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Reduced GWP Refrigerant for Residential and Commercial Air Conditioning Systems

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ABSTRACT

R-410A is widely used in residential and light commercial air-conditioning, heat pump and chiller systems. Due to increasing concerns about climate change, various environmental regulations have been proposed to phase out this refrigerant. A new refrigerant, R-466A, has been developed, which offers high energy efficiency and low global warming potential (GWP), resulting in low overall environmental impact. This paper discusses the thermal properties as well as the performance of this new refrigerant in a representative air conditioning system showing the benefits of using this new refrigerant. The thermal stability, material compatibility and refrigerant/lubricant interactions of R-466A are also discussed. Finally, a simulation model is used to evaluate the lifetime thermal stability of R-466A under real operating conditions for a heat pump system.
Keywords: HFO-Refrigerants, Global Warming, Air Conditioning, Unitary Air Conditioners, Heat Pumps

1. INTRODUCTION

R-410A is widely used in air-conditioning applications ranging from residential unitary air-conditioners to heat pumps and light commercial chillers. R-410A has relatively high global warming potential (GWP) (GWP = 2088), and is increasingly becoming a target of many environmental regulations. In Europe, F-Gas regulations (2014) limit the GWP to 750 in single split unitary air conditioning systems with refrigerant charge less than 3 kg. In all these applications, R-410A will be banned. In this context, several lower-GWP R-410A replacements are under evaluation by the industry.

However, most of the new lower GWP refrigerants are flammable in nature (Zou et al. 2016), which restricts their early adoption by the HVACR industry. The industry is investing heavily in understanding the use of flammable refrigerants, but it will be years before mandatory emission reductions can be realized. With a viable option of nonflammable lower-GWP refrigerants with equivalent or better energy efficiency, actions can be implemented in the stationary air-conditioning segment with the potential to ensure carbon footprint reduction.

This study focuses on non-flammable R-410A replacement: R-466A (R32/R125/R13I1 49%/11.5%/39.5%). This refrigerant is nonflammable and is classified as A1 according to ASHRAE Standard 34. It has GWP less than 750, complying with the F-Gas regulation. A reversible heat pump system was selected to evaluate the performance of the refrigerant. A reversible heat pump is a special vapor compression system which can work in both cooling and heating modes of operation. The refrigerant for this type of system must be carefully selected since the system has dual modes of operation. Starting from this background, this paper aims to present performance of R-466A in a residential reversible heat pump. This paper also presents the thermal stability and material compatibility results for R-466A with polyol ester (POE) lubricant. A comparison of solubility and miscibility comparison of R-466A and R-410A with POE ISO 32 3MAF lubricant is also presented. Finally, a model is used to highlight the lifetime thermal stability of R-466A under real operating conditions for a heat pump system.

2. SAFETY

Residential A/C systems are often operated until they fail, without any preventative maintenance services performed by a professional. When such systems fail, there are many safety risks that can develop when using flammable refrigerants. For example, high concentrations of refrigerant can leak and accumulate in the surrounding area when a component fails. Additionally, improperly trained maintenance personnel can contribute to faulty installation and/or poor service procedures, which can increase safety risks. Apart from lack of maintenance and human error, for regions in the earthquake fault zone such as California, there is a higher probability that installed air-conditioning systems in residential and commercial buildings may experience additional system failure and refrigerant leakage. Nonflammable refrigerants are therefore an advantage for these applications. The proposed refrigerant R-466A fulfils this requirement by being nonflammable, and is classified as A1 according to ASHRAE Standard 34.

A nonflammable solution would allow for additional benefits across the value chain, such as allowing simpler storage and handling of refrigerants during transportation, distribution and repair. The less complex/costly systems will not require additional leak detection sensors, controls and other safety mitigation strategies as mentioned in Lewandowski (2012). There is virtually no additional training required for contractors and system operators, as the proposed refrigerant shares many of the same characteristics as R-410A, lowering costs for the service industry and consumers. No significant change to assembly lines at OEM plants is needed. The proposed refrigerant complies with existing National Building Codes (fire codes, mechanical codes, etc.) as adopted by states and cities, which allows immediate implementation. It has lower expenses for both new installations and repair scenarios, which benefits end users (no mitigation expenses for A1 refrigerants).

3. PERFORMANCE IN RESIDENTIAL AC SYSTEMS

3.1. System Description

An experimental investigation of a ducted split heat pump system was conducted to evaluate the R-410A replacement under both cooling and heating conditions. All tests were performed inside environmental chambers equipped with instrumentation to measure both air-side and refrigerant-side parameters. Refrigerant flow was measured using a Coriolis flow meter, while air flow and capacity was measured using an air-enthalpy tunnel designed according to industry standards (ASHRAE Standard 41.2 and AHRI Standard 210/240). The humidity of the air was measured using dew point meters with an accuracy of ± 0.2 ºC. All primary measurement sensors were calibrated to ± 0.15 ºC for temperatures and ± 0.04 kPa for pressure.

