Optimized Low GWP Replacements for R-410A in Stationary Air Conditioning

Joshua HUGHES*, Sonali SHAH

The Chemours Company, Fluorochemicals,
Wilmington, Delaware, USA
joshua.hughes@chemours.com

* Corresponding Author

ABSTRACT

R-410A is one of the most widely used fluids for small and mid-sized air conditioning systems globally. While R-410A has many positive attributes for cooling, it is the subject of valid criticisms regarding its high direct global warming potential (GWP) and environmental impact.

Although no single refrigerant fluid has yet been developed that meets every proposed requirement for use in conventional R-410A type stationary air conditioning system designs, blended HFO-based refrigerant compositions have been developed and optimized to provide improved overall safety and performance, while retaining significant environmental sustainability properties versus the legacy refrigerants. This paper discusses two potential alternative fluids, DR-55 and DR-5A, that have been developed to most nearly meet the most often cited sets of environmental, physical and performance properties for air conditioning. DR-55 and DR-5A are optimizations of GWP, flammability, and performance while retaining compatibility with existing R-410A system designs to enable an orderly transition to low GWP.

Data presented will include thermodynamic properties, performance test results, thermal stability, lubricant miscibility, and materials compatibility compared to the existing refrigerant. Performance will be evaluated in a residential air conditioning system designed for R-410A with minimal equipment modifications at both standard air conditioning and high ambient temperature operating conditions. These new refrigerant blends provide useful options to help maintain the quality of life and health benefits from air conditioning and refrigeration, but in an energy efficient, cost effective, and environmentally sustainable manner.

1. INTRODUCTION

As comfort cooling is highly valued by society, research has been conducted to identify cooling solutions that have less impact on the earth's environment, and at the same time do not create negative consequences to human health or safety. There is no single refrigerant that is ideal for every application, however it is possible to balance desired properties in refrigerant blends to achieve an optimal working fluid that considers not only performance and energy efficiency, but safety and sustainability including low GWP, favorable toxicity and low flammability. Another important consideration is total cost to use, including first cost, equipment redesign, operating, and end of life cost. A refrigerant with properties and cooling capacity similar to R-410A can significantly reduce equipment redesign costs by being compatible in existing system designs, thereby minimizing the need for changing or redesign of compressors, heat exchangers, and other system components.

The fluid that most closely meets these design criteria is DR-55, also known as XL55 and R-452B. DR-55 is a mixture containing 67 wt% R-32, 7 wt% R-125, and 26 wt% of HFO-1234yf. Its GWP is 698 based on IPCC Fourth Assessment Report (AR4) (IPCC, 2007) and 676 based on IPCC's Fifth Assessment Report (AR5) (IPCC, 2013).

Research has also been done to find a refrigerant to meet these design criteria with the lowest GWP possible while still matching the cooling capacity and performance of R-410A. That fluid is DR-5A, also known as XL41 and R-454B. DR-5A is a mixture containing 68.9 wt% R-32 and 31.1 wt% of HFO-1234yf. Its GWP is 466 based on AR4 and 467 based on AR5. Both DR-55 and DR-5A are mildly flammable and have received a safety classification of A2L under ASHRAE SSPC 34 (ASHRAE, 2013). Performance in a residential air-conditioning system has been evaluated in a system originally designed for R-410A. Other properties such as lubricant miscibility, lubricant miscibility, thermal stability, and materials compatibility have also been assessed.

2. THERMODYNAMIC PROPERTIES

Development of refrigerant blends begins by measuring many properties, including measurements to obtain interaction parameters for all of the binary pairs considered for mixtures. In addition, high order thermodynamic mixture modeling techniques have been developed and validated to facilitate accurate property determination for the candidate mixtures. Modeled results are ultimately validated by equipment tests in order to determine impacts of pressure drop and heat transfer characteristics of the candidate refrigerant blends, as well as efficiencies and power consumption by the compressor and motor. A comparison of thermophysical properties of DR-5A and DR-55 with R-410A is shown in Table 1. The pressure-temperature relationships of both candidates are very similar to R-410A.

