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AHRI Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP) â€“ Summary of Phase II Testing Results

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ABSTRACT

The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) recently completed the second phase of its Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP). This industry-wide cooperative research program identified and evaluated promising alternative refrigerants over the past five years. Seventeen low-GWP refrigerants were tested during the second phase of the program in a variety of products; including air conditioners, heat pumps, chillers, ice makers and commercial refrigeration displace cases. Phase II also included performance testing under high ambient conditions up to 52ºC. This paper provides a comprehensive high level summary of the refrigerants tested and results obtained during phase II.

1. INTRODUCTION

AHRI is currently leading an industry-wide cooperative research program, the Low Global Warming Potential Alternative Refrigerants Evaluation Program (Low-GWP AREP). The program aims at identifying and evaluating promising low-GWP alternative refrigerants for major air conditioning and refrigeration products. Phase I testing of the program was completed at the end of 2013 and produced 40 test reports (Wang et al., 2014). Phase II testing started in 2014, and produced 33 test reports. Phase II reports included compressor calorimeter testing, system drop-in testing, and soft-optimized system testing. Seventeen refrigerant were tested by U.S. and international manufacturers and laboratories. The intent of the program is to help industry select promising alternative refrigerants, understand technical challenges and identify the research needed to implement these refrigerants. The program's objectives are to identify potential replacements for high GWP refrigerants, test and present the performance of these replacements in a consistent manner. However, the program will not prioritize the alternative refrigerants. This paper is an overall summary of the test results obtained in Phase II.

2. LOW GWP REFRIGERANTS

In Phase II testing, twenty-nine refrigerants were proposed by refrigerant producers, and seventeen of them were actually tested according to test companies' interest. The tested refrigerants and their compositions are listed in Table 1. Neither an upper numerical limit on refrigerants' GWP values nor the safety classifications were limitations to nominating refrigerants, as long as the alternative candidate had a significant reduction in its GWP relative to the refrigerant it is intended to replace.

3. TESTING

Tests conducted during Phase II of the program included: (1) compressor calorimeter tests, (2) drop-in system tests, and (3) soft-optimized system tests. Compressor calorimeter tests were conducted in accordance with ASHRAE Standard 23-2010 (testing companies in Europe may alternatively use EN 13771.). The drop-in tests were conducted with the alternative refrigerants placed in systems designed for baseline refrigerants with only minor adjustment, if any, such as charge or superheat setting. Soft-optimized tests were performed using baseline refrigerant systems.

These systems were modified for the alternative refrigerants using standard production line components. In addition, the heat transfer area of the soft-optimized system's evaporator and condenser may be changed, provided that the sum of the total area remains the same as the baseline system. Manufacturers conducting tests may change components to get optimized performance, but are required to provide enough information to show these changes. All tests were conducted by following the latest industry-wide accepted standards. The following subsections summarize the low-GWP refrigerants tested, and the type of test conducted in Phase II for different product categories. The Low-GWP AREP Report Number corresponding to a particular equipment tested is also listed, in order to direct readers to the detailed test information and results.

Table 1: List of low GWP refrigerant candidates in Phase II

Baseline	Refrigerant	Composition	(Mass%)	Classification (Note 1)	GWP_{100} (Note 2)
R22/R-407C	DR-93	R-32/R-125/R-1234yf/R-134a	20/20/31/29	A1	1251
	N-20b	R-32/R-125/R-134a/R-1234yf	13/13/31/43	A1	988
	R-449B	R-32/R-125/R-1234yf/R-134a	25.2/24.3/23.2/27.3	A1	1412
	ARM-20b	R-32/R-1234yf/R-152a	35/55/10	A2L	251
	DR-3	R-32/R-1234yf	21.5/78.5	A2L	148
	L-20a (R-444B)	R-32/R-1234ze/R-152a	41.5/48.5/10	A2L	295
R404A	ARM-35	R-32/R-125/R-1234yf	12.5/61/26.5	A1	2220
	DR-34 (R-452A)	R-32/R-125/R-1234yf	11/59/30	A1	2140
	N-40c (R-448A)	R-32/R-125/R-134a/R-1234yf/R-1234ze	26/26/21/20/7	A1	1387
	ARM-20a	R-32/R-1234yf/R-152a	18/70/12	A2L	139
	HDR110	R-32/R-1234yf/CO2	21.5/75.5/3	A2L	148
R410A	ARM-71a	R-32/R-1234yf/R-1234ze(E)	68/26/6	A2L	460
	DR-5A (R-454B)	R-32/R-1234yf	68.9/31.1	A2L	466
	DR-55	R-32/R-125/R-1234yf	67/7/26	A2L	698
	HPR2A	R-32/134a/1234ze(E)	76/6/18	A2L	600
	L-41-1 (R-446A)	R-32/R-1234ze/Butane	68/29/3	A2L	461
	L-41-2 (R-447A)	R-32/R-1234ze/R-125	68/28.5/3.5	A2L	583

