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ABSTRACT

The Air-Conditioning, Heating, and Refrigeration Institute (AHRI) recently completed the first 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' performance over the past two years. Thirty-eight low-GWP refrigerants were tested during the first phase of the program in a variety of products; including air conditioners, heat pumps, chillers, ice makers and commercial bottle coolers. This paper provides a comprehensive summary of the test results obtained during phase I. Furthermore, AHRI launched a second phase of testing at the beginning of 2014 that includes newly developed refrigerants and performance testing under high ambient conditions that were not covered in the first phase.

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. Phase I included compressor calorimeter testing, system drop-in testing, and soft-optimized system testing. Thirty-eight refrigerant candidates were tested by twenty one 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 use these refrigerants. The program's objectives are to identify potential replacements for high GWP refrigerants and present the performance of these replacements in a consistent and standard manner. However, the program will not prioritize the alternative refrigerants. This paper is an overall summary of the test results obtained in Phase I.

2. LOW GWP REFRIGERANTS

The tested refrigerants and their compositions are listed in Table 1. These refrigerants were proposed by refrigerant manufacturers and members of the AHRI technical committee overseeing the program. Neither an upper numerical limit on refrigerants' GWP values nor the safety classifications were limitations to nominating refrigerants, as long as a candidate low-GWP refrigerant had a significant reduction in its GWP relative to the refrigerant it is intended to replace.

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

Baseline	Refrigerant	Composition	(Mass%)	Classification (Note 1)	GWP_{100} (Note 2)
R22	ARM-32a	R-32/R-125/R-134a/R-1234yf	(25/30/25/20)	A1	1577
	LTR4X	R-32/R-125/R-134a/R-1234ze(E)	(28/25/16/31)	A1	1295
	N20	R-32/R-125/R-134a/R-1234yf/R-1234ze(E)	(12.5/12.5/31.5/ 13.5/30)	A1	975
	D52Y	R-32/R-125/R-1234yf	(15/25/60)	A2L	979
	L20	R-32/R-152a/R-1234ze(E)	(45/20/35)	A2L	331
	LTR6A	R-32/R-744/R-1234ze(E)	(30/7/63)	A2L	206
	R290	R290	100	A3	11
	R1270	R1270	100	A3	11
R-134a	AC5X	R-32/R-134a/R-1234ze(E)	(7/40/53)	A1	622
	ARM-41a	R-32/R-134a/R-1234yf	(6/63/31)	A1	943
	D-4Y	R-134a/R-1234yf	(40/60)	A1	574
	N13a	R-134a/R-1234yf/R-1234ze(E)	(42/18/40)	A1	604
	N13b	R-134a/R-1234ze(E)	(42/58)	A1	604
	XP-10	R-134a/R-1234yf	(44/56)	A1	631
	AC5	R-32/R-152a/R-1234ze(E)	(12/5/83)	A2L	92
	ARM-42a	R-134a/R-152a/R-1234yf	(7/11/82)	A2L	117
	R1234yf	R1234yf	100	A2L	4
	R1234ze	R1234ze	100	A2L	6
	R600a	R600a	100	A3	11
	R290/R600a	R290/R600a	(40/60)	A3	11
R404A	ARM-32a	R-32/R-125/R-134a/R-1234yf	(25/30/25/20)	A1	1577
	DR-33	R-32/R-125/R-134a/R-1234yf	(24/25/26/25)	A1	1410
	N40a	R-32/R-125/R-134a/R-1234yf/R-1234ze(E)	(25/25/21/9/20)	A1	1346
	N40b	R-32/R-125/R-134a/R-1234yf	(25/25/20/30)	A1	1331
	ARM-30a	R-32/R-1234yf	(29/71)	A2L	199
	ARM-31a	R-32/R-134a/R-1234yf	(28/21/51)	A2L	491
	D2Y65	R-32/R-1234yf	(35/65)	A2L	239
	DR-7	R-32/R-1234yf	(36/64)	A2L	246
	L40	R-32/R-152a/R-1234yf/R-1234ze(E)	(40/10/20/30)	A2L	285
	R-32	R-32	100	A2L	675
	R-32/R-134a	R-32/R-134a	(50/50)	A2L	1053
	R290	R-290	100	A3	11
R410A	ARM-70a	R-32/R-134a/R-1234yf	(50/10/40)	A2L	482
	D2Y60	R-32/R-1234yf	(40/60)	A2L	272
	DR-5	R-32/R-1234yf	(72.5/27.5)	A2L	490
	HPR1D	R-32/R-744/R-1234ze(E)	(60/6/34)	A2L	407
	L41a	R-32/R-1234yf/R-1234ze(E)	(73/15/12)	A2L	494
	L41b	R-32/R-1234ze(E)	(73/27)	A2L	494
	R32	R32	100	A2L	675
	R-32/R-134a	R-32/R-134a	(95/5)	A2L	713
	R-32/R-152a	R-32/R-152a	(95/5)	A2L	647