Table 1: Thermophysical Properties

	R-410A	**DR-5A (R-454B)**	**DR-55 (R-452B)**
Global Warming Potential (AR4/AR5)	2088/1924	466/467	698/676
Boiling Point °C (°F)	-51.5°C (-60.7°F)	-50.9°C (-59.7°F)	-51.0°C (-59.9°F)
Critical Point °C (°F)	71.3°C (160.4°F)	76.5°C (169.7°F)	75.7°C (168.2°F)
Vapor Pressure at 25°C, 77°F in kPa (psia)	1652 (240)	1522 (221)	1544 (224)
Liquid Density at 25°C, 77°F in kg/m3 (lb/ft3)	1059 (66.1)	980 (61.2)	990 (61.8)
Vapor Density at 25°C, 77F in kg/m3 (lb/ft3)	66.0 (4.12)	51.1 (3.19)	52.8 (3.30)

As shown in Figure 1, the critical temperature is also higher for both candidates and both have a wider pressure-enthalpy dome close to the critical temperature, which should contribute to improved capacity at higher ambient temperatures compared with R-410A. The evaporating and condensing pressures for DR-5A and DR-55 are slightly lower than with R-410A.

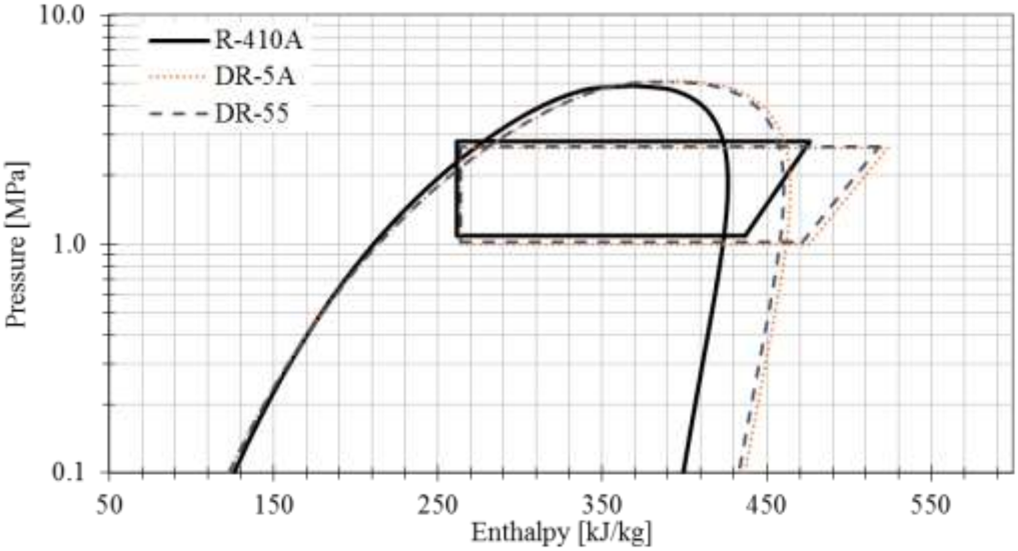

Figure 1: Pressure-Enthalpy Diagram

Ideal thermodynamic cycle modeling was performed to evaluate thermodynamic cooling performance. Selected based on air conditioning system test results, the following conditions were used for model inputs: average evaporating temperature = 10.0°C (50°F), average condensing temperature = 46.1°C (115°F), subcool amount = 8.3 K (15°R), superheat amount = 8.3K (15°R), compressor isentropic efficiency = 0.7.

Table 2: Ideal Thermodynamic Cycle Performance

	R-410A	**DR-5A (R-454B)**	**DR-55 (R-452B)**
Suction Pressure, kPa (psia)	1086 (158)	1018 (148)	1031 (150)
Discharge Pressure, kPa (psia)	2801 (406)	2631 (382)	2663 (386)
Evaporator Glide, K (°R)	0.1 (0.2)	1.3 (2.3)	1.1 (2.0)
Discharge Temp. °C (°F)	78 (172)	84 (183)	84 (182)
Capacity vs. R-410A	-	- 3%	- 3%
COPc vs. R-410A	-	+ 1%	+ 1%

Modeling results for DR-5A and DR-55 show slightly lower evaporating and condensing pressures and capacity than R-410A. However, the thermodynamic cycle efficiency is slightly higher than R-410A. Evaporator glide is relatively low at 1 K. Discharge temperatures are predicted to be about 6°C higher than R-410A but well below temperatures which may require compressor cooling such as liquid or vapor injection and well below many other alternatives such as R-32.