Notes:
1. Refrigerants' classifications or intended classifications according to the ASHRAE Standard 34 (ASHRAE, 2013).
2. GWP values are calculated based on IPCC AR-4 100 year.

3.1 Compressor Calorimeter Tests

Eight hermetic compressors were tested at four different testing facilities. The compressors included reciprocating, scroll, and rotary types. Specific information on the tested compressors is listed in Table 2.

Table 2: Tested compressors with low-GWP refrigerants

No.	Compressor Type	Voltage	Disp. Volume	Baseline Refrigerant	Refrigerants Tested	AREP Report No.
1	hermetic reciprocating	115V, 60Hz, single phase	8.77 cm3	R-404A	HDR-110, DR3	49 and 50(Sedliak, 2015a and 2015b)
2	Semi-hermetic reciprocating	380-420v, 50Hz, three phase	971.2 cm3	R-404A	DR-33 (R449A)	51 (Boscan et al, 2015)
3	hermetic reciprocating, Low back pressure	230V, 50 Hz, single phase	74.2 cm3	R-404A	DR-7, ARM-25	64 and 67 (Pérouffe et al, 2016a and 2016b)
4	hermetic reciprocating, High back pressure	230V, 50 Hz, single phase	74.2 cm3	R-404A	DR-7, ARM-25	64 and 67 (Pérouffe et al, 2016a and 2016b)
5	hermetic scroll	230V, 50 Hz, single phase	29.5 cm3	R-410A	DR-5A	58 (Rajendran et al, 2016)
6	hermetic reciprocating	230/208, 60Hz, single phase	30.5 cm3	R-410A	L41-1, DR-5A, ARM-71a, D2Y-60 and R-32	59 (Lenz et al, 2016)
7	hermetic scroll	380V, 50 Hz, three phase	112.3 cm3	R-410A	L-41-2 (R-447A)	65 (Rajendran et al, 2016)
8	hermetic scroll	400V, 50 Hz, three phase	151.7cm3	R-410A	HPR2A	66 (Suindykov et al, 2016)

3.2 Air-conditioners, Heat Pumps, and Water Chillers

Thirteen air-conditioners and heat pumps as well as a water chiller were tested with different low-GWP refrigerants. Information about the equipment tested and the type of tests conducted is summarized in Table 3. Eight of them were tested under a high ambient condition of 52°C.