The ducted split heat pump system has a capacity of 9.6 kW at rating conditions, Seasonal Energy Efficiency Ratio (SEER) rating of 13, and Heating Seasonal Performance Factor (HSPF) of 8. The system has a fixed-speed scroll compressor lubricated by POE ISO 32 3MAF oil. The indoor and outdoor coils are fin-tube heat exchangers with fixed-speed fans. A thermal expansion valve is used as an expansion device. Details of the unit are shown in Table 1.

Table 1. System specifications

R-410A Reversible Heat Pump	
Compressor	Scroll Compressor
Condenser	
Rows	1
Tubes per row	24
Tube Diameter (microfin)	0.375" (9.5mm)
Fin Type	Louver
Fin Pitch	866 fins per meter
Air Flow	2000 cfm
Fan Power	265 W
Evaporator	
Rows	2
Tubes per row	20
Tube Diameter (microfin)	0.3125" (7.9mm)
Fin Type	Louver

As shown in Tables 2 and 3, the test conditions were based on AHRI Standard 210/240 and Abdelaziz et al. (2016). The A condition is the cooling rating condition for capacity and the B condition is the cooling rating condition for efficiency. The MOC, Hot and Extreme conditions are the high ambient conditions for cooling mode. The H1 condition is the heating rating condition for capacity and efficiency. The H2 condition is the frost/defrost condition, and the H3 condition is the low temperature condition for heating mode. For each refrigerant, the system charge was optimized at AHRI B and AHRI H1 conditions and was kept fixed at other test conditions. The evaporator superheat was 5.5°C at AHRI B condition for R-410A. The superheat was taken from the mid-point temperature of evaporator for refrigerants that have an evaporator temperature glide. For tests of R-466A, the electronic expansion valve was used to match the R-410A superheat.

Table 2. Cooling mode test conditions

Test Conditions	Indoor Ambient		Outdoor Ambient	
	DB (°C)	WB (°C)	DB (°C)	WB (°C)
AHRI C	26.7	13.9	27.8	18.3
AHRI B	26.7	19.4	27.8	18.3
AHRI A	26.7	19.4	35.0	23.9
AHRI MOC	26.7	19.4	46.1	23.9
Hot[1]	29.0	19.0	52.0	-
Extreme[1]	29.0	19.0	55.0	-

[1] These high ambient conditions are based on Abdelaziz et al. (2016).

Table 3. Heating mode test conditions

Test Conditions	Indoor Ambient		Outdoor Ambient	
	DB (°C)	WB (°C)	DB (°C)	WB (°C)
AHRI H1	21.1	15.6	8.3	6.1
AHRI H2	21.1	15.6	1.7	0.6
AHRI H3	21.1	15.6	- 8.3	- 9.4

3.2. Test Results

Figure 1 shows the experimental results in the cooling and heating modes. The results of capacity and efficiency for the equipment and conditions are presented relative to the performance of R-410A. The results indicate that R-466A shows a 100% matched capacity at the A condition and a 100% matched efficiency at the B condition. R-466A shows an improvement in performance compared to R-410A at high-ambient conditions. At the highest temperature Extreme condition, the capacity is 102% and efficiency is 105% of R-410A. At the heating rating condition H1, R-466A shows a capacity of 97% and a 100% matched efficiency of R-410A. At the frost and low-temperature conditions, the capacity and efficiency are similar, which indicates that the small glide does not show significant impact on the performance.

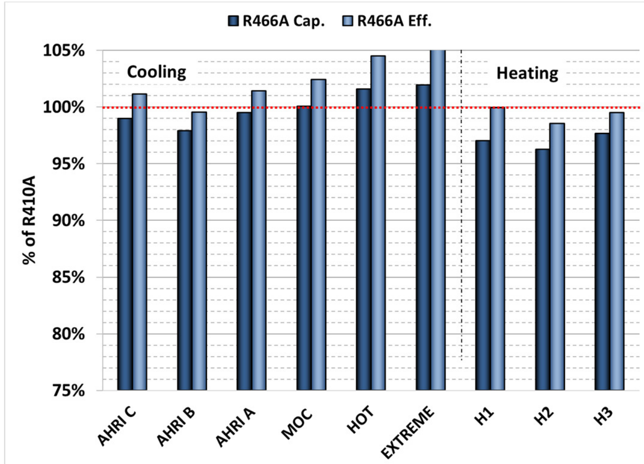
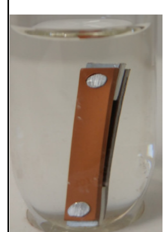


Figure 1. Performance of a 3-ton residential ducted split heat pump system

4. THERMAL STABILITY

ASHRAE 97 testing was performed with R-410A and R-466A with POE ISO 32 3MAF lubricant for 2 weeks at 150 °C. The test was performed with 50/50 wt% ratio of refrigerant/lubricant. Elevated levels of moisture (300 ppm) and air (1.7 vol%) were used at levels often found in real A/C equipment. Copper, iron and aluminum coupons were used as representative metals. An additive package was developed for R-466A, which was added to the lubricant. The tests were performed with POE ISO 32 3MAF and POE ISO 32 3MAFwith additive package to compare the results.

