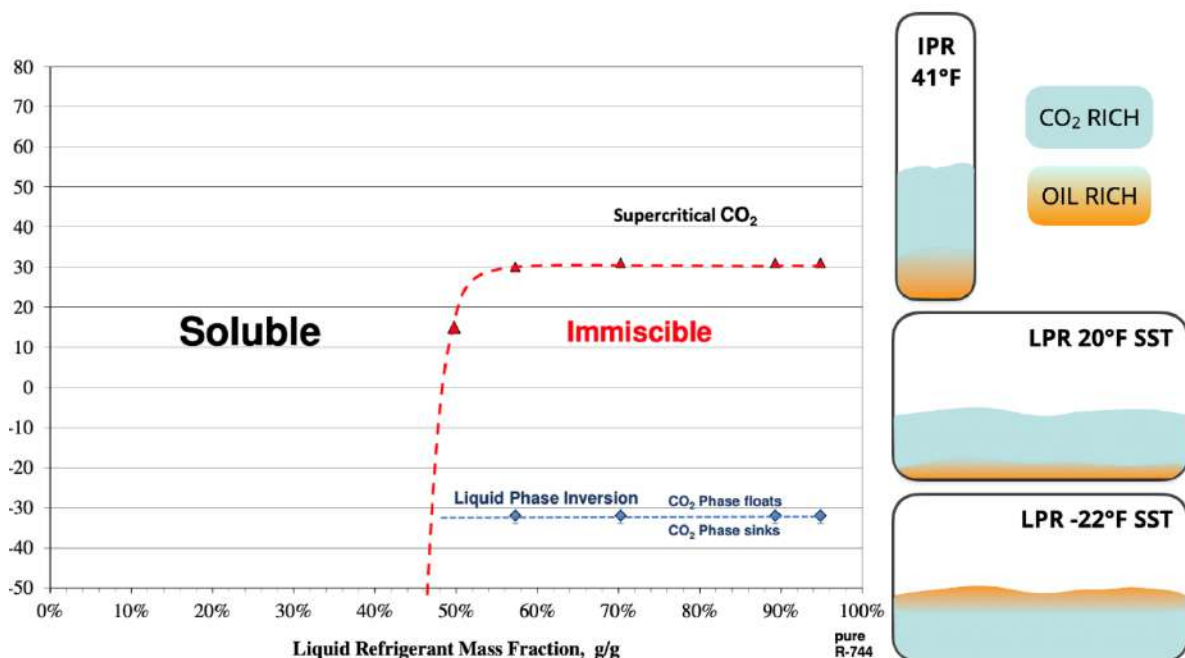


Figure 17. PAG68 oil-rich phase, depending on the saturated conditions.

## Conclusions

This work dealt with lubricants used in CO<sub>2</sub> refrigeration systems, both from a compressor and a systems perspective. The two most common lubricants used in such systems are POE85 and PAG68.

Compressor-wise, both lubricants were appropriate as they exhibited an acceptable viscosity drop and thus assured a proper oil film with the correct viscosity throughout the compressor's lifetime.

On the other hand, there are specific considerations regarding the oil management strategy, depending on the system's design. Several configurations were considered and the findings are summarized in the figure below.









|       | BOOSTER DX  | PUMPED MT   | PUMPED LT   | OVERFED EJECTORS  |
|-------|---|---|---|---|
| POE85 |  |  |  |  |
| PAG68 |  |  |  |  |

Figure 18. Adequacy of POE85 and PAG68 for various applications.

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## Notes:

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