Table 3: Tested air-conditioners, heat pumps and water chiller

Unit No.	Equipment Type	Baseline Refrigerant	Refrigerants Tested	Test type	Test Standard	AREP Report No.
1	3-ton air source, split	R-410A	R-32	soft-optimization	AHRI Standard 210/240*	42 (Li et al, 2015)
2	3-ton air source, split	R-410A	ARM-71a, DR-5A, HPR2A, L-41-1, L-41-2	drop-in	AHRI Standard 210/240*	52 (Burns, et al, 2015)
3	3-ton air source, split	R-410A	R-32, DR-5A, L-41-2	drop-in	AHRI Standard 210/240*	54 (Stöben et al, 2015)
4	5-ton air source, rooftop packaged unit	R-410A	R-32, ARM-71a, DR-5A, DR-55, HPR2A, L-41-2	drop-in	AHRI Standard 210/240*	47 and 53 (Uselton et al, 2015a and b)
5	6-ton air source, rooftop packaged unit	R-410A	R-32	soft-optimization	AHRI Standard 340/360	55 (Abbadi et al, 2015)
6	4-ton air source, rooftop packaged unit	R-410A	R-32, DR-5A, DR-55	soft-optimization	AHRI Standard 210/240*	56 and 63 (Schultz et al., 2015 and 2016)
7	2.5-ton air source, rooftop packaged unit	R-22	R-410A, R-32	soft-optimization	AHRI Standard 210/240*	57 (Allen et al, 2015)
8	1.5-ton air source, mini-split	R-410A	R-32, ARM-71a, DR-55, HPR2A, L-41-2	soft-optimization	AHRI Standard 210/240*	62 (Abdelaziz et al., 2016)
9	1.5-ton air source, mini-split	R-22	N-20b, DR-3, ARM-20b, L-20a, DR-93, R-290	soft-optimization	AHRI Standard 210/240*	62 (Abdelaziz et al., 2016)
10	1-ton water-to-water, heat pump	R-410A	R-32, L-41-1, L-41-2	drop-in	ISO Standard 13256-2 and EN Standard 14511-2	43 (Park et al., 2015)
11	1-ton, single packaged vertical heat pump (SPVH)	R-410A	R-32	drop-in	AHRI Standard 390	44 (Wuesthoff et al, 2015)
12	3-ton water-to-air, heat pump	R-410A	R-32, DR-5A, DR-55, L-41-2	drop-in and soft-optimization	ISO Standard 13256-1	60 (Brown et al., 2016)
13	4.5-ton air-to-water heat pump	R-407C	DR-3, L-20a, R-290	drop-in	EN Standards 14511 and 14825	61 (Stöben et al, 2016)
14	2-ton air-to-water chiller	R-410A	R-32, DR-5A, L-41-1, L-41-2	drop-in	Tester defined conditions	46 (Hanna et al, 2015)
"*":Standard rating conditions and high ambient conditions up to 52^{o}C						

3.4 Refrigeration Equipment

Two commercial ice machines, one trailer refrigeration unit and one commercial bottle cooler/freezer were tested by three manufacturers participating in the program. Information about the equipment tested and the test procedures is summarized in Table 4.

Table 4: Tested refrigeration equipment

Unit No.	Equipment Type	Baseline Refrigerant	Refrigerants Tested	Test type	Test Standard	AREP Report No.
1	trailer refrigeration unit	R-404A	DR-34 (R-452A)	drop-in	AHRI Standard 1110	41 (Hegar et al, 2015)
2	a split system air-cooled commercial ice machine	R404A	ARM-20b, N-40c	drop-in	AHRI Standard 810 and ASHRAE Standard 29	45 (Olson, 2015)
3	a split system air-cooled commercial ice machine	R-404A	L-20a (R-444B), N-40c (R-448A)	drop-in	AHRI Standard 810 and ASHRAE Standard 29	48 (Urbieta, 2015)