3. SYSTEM TESTING

To validate the ideal thermodynamic modeling results, air conditioning and heat pump system performance has been evaluated in a commercially available heat pump system originally designed for R-410A. “Drop-in” performance of R-410A alternatives was previously measured in this system with no modifications to the original equipment, including to the thermostatic expansion valve (TXV) since the OEM valve was not adjustable. These results showed DR-5A had higher cooling capacity and energy efficiency than R-410A even in drop-in tests with no modifications (Hughes, 2015). The next step in testing presented in this paper includes “soft-optimized” tests, which are tests in a production air conditioning unit that has undergone only minor modifications such as refrigerant charge optimization, lubricant change, and flow control device changes to run with different refrigerant (Abdelaziz, 2015).

Performance was measured in a psychrometric test chamber with a test unit that was an 8.79 kW, 16 SEER ducted heat pump designed for use with R-410A. The only modifications from the original OEM equipment were the installation of measurement instrumentation and replacement of the OEM non-adjustable TXV with an electronic expansion valve to match the original amount of superheat of the system with R-410A refrigerant. Since system pressures and mass flow rates of DR-5A and DR-55 are similar to R-410A, an adjustable TXV designed for R-410A could have alternatively been used but an electronic valve was selected in this case to test a wide variety of alternatives with varied flow rates. The refrigerant charge sizes were determined by optimization of the refrigerant charge to yield the peak energy efficiency in cooling tests. The POE 32 centistoke lubricant used was the same as specified for the compressor with R-410A. Air conditioning tests were done in accordance with ASHRAE Standard 37 and ambient conditions were determined by AHRI 210/240 and ISO 5151.