Notes:

1. Refrigerants' classifications or intended classifications according to the ASHRAE Standard 34 (ASHRAE, 2010).
2. Estimated GWP values from chemical producers

3. TESTING

Tests conducted during Phase I 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 I for different product categories. The corresponding Low-GWP AREP Report Number for particular tested equipment is also listed, in order to direct readers to the detailed test information and results.

3.1 Compressor Calorimeter Tests

Ten 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	Displacement Volume	Baseline Refrigerant	Refrigerants Tested	AREP Report No.
1	hermetic reciprocating	220/240V, single phase, 50Hz	34.38 cm^3	R-22	R-1270	17 (Ribeiro *et al.*, 2013a)
2	hermetic reciprocating	220/240V, single phase, 50Hz	6.36 cm^3	R-134a	ARM-42a, N-13a	18 (Ribeiro *et al.*, 2013b)
3	hermetic reciprocating	115V, single phase, 60Hz	16.8cm^3	R-134a	R-1234yf	30 (Sedliak, 2013c)
4	hermetic reciprocating	208/230V, three phase, 60Hz	47.14cm^3	R-404A	DR-7, L-40	35 and 37 (Rajendran *et al.*, 2014b and d)
5	hermetic reciprocating	115V, single phase, 60Hz	8.77 cm^3	R-404A	DR-7, L-40	28 and 29 (Sedliak, 2013a and b)
6	hermetic scroll	208/230V, single phase, 60 Hz	50.96 cm^3	R-404A	ARM-31a, D2Y-65, L-40, and R-32/R-134a (50/50)	21 (Shrestha *et al.*, 2013b)
7	hermetic scroll	460V, three phase, 60Hz	98.04 cm^3	R-404A	DR-7, L-40	34 and 36 (Rajendran *et al.*, 2014a and c)
8	hermetic scroll	208/230V, single phase, 60 Hz	20.32 cm^3	R-410A	R-32, R-32/R-134a (94/6), DR-5, L-41a	11 and 33 (Shrestha *et al.*, 2013a and 2014)
9	hermetic scroll	208/230V, single phase, 60Hz	29.5 cm^3	R-410A	DR-5, L-41b, R-32	24, 38 and39 (Rajendran *et al.*, 2013, 2014e and f)
10	hermetic rotary	220V, single phase, 50Hz	28cm^3	R-410A	DR-5, R-32	26 and 40 (Zhang *et al.*, 2013 a and 2014)

3.2 Air-conditioners and Heat Pumps

Eleven air-conditioners and heat pumps (air-source and water-source) were tested with different low-GWP refrigerants. Information about the equipment tested and the type of tests conducted is summarized in Table 3.

3.3 Chillers

Six chillers were tested in Phase I. These chillers ranging from 5-ton to 230-ton capacity included both air-cooled and water-cooled products. The test information is shown in Table 4.

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 5.