4. TEST RESULTS SUMMARY

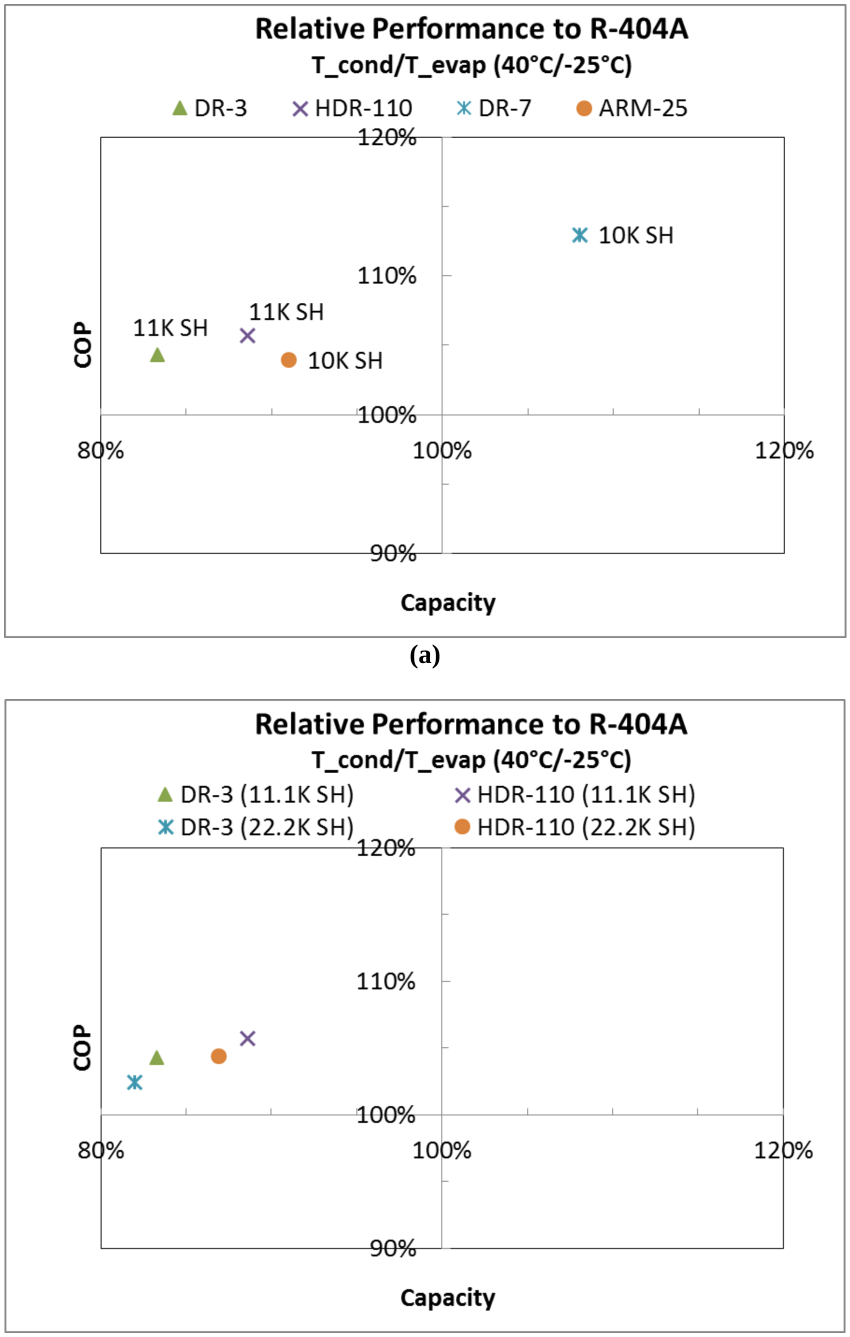
Test results are summarized according to equipment types. The performance of the low GWP refrigerants is normalized to their baseline refrigerants. Therefore, the comparison figures only show their relative performance to their respective baselines. To keep the paper concise, only partial results are shown (e.g. at one particular test condition, a particular baseline refrigerant etc.). Readers should refer to the individual test reports for all the data. The Coefficient of Performance (COP) is defined as a ratio of the capacity to the power consumption; and the Energy Efficiency Ratio (EER) is defined as a ratio of the cooling capacity in Btu/h to the power input value in watts

4.1 Compressors

The results shown in this subsection were obtained from compressor performance maps. Test companies used multiple test points to generate compressor performance maps in accordance with AHRI Standard 540. These maps were used to predict the performance of the compressors at any given set of evaporating and condensing temperatures within operating envelopes.

Figure 1 shows the test results of compressors No. 1 and 3 in Table 2 under a typical refrigeration condition (40°C condensing temperature, and -25°C evaporating temperature). The compressors were both tested at 10~11K superheat. The compressor No. 1 was tested under two different sets of superheat (11K and 22K).

Figure 1a shows that the four low GWP refrigerants have higher COP (4%~13%) at ~11K superheat compared to R-404A; however only DR-7 has a higher capacity (8%) at the same time. The other three refrigerants experienced some capacity degradation although the degree varies (-16%~-9%). When the compressor No.1 was tested at a higher superheat (22K), the low GWP refrigerants' performance decreased. Their relative capacity decreased further apart from the R-404A, and relative COP got closer to the R-404A.