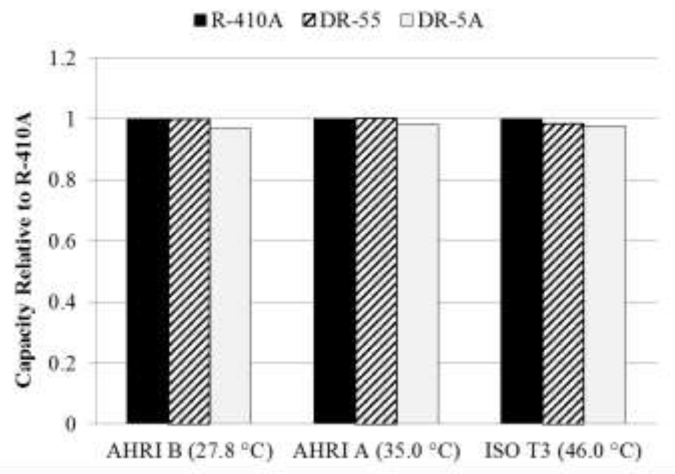

Figure 2: Cooling Capacity Relative to R-410A

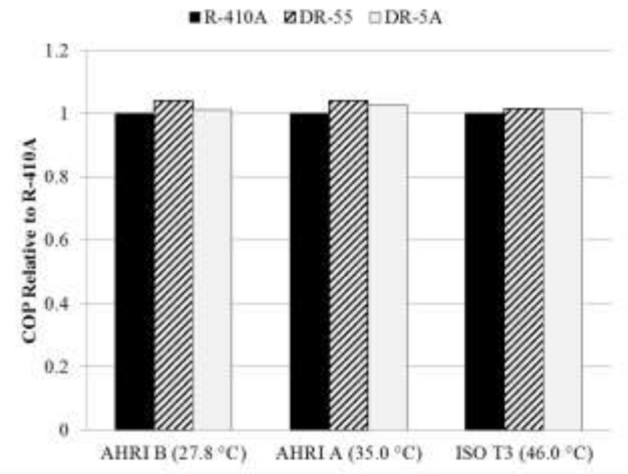

Figure 3: COP Relative to R-410A

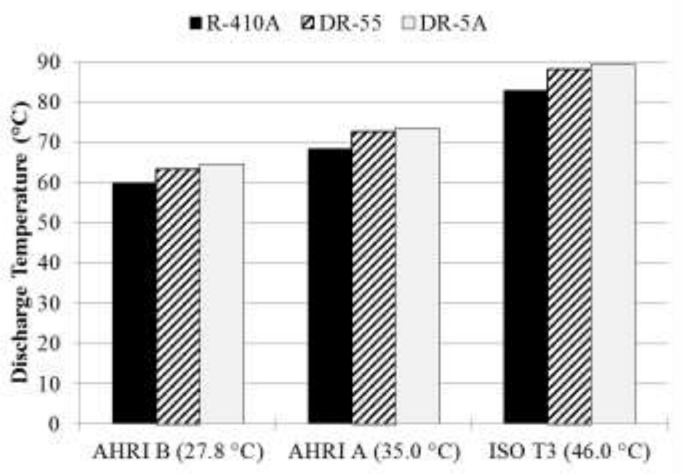

Figure 4: Discharge Temperature

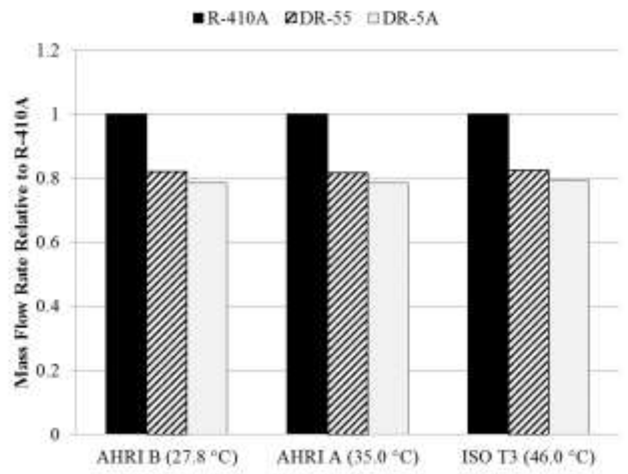

Figure 5: Refrigerant Mass Flow Rate Relative to R-410A

The optimum refrigerant charge sizes were determined to be about 5% less than the charge size for R-410A. The cooling capacity for DR-55 and DR-5A was very similar to R-410 capacity. The close match in capacity helps the alternative refrigerants to be used in R-410A-type heat exchangers without a need for significant redesign. The COP of the system is immediately improved even in a system designed for R-410A. DR-55 averaged about 3-4% energy efficiency improvement over R-410A.

Discharge temperatures were slightly higher for DR-5A and DR-55, however they are still well below the temperatures at which compressor cooling, such as by liquid or vapor injection, would be needed. The refrigerant mass flow rates are close to 20% lower with R-410A. Results have shown that only a slight adjustment of an adjustable TXV designed for R-410A is needed to maintain equivalent amount of suction superheat with R-410A (Kujak and Shultz, 2015). In some cases there may be oil return concerns with a lower refrigerant mass flow rate with replacement refrigerants due to an expected reduction in suction line velocity which could hinder oil return to the compressor. However, although the refrigerant mass flow rate is lower than R-410A, the vapor density is also similarly lower than R-410A by approximately the same ratio such that actual vapor velocity through the suction line is actually very similar to R-410A.

4. DIRECT GWP VALUES VS. LCCP

In many instances, only the direct GWP value has been considered in determining the prediction of environmental and climate change impact of a refrigerant. This value, however, gives neither the sole nor the primary prediction of the impact a refrigerant operating in refrigeration and air conditioning systems will have during its entire lifetime. During operation, all of these systems consume energy in the generation of electricity, most commonly by the burning of fossil fuels. These processes produce carbon dioxide (CO2), a harmful global warming gas. Over the lifetime of a typical system, substantial quantities of CO2 are produced from power generation and subsequently released to the atmosphere. The direct and indirect emissions are a more complete assessment of the relationship a working fluid will have with its surrounding environment than merely its direct GWP value, because they consider the full operational lifetime. A cooling system that operates more efficiently and uses less power over its lifetime will have less climate change impact than a less efficient system that produces the same amount of cooling. Consequently, in considering the global warming impact of a refrigerant in a system, the life cycle climate performance (LCCP) of a refrigerant must be identified as well.