Table 3: Tested air-conditioners and heat pumps

Unit No.	Equipment Type	Baseline Refrigerant	Refrigerants Tested	Test type	Test Standard	AREP Report No.
1	5-ton air source, split system	R-410A	R-32/R-152a (95/5)	drop-in	AHRI Standard 210/240	3 (Tio *et al.*, 2012)
2	3.5-ton air source, split system	R-410A	R-32, R-1234yf	drop-in for R-32, soft-optimization for R-1234yf		4, 10 (Crawford *et al.*, 2012), (Uselton, 2013)
3	3-ton air source, split system	R-410A	R-32	soft-optimization		5 (Li *et al.*, 2012)
4	3-ton air source, split system	R-410A	R-32, D2Y-60, L-41a	drop-in and soft-optimization for D2Y-60 and L-41a		20, 23, 32 (Alabdulkarem *et al.*, 2013a, b and c)
5	3-ton air source, split system	R-410A	R-32, ARM-70a, DR-5, L-41a, L-41b	drop-in		22 (Burns *et al.*, 2013)
6	2-ton air source, split system	R-410A	R-32	drop-in		31 (Zhang *et al.*, 2013 b)
7	8-ton air-source, VRF	R-410A	R-32	drop-in	AHRI Standard 1230	15 (Tsujii *et al.*, 2013)
8	3-ton water-to water	R-410A	R-32, R-32/R-134a (95/5), DR-5	drop-in and soft optimization for DR-5	ISO Standard 13256-2	16 (Lim *et al.*, 2013)
9	air-to-water	R-410A	ARM-70a, DR-5	drop-in	AHRI Standard 551/591	27 (Besbes *et al.*, 2013)
10	bus air-conditioning	R-134a	AC5, N-13a	drop-in	OEM defined conditions	12 (Kopecka *et al.*, 2013b)
11	bus air-conditioning	R-407C	D52Y, L-20	drop-in	OEM defined conditions	13 (Kopecka *et al.*, 2013c)

Table 4: Tested chillers

Unit No.	Equipment Type	Baseline Refrigerant	Refrigerants Tested	Test type	Test Standard	AREP Report No.
1	5-RT Air-Cooled Water Chiller	R-410A	ARM-32a, ARM-70a, DR-5, HPR1D, L-41a, L-41b, and R-32	drop-in	AHRI Standard 550/590	1 (Schultz *et al.*, 2012)
2	5-RT Air-Cooled Water Chiller	R-22	ARM-32a, DR-7, L-20, LTR4X, LTR6A, and D52Y	drop-in	AHRI Standard 550/590	6 (Schultz *et al.*, 2013a)
3	175-ton Air-Cooled Screw Chiller	R-134a	ARM-42a	drop-in	AHRI Standard 550/590	14 (Kulankara *et al.*, 2012)
4	230-Rt Water-Cooled screw Chiller	R-134a	ARM-42a, N-13a, N-13b, R-1234ze(E), and Opteon™ XP10	drop-in	AHRI Standard 550/590	7 (Schultz *et al.*, 2013b)
5	200 RT Air-Cooled Screw Chiller	R-134a	R1234ze(E) and D4Y	drop-in	AHRI Standard 550/590	25 (Kasai *et al.*, 2013)
6	Water-cooled Centrifugal Chiller	R-134a	R-1234ze(E) and ARM-42a	drop-in and soft-optimized tests	AHRI Standard 550/590	Not published, in revision

Table 5: Tested refrigeration equipment

Unit No.	Equipment Type	Baseline Refrigerant	Refrigerants Tested	Test type	Test Standard	AREP Report No.
1	self-contained air-cooled commercial ice machine	R-404A	L-40, N-40b	drop-in	AHRI Standard 810 and ASHRAE Standard 29	2 (Schlosser, 2012)
		R-410A	L-41a	drop-in	AHRI Standard 810 and ASHRAE Standard 31	2 (Schlosser, 2012)
2	a split system air-cooled commercial ice machine	R404A	L-40, N-40b	drop-in	AHRI Standard 810 and ASHRAE Standard 30	2 (Schlosser, 2012)
		R-410A	L-41a	drop-in	AHRI Standard 810 and ASHRAE Standard 32	2 (Schlosser, 2012)
3	commercial bottle cooler/freezer	R-134a	R-1234yf, R-1234ze(E), XP-10, N-13a	drop-in	ASHRAE Standard 72	8 (Shapiro, 2013)
4	trailer refrigeration unit	R-404A	ARM-30a, DR-7, L-40	drop-in	AHRI Standard 1110	9 (Kopecka *et al.*, 2013a)

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. It needs to be pointed out that graphs show only some of the results (e.g. at one particular test conditions, a particular baseline refrigerant etc.) due to the page limit. Readers should refer to the individual test reports for all the data.

4.1 Compressors

The results shown in this subsection were obtained from experimental data only. Some test companies generated 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 the operating envelopes. However, performance ratios predicted in this manner are not included on the figures below.