(b)

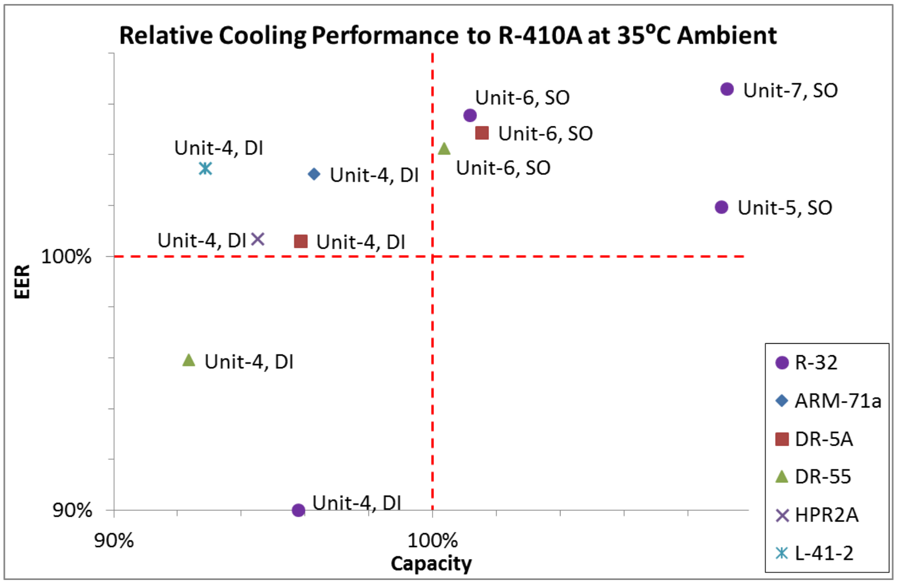
Figure 1: Low GWP refrigerants relative performance to R-404A

4.2 Air-conditioners and Heat Pumps

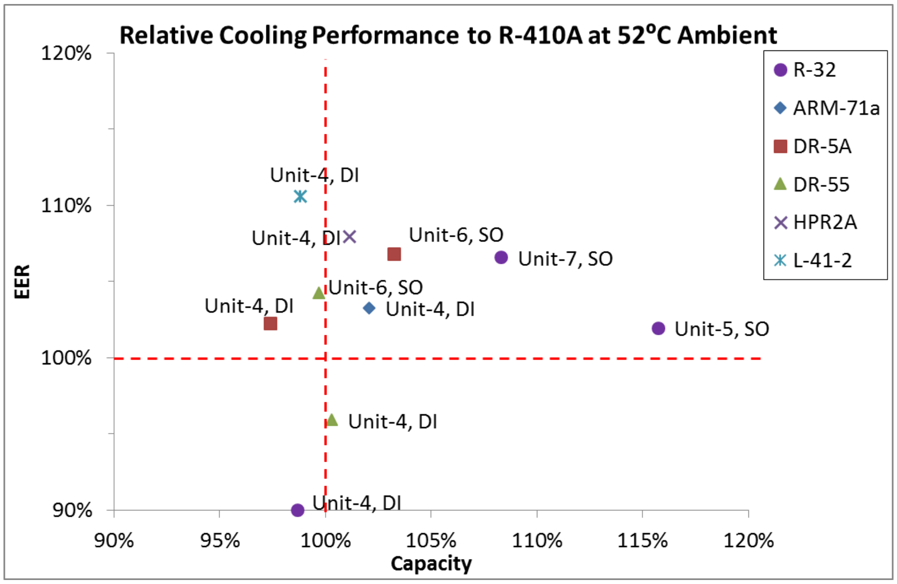
Test results for rooftop packaged units and residential split air-conditioners and heat pumps are summarized in Figures 2 and 3 (Unit No.1~7 in Table 3). The relative cooling performance to the baseline R-410A under the standard rating condition of 35°C and a high ambient condition of 52°C is shown in both figures.

R32, DR-5A, and DR-55 were tested in multiple units from different manufacturers. Figure 2 generally shows that it is possible for R-32, DR-5A and DR-55 to achieve higher capacity and EER than R-410A after simple soft-optimization. Other blends had lower capacity but higher efficiency than R-410A on a drop-in basis. It is also shown that these low GWP refrigerants relative performance to R-410A improved under the high ambient condition. They all showed very close or higher capacity and, in most of case, higher efficiency than R-410A.