Table 4. Sealed Tube Tests with R-466A/POE ISO32

Lubricant	R-410A	R-466A	
	POE ISO 32 3MAF	POE ISO 32 3MAF	POE ISO 32 3MAF (with additives)
Visual (After)			
Fluoride (ppm)	2	50	2
Iodide (ppm)	<0.1	22	< 1.5
Al (ppm)	<3	< 3	< 3
Fe (ppm)	<2	5	< 2
Cu (ppm)	8	26	3
Initial TAN	<0.1	<0.1	<0.1
Final TAN	<0.1	4.0	0.25
Δ TAN	~0	4.0	0.25

The results indicate additives improve the stability as illustrated by very low levels of anions (fluoride, iodide), low level of metals, and only a slight increase in acidity level. The results for R-466A with additives are very similar to baseline refrigerant R-410A. This suggests that combination of R-466A with POE ISO 32 3MAF oil and additives should be satisfactory for use in system.

5. MATERIAL COMPATIBILITY

Another important consideration when assessing the suitability of a next-generation refrigerant for use with current HVAC&R systems is its compatibility with materials of construction. System materials must be compatible with not just the refrigerant, but the working fluid, consisting of a mixture of the refrigerant and lubricant. In order to assess the compatibility of R-466A with various elastomers, material samples were placed in metal pressure vessels, along with a working fluid composition of 50% POE ISO 32 3MAF lubricant and 50% R-466A refrigerant by weight. Material samples were placed in each test vessel to allow liquid exposure for each material. Vessels were placed in the oven for 14 days at 100 ºC. This work is meant only to give a broad indication of the appropriateness of a material with a working fluid, so only volume change and hardness change results will be discussed. Before and after the exposures, all materials were weighed, and density was determined in order to assess the changes in volume for each of these materials due to the exposure. The results for all materials tested are shown in Table 5. The results for R-466A were compared to R-410A tested under similar conditions. All exhibited volume and hardness changes were within approximately ± 5% of R-410A except for Viton, which showed larger deviation in volume change compared to R-410A. Overall, all of these common materials appear to be good candidates.

Table 5. Material Compatibility Results for R-466A/POE ISO 32 3MAF

Elastomer	Hardness % change		Volume % change		Weight % change	
	R-410A	R-466A	R-410A	R-466A	R-410A	R-466A
NBR	-19.10%	-20.90%	26.30%	15.00%	1.80%	-0.40%
Neoprene	0.00%	-5.40%	1.20%	2.30%	2.10%	1.60%
EPDM	-4.70%	0.00%	2.70%	-0.30%	1.50%	0.50%
Nylon 66	0.80%	-1.00%	1.00%	1.20%	1.10%	1.90%
Nitrile	-7.40%	-2.40%	6.10%	2.90%	6.00%	5.60%
Polypropylene	1.00%	-3.10%	3.10%	2.80%	1.40%	4.40%
Viton	-12.90%	-6.80%	21.40%	2.90%	8.30%	3.60%

6. SOLUBILITY AND MISCIBILITY IN OIL

In refrigeration and air conditioning systems, for the compressor to perform properly, oil is required to lubricate the compressor bearings, pistons, valves and other moving parts. The oil properties significantly change when refrigerant dissolves in the oil. The degree of solubility is important as it affects the viscosity of the oil. A high degree of solubility of refrigerant in the oil causes low viscosity. A lubricant with refrigerant in solution should have adequate viscosities across the system. The degree of miscibility between the refrigerant and lubricant is also important. For example, immiscibility of refrigerant oil mixture causes separation of refrigerant and lubricant in the liquid phase. This may cause the lubricant to accumulate in regions of evaporator and suction line, and enough lubricant might not return to the compressor. In summary, a good solubility of oil and refrigerant is required for proper compressor lubrication, maximum heat transfer performance in the evaporator and lubricant return to the compressor. As the oil circulates with refrigerant throughout the system, the important requirement of an oil is that it should be miscible with refrigerant at all the operating conditions, otherwise it may lag behind in some components such as the liquid receiver and suction accumulator.

6.1. Vapor pressure (solubility) of R-466A and POE ISO 32 3MAF

R-466A was evaluated for solubility and working viscosity with a POE ISO 32 3MAF lubricant candidate and compared to solubility and working viscosity data of the same POE ISO 32 3MAF lubricant with R-410A. Experimental measurements of liquid density, vapor pressure (solubility) and viscosity at concentrations of 40, 30, 20, 10, 5 and 0 w/w percent R-466A are recorded over a temperature range of -20°C to 100°C. Results of the solubility and liquid viscosity are presented in the form of plot of the vapor pressure and isobaric viscosity curves as a function of temperature and composition, a Daniel Plot, Figure 2. A Daniel plot provides information for bearing wear protection. Figure 2 shows the Daniel Plot for POE ISO 32 3MAF lubricant with R-466A.