Figure 1 shows the test results of compressors No. 5 and 6 in Table 2 (Sedliak, 2013a and b, Shrestha *et al.*, 2013b). The compressors were tested at different sets of evaporator dew point and condenser dew point temperatures. Only tests having same/similar evaporating dew point (~-20°C and -12°C) and relatively close condenser dew point (43°C and 45°C) are normalized in the figure. The T_eavp dew/T_cond dew for each data point is shown in the figure. The compressors were tested under two different sets of superheat (11K and 22K).

The five low GWP refrigerants have higher COP (3%~11%) at 11K superheat compared to R-404A; however only D2Y65 and R-32/R-134a (50/50) could maintain slightly higher or similar capacity (-0.1%~3%) at the same time. The other three refrigerants had some capacity degradation although the degree varies (-13%~-2%). When the compressors were tested at higher superheat (22K), the low GWP refrigerants' performance decreased. Their relative capacity decreased further apart from the R-404A (-15%~-4%), and relative COP got closer to the R-404A. For the R-32/R-134a mixture, its COP decreased significantly when the superheat changed from 11K to 22K.

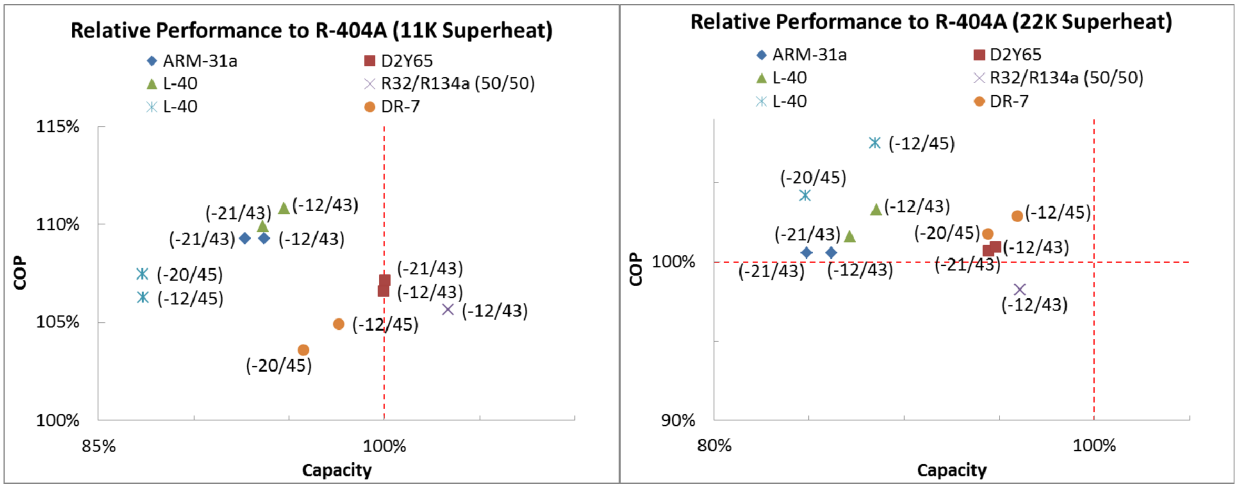

Figure 1: Low GWP refrigerants relative performance to R-404A

4.2 Air-conditioners and Heat Pumps

Test results for residential air-source air-conditioners and heat pumps are summarized in Figures 2 and 3 (Unit No.1~7 in Table 3). The relative cooling and heating performance to the baseline R-410A under standard rating conditions is shown in Figure 2; while Figure 3 shows the relative seasonal performance.

Some refrigerants were tested in multiple units (i.e. R-32, L-41a) from different manufacturers. In general, Figure 2 shows that R-32 had higher capacity than R-410A; however, the test results did not show consistency in the efficiency as the results are scattered. This inconsistency could be from variations in the equipment, or test facilities and test conditions. This deserves further investigation in the future. The R-32/R-152a (95/5) mixture showed improvement in capacity and COP. All other blends had different performance than R-410A on a drop-in basis. Some of them were significantly lower in both cooling and heating capacity than R-410A. Most of them showed improvements in the Heating Seasonal Performance Factor (HSPF) and a decrease in the Seasonal Energy Efficiency Ratio (SEER).

It should be stressed that these results were obtained from drop-in or simple soft-optimization tests and that the equipment tested was designed for R-410A and not specifically designed/optimized for these alternative refrigerants. Additional study is needed to evaluate potential improvements through further "soft optimization".