The predicted LCCP of R-410A, DR-5A and DR-55 were evaluated using both air conditioning and heating test results at AHRI 210/240 test conditions as inputs to the Life Cycle Climate Performance Model for Residential Heat Pump Systems developed by AHRI (Zhang, et al., 2011). This study investigated four regions across the US and assumed the same equipment was used for all refrigerants. The refrigerant charge sizes were as determined by refrigerant charge optimization in air conditioning system tests.

As shown in the LCCP analysis below, DR-5A and DR-55 have a smaller contribution to direct emissions due to their significantly lower GWP. However, the direct refrigerant emissions contributions in air conditioning systems are a small portion of the total emissions over the lifetime of the equipment. A more significant factor in reducing the total emissions is the energy efficiency of the system. The energy efficiency of DR-5A and DR-55 are higher than R-410A in air conditioning tests in similar equipment, and significant total emissions reductions can be gained with refrigerants with higher energy efficiency. In addition to being favorable to R-410A in GWP value and direct emissions contributions, the total life cycle climate performance for DR-55 and DR-5A results in lower total impact to the environment throughout the lifetime of the system.

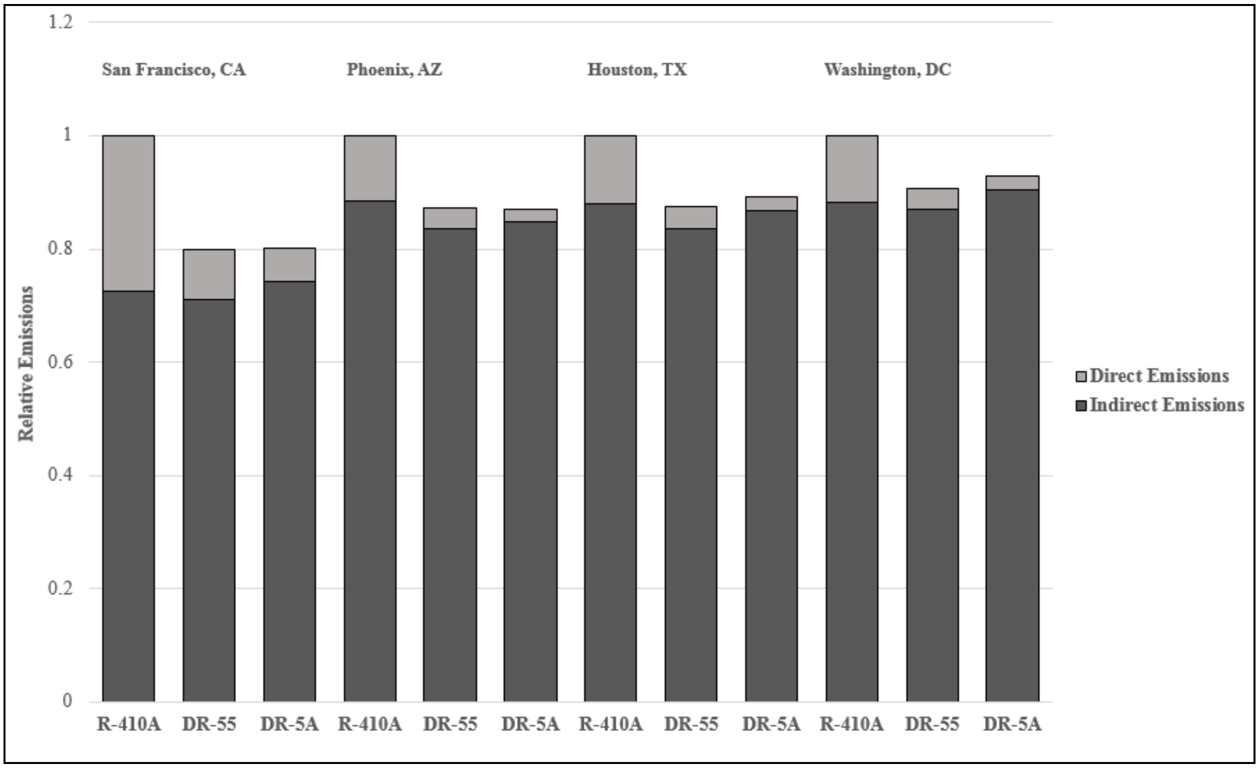

Figure 6: LCCP Analysis – Total Direct and Total Indirect Emissions Relative to R-410A

5. THERMAL STABILITY

DR-55 and DR-5A were tested for thermal stability in sealed glass tubes using ASHRAE Standard 97 (ASHRAE, 2007) with a POE 32 lubricant. Sealed glass tubes were prepared containing refrigerant, POE lubricant, and carbon steel, copper, and aluminum coupons. The tubes were aged at 175°C for 14 days. After aging the tube contents were visually examined for change in lubricant color,

The tube contents were also analyzed by gas chromatography (GC) for Total Acid Number (TAN) and by ion chromatography (IC) to measure chloride, fluoride, and organic acid ion concentrations to determine refrigerant and/or lubricant decomposition.

Table 3: DR-55 Thermal Stability Results

Refrigerant	**Air (ppm)**	**Water (ppm)**	**Fluoride ion F- (ppm)**	**Coupon and Fluid Visual Inspection**
DR-55	None	None	10.49	No Change
DR-55	None	500	<MDL	No Change
DR-55	2000	None	8.06	No Change