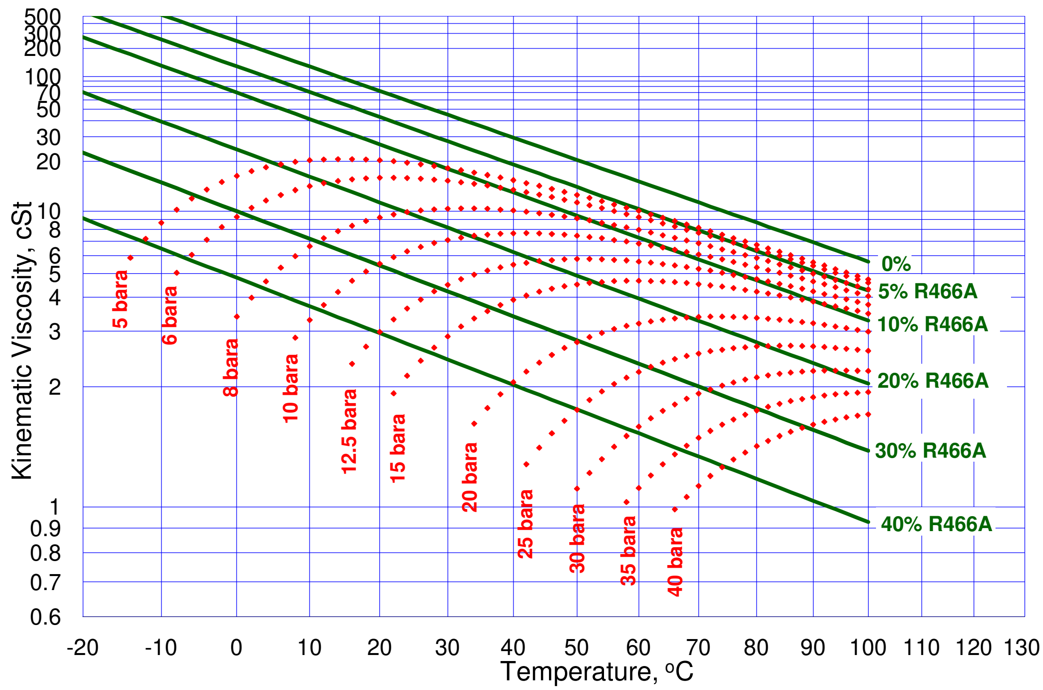


Figure 2: Viscosity and Vapor Pressure of RL32-3MAF with R-466A

Using Daniel Plot data from POE ISO 32 3MAF with R-466A and POE ISO 32 3MAF with R-410A, Figure 3 and Figure 4 show the working viscosity comparison of R-410A and R-466A over a range of temperatures 40 °C to 120 °C at two different pressures with the same POE ISO 32 3MAF lubricant. The two pressures are corresponding to evaporating temperatures in air conditioning 10 °C and evaporating temperature in heat pump for low ambient condition -15°C. The results indicate that when using the same POE ISO 32 3MAF lubricant for both R-410A and R-466A the working viscosities provided to the bearings will be similar.

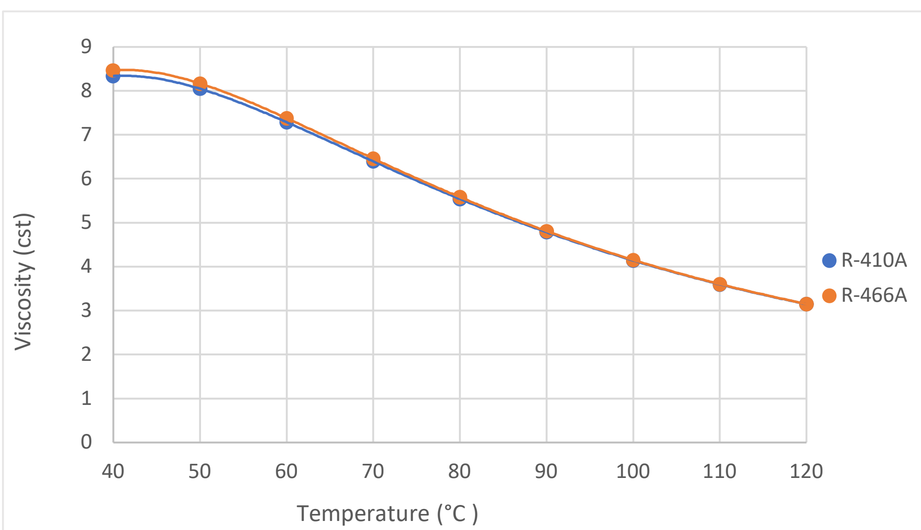


Figure 3: Working viscosity differences of R-466A and R-410A at pressure corresponding to evaporating temperature 10 °C