Similarly, Figure 3 indicates that R-32 has a higher capacity than R-410A, and that it is also possible to achieve higher EER with soft-optimization. DR-5A, ARM-71a and L-41-2 showed comparable EER with slightly lower capacity than R-410A for drop-in test at 35°C ambient temperature. When performing under the high ambient temperature, these low GWP refrigerants demonstrate an improved relative performance to R-410A. They showed comparable capacity closely matching R-410A, and their efficiency is higher than or almost equal to R-410A. R-32 was not tested in the Units 2 and 3 under the 52°C ambient condition due to high discharge temperatures. Unit 1 used a specially formulated POE lubricant for R-32 (different from R-410A), and was able to operate and complete the test.

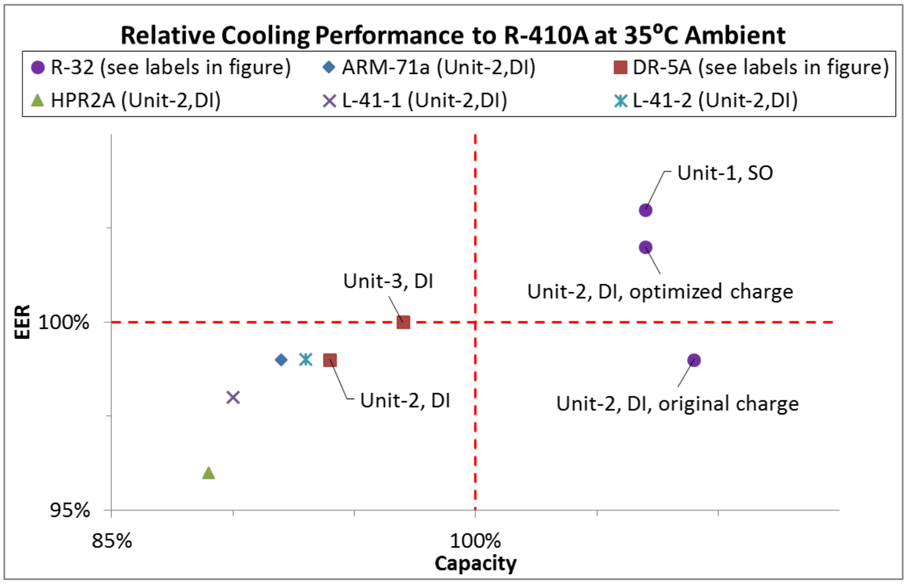


(a)

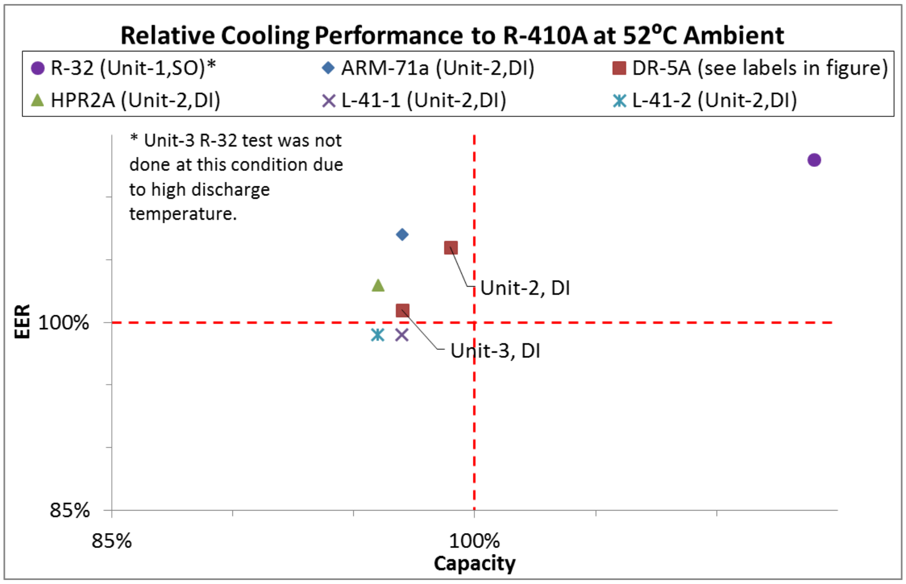


(b)

Figure 2: Low GWP refrigerants relative performance to R-410A in rooftop packaged units



(a)