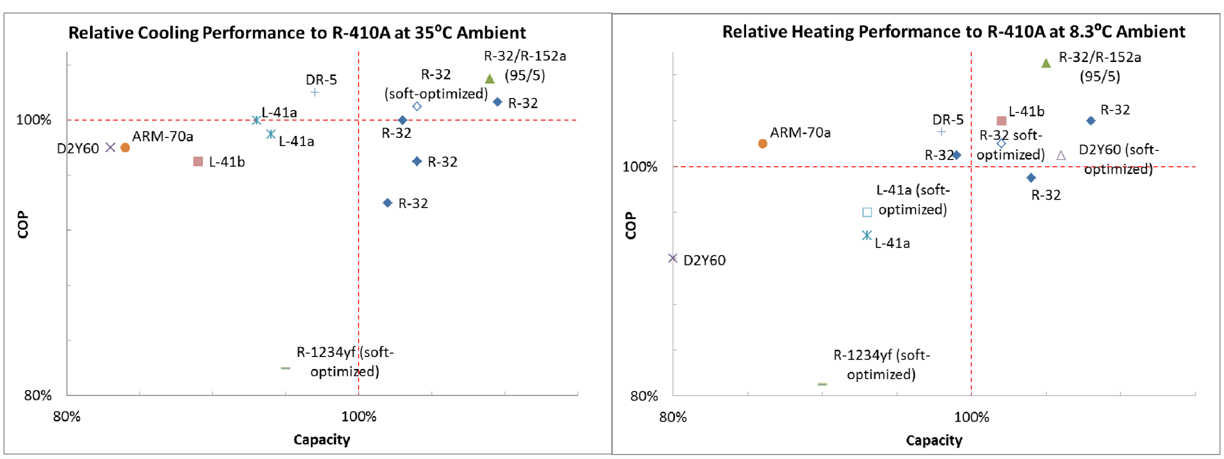

Figure 2: Low GWP refrigerants relative performance to R-410A in air-source air-conditioners and heat pumps

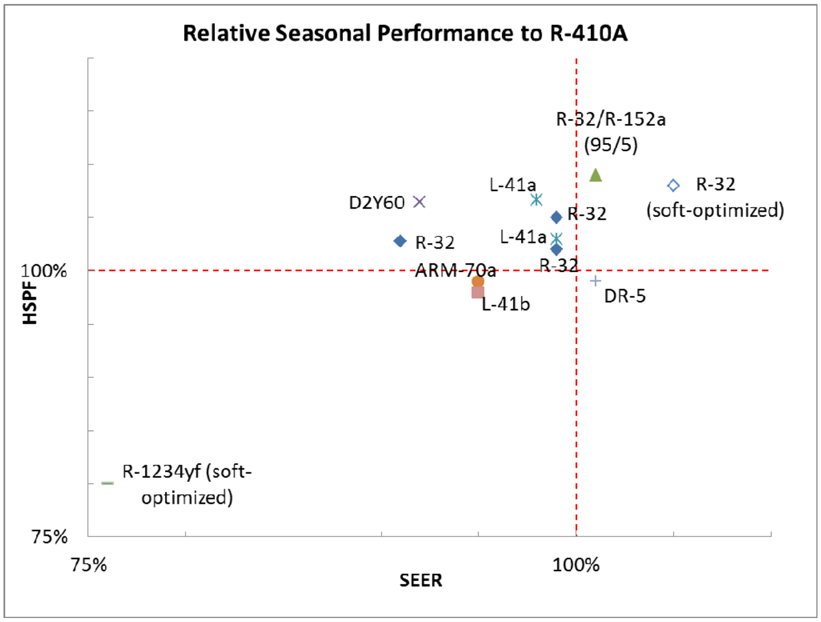

Figure 3: Low GWP refrigerants relative seasonal performance to R-410A in air-source air-conditioners and heat pumps

4.3 Refrigeration Equipment

L-40 and N-40b were tested as drop-in refrigerants in two commercial ice machines. One was a self-contained air-cooled commercial ice machine and another was a split system. Figure 4 illustrates the low GWP refrigerants' relative performance to the baseline R404A at the AHRI rating condition (ambient temperature: 32 °C; water temperature 21°C) (Schlosser, 2012). N-40b appears to be a direct drop-in for the self-contained ice machine at least in terms of the capacity and efficiency. It also showed an increased capacity (~3%), and reduced power consumption (~3%) compared to R-404A for the split system. The L-40 had completely opposite results for the self-contained and the split systems. It performed better in self-contained system and worse in the split system than R-404A did.