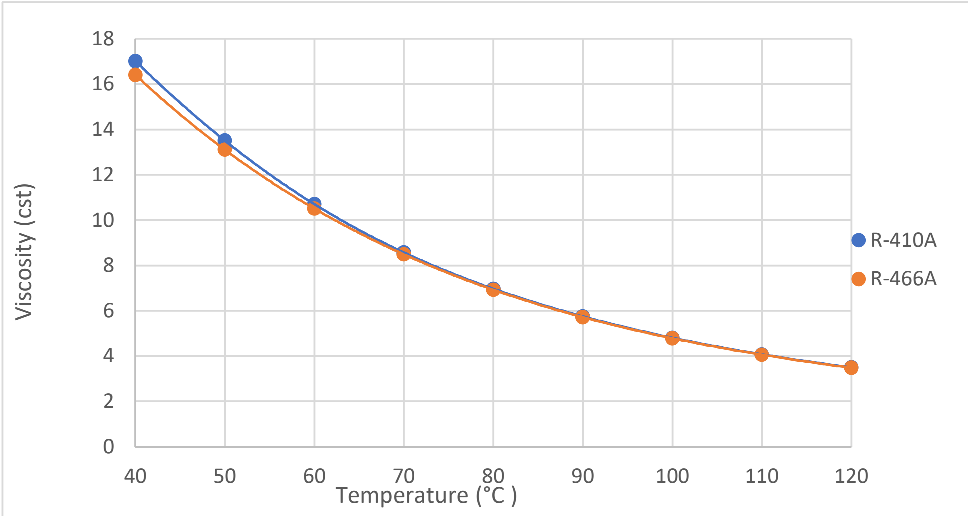


Figure 4: Working viscosity differences of R-466A and R-410A at pressure corresponding to evaporating temperature -15°C

6.2. Miscibility of R-466A and POE ISO 32 3MAF

The miscibility of oil and refrigerant is very important for the proper oil return to the compressor in the condenser side. It is desirable that the oil circulation ratio of < 5%, the lubricant dissolves with the refrigerant and returns to the compressor. However, if the oil circulation ratio increases more than the lubricant miscibility concentration, the lubricant can accumulate and cause shortage of oil in the compressor. This could lead to damage of bearings, valves and other moving parts in the compressor.

Miscibility data was generated for refrigerant lubricant mixtures of R-410A/POE ISO 32 3MAF and R-466A/POE ISO 32 3MAF. The miscibility measurements were performed in a series of cells kept inside a temperature-controlled chamber. A typical miscibility cell has a glass window in front for visual inspection. The chamber temperature was maintained over a wide range from -40 °C to 75 °C. The exact temperature was recorded by measuring the temperature inside the test cell filled with lubricant with a thermocouple. The miscibility results are shown in Figure 5.

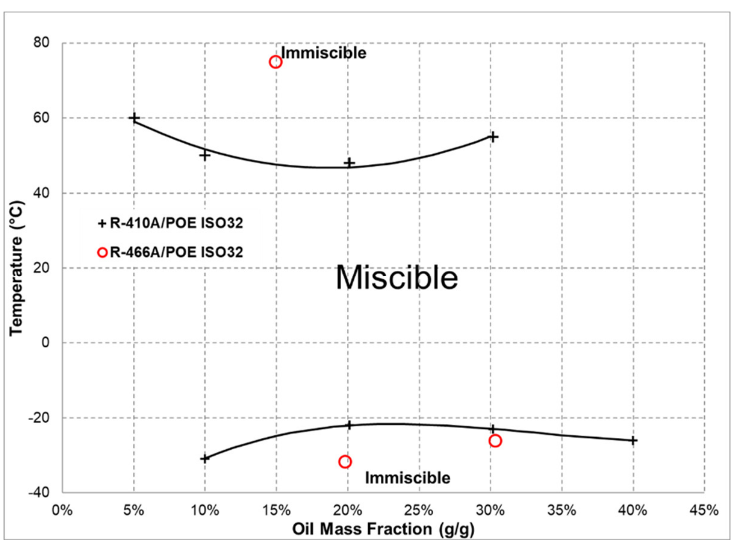


Figure 5: Miscibility Comparison of R-466A and R-410A with POE ISO 32 3MAF

Figures 5 indicates that R-466A is miscible with the POE ISO 32 3MAF over a wider range of temperatures than R-410A. For an evaporator under conditions of typical air conditioning (evaporator temperature around 7 °C) and heat pump at low ambient (evaporator temperature around -15 °C), both R-466A and R-410A are miscible with POE ISO 32 3MAF lubricant. Figure 5 indicates that, under concentrations greater than 95%, R-410A is miscible at temperatures below 60°C while R-466A is miscible up to 75°C.

7. THERMAL STABILITY IN ACTUAL AIR CONDITIONING SYSTEMS

Residential air conditioning systems typically have an operating lifetime of 15 to 25 years and can operate under a wide range of operating conditions. System testing is conducted under extreme operating conditions such as high discharge temperature, high compression ratio to study the reliability of a system with a combination of refrigerant and lubricant. This testing is usually conducted for 2000 to 5000 hours of continuous runtime under extreme conditions to simulate either a portion or sometimes the complete lifetime of system operation.

In this paper, a methodology is proposed to evaluate the reliability of a system designed with R-466A and predict the lifetime of a system operating under different climate conditions. Among the various constituents of R-466A, R-13I1 has been well known in the literature to have higher thermal reactivity compared to HFCs (R-32, R-125).

Nimitz (1994) studied the thermal stabilities of various fluoroiodocarbons including R-13I1. They reported R-13I1 decomposition reaction is a first-order based on experimental data for Ikon-12 refrigerant. ASHRAE 97 testing was performed for R-466A at various temperatures to obtain the fundamental reaction rates for R-466A. Figure 6 below shows the reaction rates for R-466A and two chlorinated refrigerants HCFC R-22, CFC R-12 used in the past for air-conditioning applications. The chart indicates reaction rates for R-466A are higher than HCFC R-22 and lower than CFC R-12.