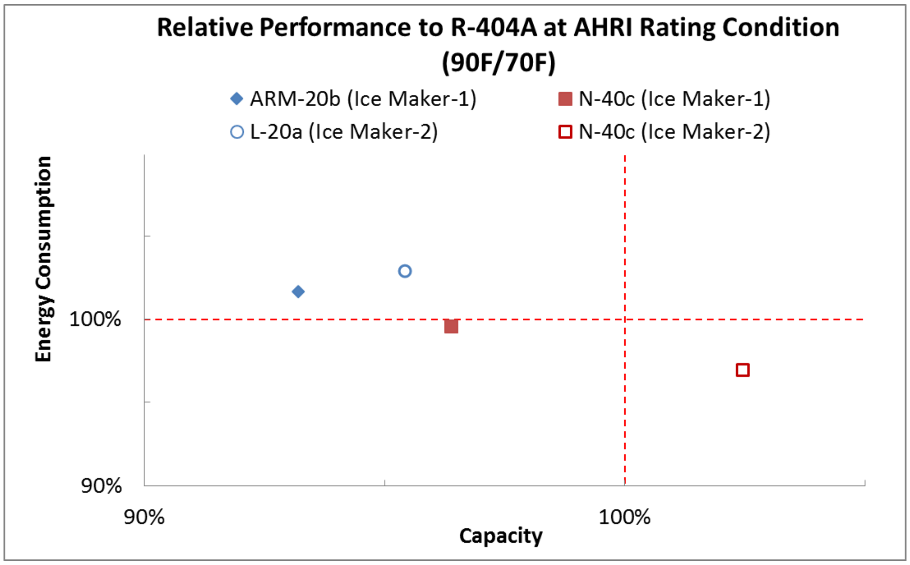


(b)

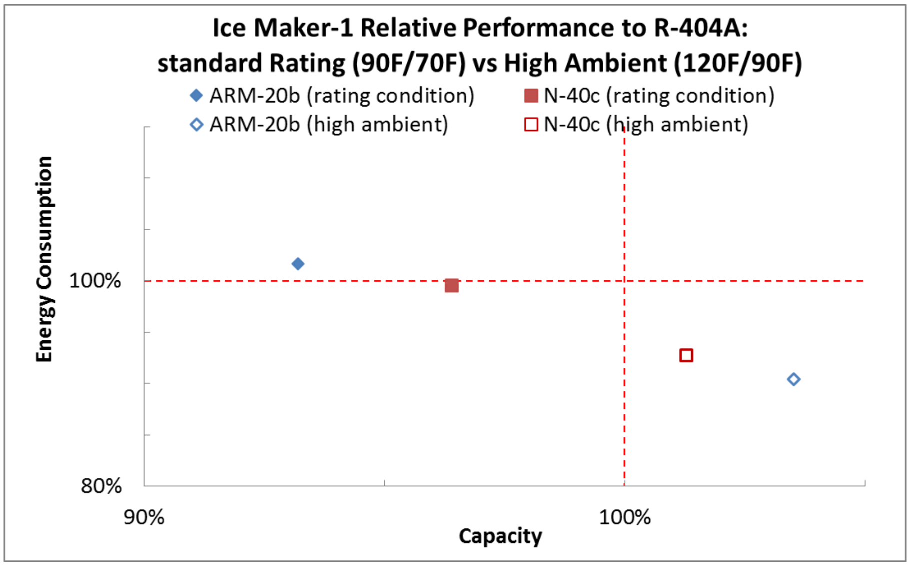
Figure 3: Low GWP refrigerants relative performance to R-410A in residential split systems

4.3 Refrigeration Equipment

ARM-20b, L-20a and N-40c were tested as drop-in refrigerants in two commercial ice machines (Units 2 and 3 in Table 4). Both were split systems. Figure 4a illustrates the low GWP refrigerants' relative performance to the baseline R-404A at the AHRI rating condition (ambient temperature: 32 °C; water temperature 21°C). N-40c consumed comparable or less power than R-410A and its relative capacity to R-410A is within 4%. ARM-20b and L-20a showed slightly increased power consumption (<3%), and reduced capacity compared to R-404A. Figure 4b showed the relative performance changes of the ARM-20b and N-40c at the high ambient condition when compared to the standard rating condition. Both refrigerants' relative performance to R-410A improved with less energy consumption and higher capacity than R-410A.