DR-55	2000	500	<MDL	No Change

Table 4: DR-5A Thermal Stability Results

Refrigerant	**Air (ppm)**	**Water (ppm)**	**Fluoride ion F- (ppm)**	**Coupon and Fluid Visual Inspection**
DR-5A	None	None		No Change
DR-5A	None	500		No Change

DR-5A	2000	None		No Change
DR-5A	2000	500		No Change

5. LUBRICANT MISCIBILITY

The miscibility of DR-55 and DR-5A were tested with a POE 32 centistoke lubricant. This lubricant was also the same as specified for use with the equipment designed for R-410A used in system tests shown previously. A range of refrigerant and oil mixture compositions were prepared in sealed glass tubes. The tubes were heated to 75°C (167°F) and then cooled to -50°C (-58°F) and observed in 5K (9F) increments. Results for DR-5A and DR-55 are very similar, so DR-55 is shown in Figure 8 for simplicity. DR-55 shows very similar miscibility characteristics to R-410A and is miscible in the typical operating ranges for air conditioning and heat pump systems.

Refrigerant: R-410A

Lubricant: POE 32

Temperature (°C)

Refrigerant/ oil	**-50**	**-45**	**-40**	**-35**	**-30**	**-25**	**-20**	**-15**	**-10**	**-5**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
95 / 5%	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
90 / 10%	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N
85 / 15%	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N	N
80 / 20 %	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N	N
70 / 30%	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	N	N	M	M	N	N	N
40 / 60%	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
30 / 70%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

Figure 7: Miscibility of R-410A with POE lubricant

Refrigerant: DR-55

Lubricant: POE 32

Temperature (°C)

Refrigerant/ oil	**-50**	**-45**	**-40**	**-35**	**-30**	**-25**	**-20**	**-15**	**-10**	**-5**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
95 / 5%	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
90 / 10%	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N
85 / 15%	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N
80 / 20 %	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N
70 / 30%	N	N	N	N	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N
40 / 60%	N	N	N	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	N	N	M	M
30 / 70%	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M