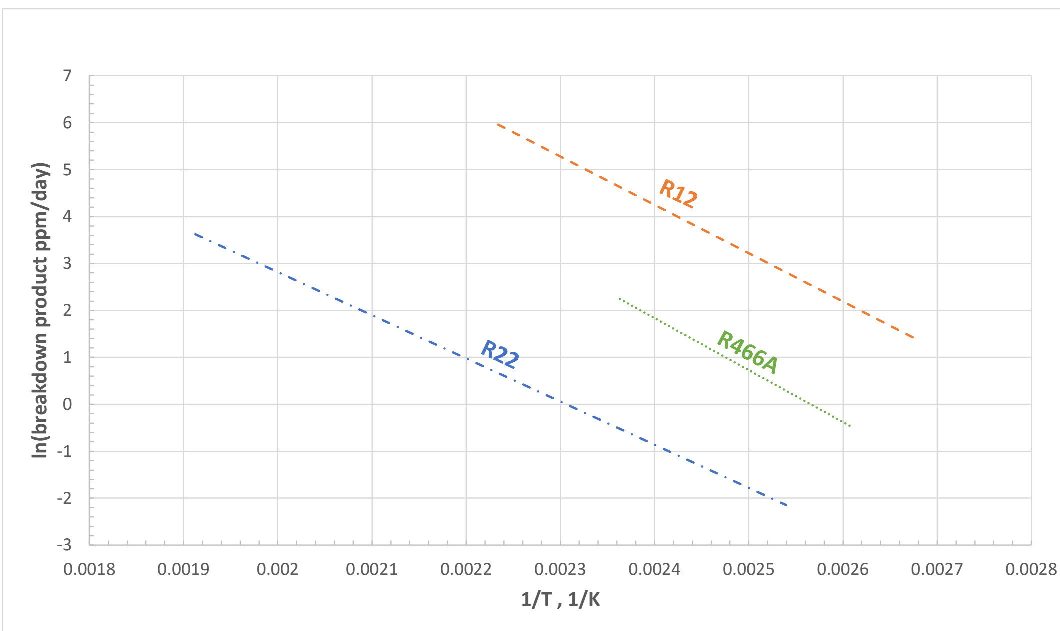


Figure 6: Reaction rates for different refrigerants over range of temperatures

A system kinetic model was developed to simulate the generation of breakdown products in various components of an air-conditioning system. This model takes into account the effect of materials of construction, temperature and residence time in different components of the air conditioning system. The model uses the fundamental equation for reaction rates from Figure 6 to estimate the generation of breakdown in various components and aggregates the generation for all the components to estimate the total generation of breakdown products for the overall system. Next, this model is calibrated using experimental data obtained from accelerated lifetime testing of a 3 Ton U.S. residential heat pump system. The fully calibrated model was then used to estimate the generation of breakdown products over the lifetime of the system. Temperature bins were obtained for regions to estimate the generation of breakdown products over the lifetime of the system (15 years). Figure 7 below shows the flow chart describing the development of model.

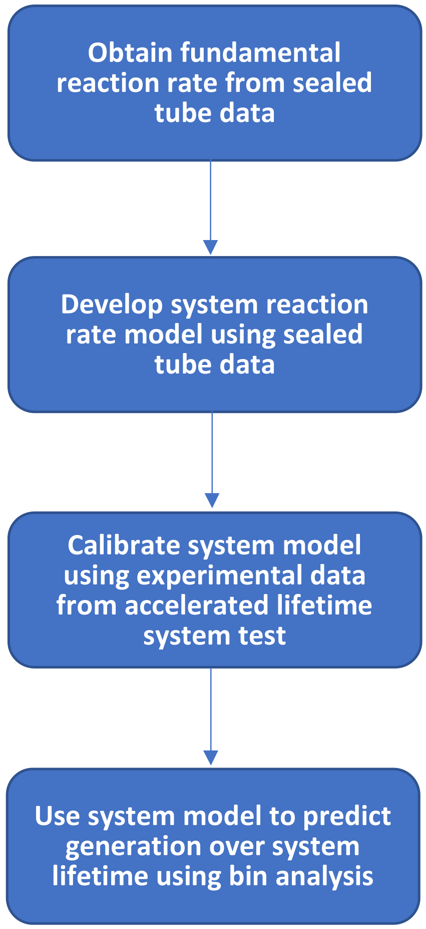


Figure 7: Flow chart for development of system kinetic model

To determine the lifetime of a typical U.S. Residential 3 Ton system operating with R-466A, a bin analysis was performed using weather data for Phoenix, Ariz. for cooling only air-conditioner and Atlanta, Ga. for a reversible heat pump. The lifetime of the system is defined as operating time for the system after which 2000 ppm of refrigerant breakdown happens (Nimitz 1994). It is necessary to restrict the breakdown of refrigerant to this limit to ensure there are no secondary reactions of refrigerant breakdown products in the system. TMY2 weather data for Phoenix and Atlanta produced by National Renewable Laboratory and available in BinMaker (r) Pro v 3.0.1 software is used for the analysis as shown in Figure 8 and Figure 9 respectively.