(a)



(b)

Figure 4: Low GWP refrigerants relative performance to R-404A in commercial ice machines

5. DISCUSSION

The Low-GWP AREP compressor tests were performed at a refrigerant's dew point temperature for suction and discharge pressure conditions. This does not have an impact when comparing compressor performance between two or more refrigerants that do not exhibit temperature glides. However, when refrigerants exhibit temperature glides, it is important to note that actual systems operate closer to the mid-point condition. When comparing compressor performance of one refrigerant with glide to another without, or comparing two refrigerants with significantly different glides, using pressures corresponding to the midpoint of the temperature glide rather than the dew point will yield results that are more representative of actual operation in a system (AHRI, 2015).

The results presented in Section 4 are for a quick initial comparison only. Cautions should be used when analyzing the data. It should be stressed that the capacity and efficiency are not strictly comparable among refrigerants when their suction vapor densities are different in drop-in testing, and when different test companies use different drop-in or soft-optimization procedures. The test procedure and results must be interpreted to account for charge quantity, expansion device, and/or compressor speed adjustment. Some test companies vary low GWP refrigerant charge quantity and/or adjust the expansion device to obtain comparable subcooling and superheating degrees to the baseline refrigerants. Some companies simply used the same charge quantity and the same expansion devices without any adjustment. As a consequence, different results may be obtained, and premature conclusions could be drawn if readers do not understand the source of variations. For example, R-32 was originally tested in Unit 2 in Figure 3 with the same charge quantity as the R-410A. The subcooling and superheat were shown in Figure 5. The R-32 with original charge had a subcooling 3K higher than the baseline suggesting that the system may be over-charged. The R-32 charge amount was reduced to 90% of the original charge. Its relative efficiency to R-410A increased 3% as shown in Figure 3.

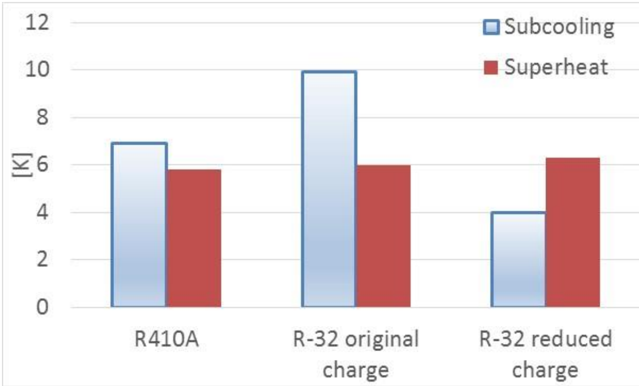


Figure 5: Unit 2 R-32 charge vs. subcooling and superheat

Another example is the N-40c test in two ice machines in Section 4.3. Results show that N-40c has different relative capacity to the baseline. This variation is likely the result of different drop-in methods used in the testing. The charge quantity of N-40c in Ice Maker-1 was optimized under the ambient temperature of -29 °C and the water temperature of 10°C. This is to determine the minimum amount of refrigerant necessary for the system to operate correctly at the low end of the operating envelope (Olson, 2015). The expansion valve was adjusted under the ambient temperature of 43°C and the water temperature of 32°C. Once the adjustment was completed, the test under the standard rating condition was conducted without further adjustment. However, the Ice Maker-2 used the same charge quantity for all tested refrigerants, and no adjustment was made to the expansion valve setting.

6. CONCLUSIONS

The test results obtained from the Low-GWP AREP showed that there are several alternative candidates with comparable performance than the baseline refrigerants they intend to replace.

It should be noted that most results were obtained from drop-in and soft-optimized tests performed on equipment designed for the baseline refrigerants and not the alternatives. Therefore, the results should not be viewed as universally applicable. The normalized comparison only provide initial quick understanding of improvement potential. The test results should be carefully interpreted along with system modifications, test procedure variations etc. Additional study is required to evaluate the potential improvement through further "soft optimization". Full optimization of systems will likely improve the performance of these refrigerants; however, this work is outside the scope of the Low-GWP AREP, and will be undertaken by individual manufacturers.

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