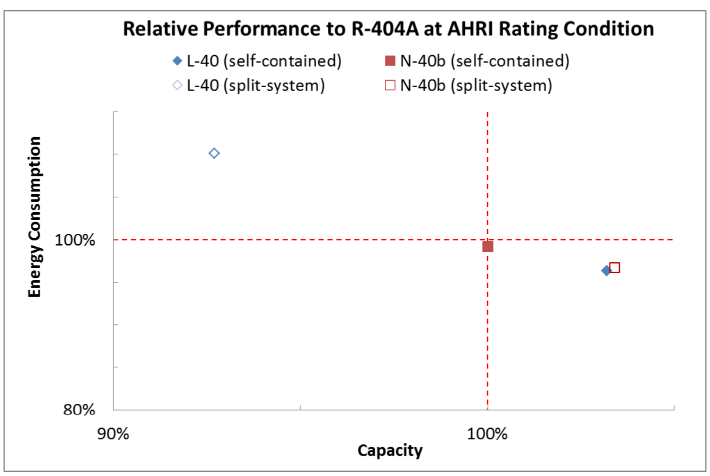

Figure 4: Low GWP refrigerants relative performance to R-404A in commercial ice machines

4.4 Chillers

Two air-cooled and one water-cooled screw chillers were tested. Their capacity ranges from 175 tons to 230 tons. Figure 5 demonstrates the normalized test results to the baseline R-134a at the full-load condition (Kulankara *et al.*, 2012, Kasai *et al.*, 2013, Schultz *et al.*, 2013b). They showed comparable efficiency than R-134a (-4%~6%) for the drop in test. D4Y, XP-10, and ARM-42a showed similar capacity than R-134a, but the efficiency was slightly lower (no more than 4% reduction). The other tested refrigerants showed 10%~25% capacity reduction.

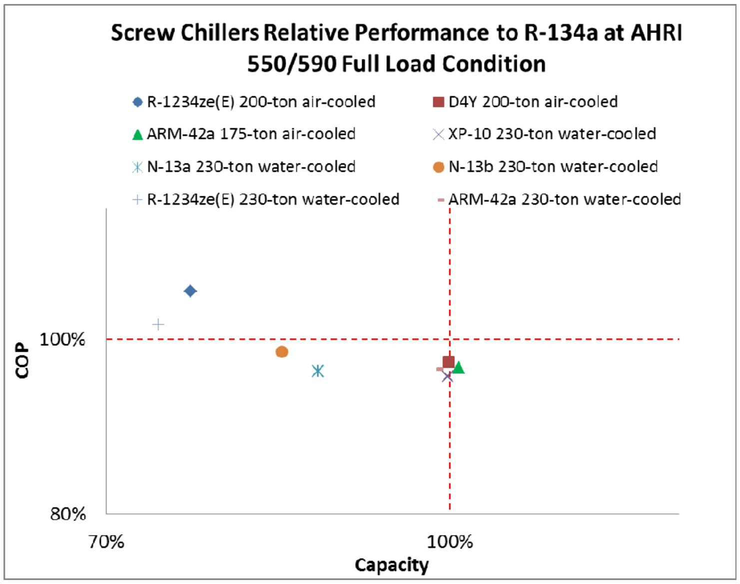

Figure 5: Low GWP refrigerants relative performance to R-134a in screw chillers

5. CONCLUSIONS AND FUTURE WORK

The test results obtained from the Low-GWP AREP Phase I show that there are several alternative candidates with comparable performance than the baseline refrigerants they intend to replace. However, based on current test results, it appears unlikely that a single refrigerant will replace R-22, R-134a, R-404A, and R-410A. Indications point to different alternatives for different applications.

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. 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.

In some cases, test results showed some inconsistency. This may be due to testing different types and sizes of equipment by different manufacturers using different testing facilities. This would warrant further investigation in the future.

Finally, AHRI launched Phase II of the Low-GWP AREP in January, 2014. Phase II of the program will focus in areas not previously addressed such as testing refrigerants at high ambient conditions (i.e., warmer climates); evaluating refrigerants in applications not tested in the first phase; and assessing the performance of new refrigerants identified since the program began in 2011.

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