In order to determine the run time of an air-conditioner in Phoenix, Ariz. a load profile was assumed. The cooling load decreased linearly from the design point of 35°C down to zero at 18°C. The air-conditioner was assumed to have 100% run time for ambient temperatures above 35°C. For the heat pump operation, the heating load was assumed to zero at 18°C and increase linearly to 100% load at design point of 8°C. The heat pump was assumed to have 100% run time for ambient temperatures below 8°C.

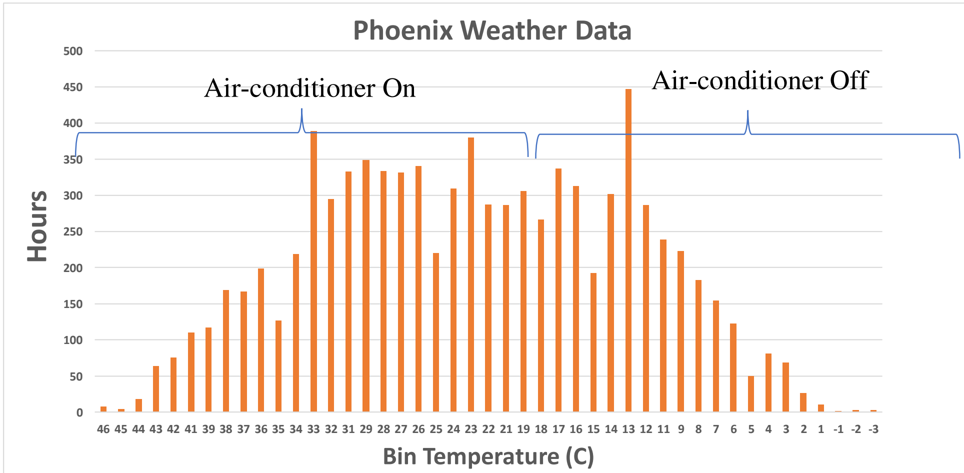


Figure 8: Weather data for Phoenix, Ariz.

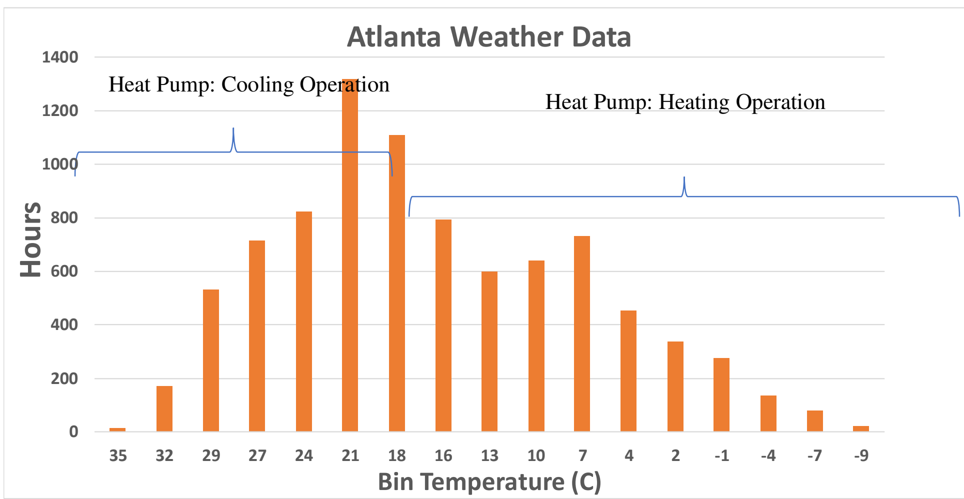


Figure 9: Weather data for Atlanta, Ga.

Using the load profile assumed and the bin temperature data, an analysis was performed for each region to estimate the system lifetime. Table 6 shows the annual cooling hours for air conditioner operating in Phoenix, Ariz. and annual cooling and heating hours for heat pump operating in Atlanta, Ga. based on the load profile assumed and the bin temperature data for the two regions.

Table 6. Annual Operating Hours

Mode of Operation	Heat Pump	Air Conditioner
	Atlanta, Ga.	Phoenix, Ariz.
Annual Cooling Hours	1,369 hours	3,300 hours
Annual Heating Hours	4,092 hours	
Total Annual Operating Hours	5,461 hours	3,300 hours

The simulation model predicts the amount of refrigerant breakdown in each of the bin temperatures for a location. Figures 10 and 11 show the model results for Phoenix and Atlanta respectively.