Figure 8: Miscibility of DR-55 with POE lubricant

6. PLASTICS AND ELASTOMERS COMPATIBILITY

An important air conditioning system and compressor design consideration is the compatibility of plastics and elastomers in refrigerant and oil to ensure durability and reliability of these materials over a long period of time. To assess materials of construction for compatibility with new refrigerants, DR-55 and DR-5A were evaluated with a wide array of plastics and elastomers used in air conditioning applications. Sealed glass tubes were prepared containing the refrigerant, POE 32 lubricant, and plastic/elastomeric material and held at 100°C for two weeks. After exposure, elastomers and plastics were removed and measured for weight change, linear swell and hardness change 24 hours after removal from tubes. The following rating system was used to characterize the compatibility of each of the materials in the refrigerant/oil mixture:

Rating:
0 < 10% weight gain, and < 10% linear swell and < 10 hardness change
1 > 10% weight gain, or > 10% linear swell or > 10 hardness change
2 > 10% weight gain, and > 10% linear swell and > 10 hardness change

Results for plastics and elastomers testing are shown in Table 5.

Table 5: Plastics and Elastomers Compatibility for DR-55 and R-410A

Material Tested	R-410A Rating	R-410A % Weight Change	R-410A % Linear Swell	Hardness Change, Delta	DR-55 Rating	DR-55 % Weight Change	DR-55 % Linear Swell	Hardness Change, Delta
Neoprene 1	0	1%	0%	-4	0	0%	2%	1
Neoprene 2	0	6%	3%	-6	0	0%	7%	-4
Epichlorohydrin	0	8%	2%	-7	0	0%	8%	-9
Butyl Rubber	0	9%	3%	-4	0	0%	8%	-9
EPDM	0	5%	2%	-6	0	0%	5%	-6
Fluorosilicone	0	4%	2%	-8	0	0%	4%	-9
HNBR	1	18%	5%	-6	1	1%	17%	-8
NBR	1	12%	5%	-5	1	1%	11%	-12
Fluorocarbon FKM	1	13%	6%	-10	1	1%	12%	-12
Viton A	1	13%	6%	-11	1	1%	12%	-11
Viton GF	0	8%	4%	-8	0	0%	7%	-9
Polyester	0	9%	3%	-4	0	0%	9%	-1
Nylon resin	0	0%	2%	-2	0	0%	0%	1
Polyamide-imide	0	0%	0%	-2	0	0%	0%	-1
Polyphenylene sulfide	0	0%	0%	-2	0	0%	0%	0
PEEK	0	1%	0%	-2	0	0%	1%	0
Nylon	0	0%	0%	-1	0	0%	0%	0
PTFE	0	1%	0%	-1	0	0%	1%	-1

7. CONCLUSIONS

Work to develop satisfactory replacements for R-410A has been on-going for several years. As regional environmental and safety requirements are being defined more clearly, it has become possible to develop optimized refrigerant compositions that can directly meet these requirements. Specifically, compositions with reduced GWP values have been developed to be used in new air conditioning systems that can be similar to current commercial air conditioning and heat pump designs.

Two viable R-410A alternatives, DR-5A and DR-55, are presented and evaluated in both physical properties and thermodynamic cycle models and were verified in performance testing in existing, commercially available air conditioning equipment. DR-55 and DR-5A are shown to have similar fluid properties, and improved performance and energy efficiency when compared to R-410A. Additional considerations for use and durability in air conditioning systems have been evaluated, including thermal stability, lubricant miscibility, and materials compatibility. DR-5A and DR-55 have also shown performance similar to R-410A in these tests and are shown to be viable options for the replacement of R-410A in small and mid-sized air conditioning systems.

The consideration of direct GWP values alone can lead to non-optimal refrigerant and equipment choices or to development of regulations that may not be best for limiting overall carbon emissions into the environment and hence, on limiting global climate change. In addition to significantly lower direct GWP values, life cycle climate performance analyses with DR-5A and DR-55 show a significant reduction in total lifetime CO2 emissions than R-410A. Also, because of their similar properties and performance characteristics to R-410A these refrigerant alternatives are compatible in existing R-410A new equipment designs, which could potentially reduce the need for significant system redesign and accelerate the adoption of low GWP refrigerants in air conditioning systems to reduce the potential impact on the environment. This work discusses environmentally and commercially viable refrigerant solutions that should be considered in order to minimize impact on the earth's climate.

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