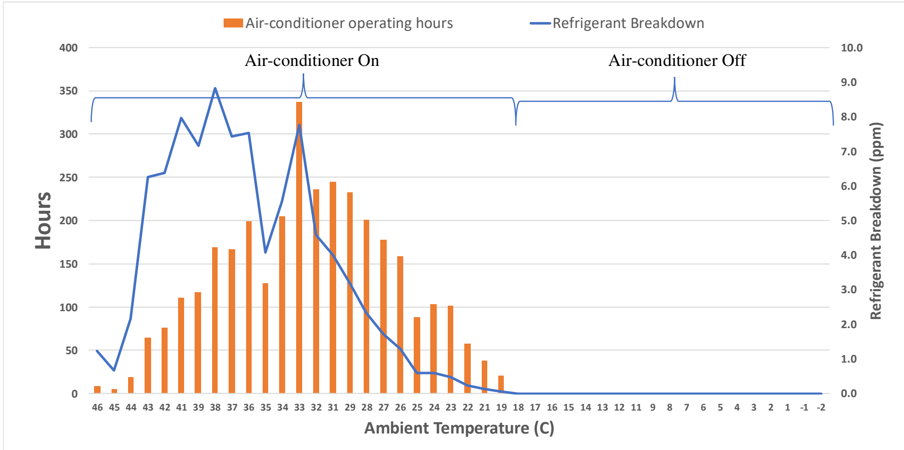


Figure 10: Refrigerant breakdown for different ambient temperatures in Phoenix, Ariz.

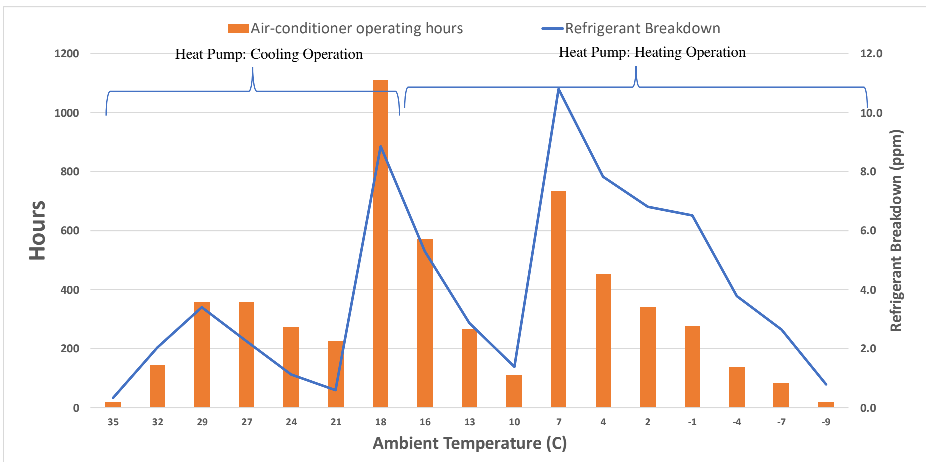


Figure 11: Refrigerant breakdown for different ambient temperatures in Atlanta, Ga.

The annual refrigerant breakdown for each region was estimated by adding the refrigerant breakdown for all bin temperatures. The total annual refrigerant breakdown for Phoenix was estimated to be 92 ppm and for Atlanta was estimated to be 67 ppm. Using these results the system lifetime was estimated using the amount of time (in years) to achieve the maximum acceptable level of refrigerant breakdown (2000 ppm, Nimitz (1994)). The results for system lifetime predictions are shown in Table 7. The system lifetime for an air-conditioner operating in Phoenix is expected to be 22 years and heat pump operating in Atlanta is estimated to be around 30 years. Therefore, the expected lifetime of R-466A system is likely to be similar to the lifetime expected from current R-410A air-conditioning systems.

Table 7. System Lifetime Prediction

	Heat Pump	**Air Conditioner**
	Atlanta, Ga.	**Phoenix, Ariz.**
Annual Refrigerant Breakdown (ppm)	67	92
System operation time to reach maximum acceptable breakdown (years)	30	22

8. CONCLUSION

This study presents a nonflammable, lower GWP R-410A replacement R-466A with GWP less than 750 that could be used as long-term solution for residential and commercial air-conditioning and heat pump systems. Experimental system evaluation in a 3 Ton R-410A residential ducted split heat pump system indicates that the lower GWP R-466A can match the performance of R-410A without significant system modification. At elevated ambient temperatures, R-466A even shows more than 5% higher efficiency than R-410A.

R-466A shows acceptable thermal stability with typical materials of construction used in air-conditioning systems today. R-466A is also compatible with most of the elastomers used commonly with R-410A today. The solubility results indicate that when using the same POE lubricant for both R-410A and R-466A the working viscosities provided to the bearings will be similar. The miscibility results of R-466A with POE ISO 32 3MAF ensure proper oil return to the compressor for its safe operation.

A system kinetic modeling approach was developed to estimate the lifetime of the system operating with R-466A. The modeling results indicate that an additized system designed for R-466A offers lifetime similar to the current R-410A system.

Different from other R-410A replacements in the market that are flammable, nonflammable solutions offer additional benefits, including simple storage and handling, no need for costly flammability mitigation, no additional training required for contractors and system operators, no significant change to assembly lines, full compliance with existing building codes, and lower expenses for both new installations and repair scenarios.

NOMENCLATURE

GWP	Global Warming Potential
COP	Coefficient of Performance
DB	Air dry bulb temperature (°C)
MOC	Maximum operating condition
Q	Cooling capacity (kW)
WB	Air wet bulb temperature (°C)

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