Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP)

TEST REPORT #8

System Drop-In Tests of R-134a, R-1234yf, Opteon™ XP10, R-1234ze(E), and N13a in a Commercial Bottle Cooler/Freezer

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This report has been made available to the public as part of the author company's participation in the AHRI's Low-GWP AREP.

The tests in this report were conducted prior to the Low-GWP AREP, and may not exactly meet the program's requirements. The results were reviewed and accepted as they are useful and informative.

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List of Tested Refrigerants' Compositions (Mass%)

R-1234yf	R-1234yf (100)
N-13a	R-134a/R-1234yf/R-1234ze(E) (42/18/40)
R-1234ze(E)	R-1234ze(E) (100)
Opteon™ XP10	R-134a/R-1234yf (44/56)

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1. Introduction:

From October 2010 through May 2011, Hussmann completed R-134a baseline testing and system drop-in testing of R-1234yf, Opteon™ XP10, R-1234ze(E), and N13a in a commercial bottle cooler/freezer. Figure 1 shows available bottle coolers in this product line.

Fig 1. Bottle coolers (center unit, Model ARV-570, was tested)

It is important to note that the results reported here were completed prior to the start of the AREP work. Nevertheless, Hussmann wishes to present the results, since they are relevant and useful as part of the overall refrigerant evaluation program. It must be understood that because the Hussmann tests were completed before the AREP work had started, parts of the test setup, conditions, and procedures may be different than specified in the AREP Participants Handbook.

2. Details of Test Setup:

a. Description of System

Figure 2 shows a photo of the test unit. As shown, the unit had a single door, approximately 1.8 m (6 ft) tall. One important difference between this unit and typical bottle coolers is that the test unit can operate below freezing, with a -5.6°C (22°F) setpoint. The unit is intended to be used with beer cans or bottles, and the -5.6°C setpoint is not quite cold enough to freeze beer. However, due to condensation, a layer of ice forms on a beer can when it is removed from the unit.

Fig 2. Model ARV-570 used for drop-in tests
Note discharge air temperature display in upper right reads 23°F (-5°C)

The evaporator and evaporator fan are located in the top-back of these coolers. The compressor, condenser, and condenser fan are located in the bottom. Other details are:

- Compressor: Fractional horsepower, hermetic, reciprocating type, 10.61 cm^3 displacement
- Nominal motor size: 270 W
- Condenser: Approximately 30 cm width x 28 cm height 3.3 cm depth, with 16 tubes total in an 8 x 2 staggered pattern with copper tubes and aluminum fins, 3.1 fins/cm
- Expansion device: Capillary tube 244 cm length with 1.24 mm ID. The capillary tube is piped through the suction tube, thus providing a liquid-to-suction heat exchanger.
- Evaporator: Approximately 49 cm width x 18 cm height x 7 cm depth, with 21 tubes total in a 7 x 3 staggered pattern with copper tubes and aluminum fins, 2.4 fins/cm

b. Description of Modifications to System

The normal refrigerant charge for these units is 266 g of R-134a. However, the additional charge needed to accommodate the refrigerant flow meter and connecting piping was calculated and included in the tests. Thus, 322 g of refrigerant was used for the tests. A refrigerant mass flow meter was installed in the compressor discharge line.

c. Description of Tests Conducted

Two types of tests were conducted: 1) "Steady-state" tests with door opening/closing cycles in accordance with ASHRAE Standard 72-2005, *Method of Testing Commercial Refrigerators and Freezers* and 2) full pull-down and half pull-down tests in accordance with a soft-drink bottler's specifications.

A detailed discussion of these two types of tests is beyond the scope of this report, but in short, the ASHRAE tests measured performance over a normal operating cycle including automated door openings and defrost period. The full pull-down test measured performance with the full product load "soaked" at 32°C (90°F). Similarly, the half pull-down test measured performance with half the product load soaked at 32°C.

The main objectives of the evaluation were:

a) Conduct performance tests in accordance with ASHRAE Standard No. 72-2005
   - Two bottle cooler thermostat settings were tested, -5.6°C (22°F) and 3.3°C (38°F).
   - Two test cell ambient conditions were tested, 23.9°C (75°F)/55% relative humidity and 26.7°C (80°F)/55% relative humidity.
b) Conduct full pull-down and half pull-down tests in accordance with a soft-drink bottler's specifications
c) Compare performance values such as discharge air temperatures, product simulator temperatures, suction pressure, discharge pressure, compressor mass flow, and compressor input power
d) Repeat each series of tests with the refrigerants listed in Table 1
e) Note any other important observations

An overview of the tests conditions is shown in Table 1, and Figure 3 shows a flow diagram of the refrigerant circuit.

Table 1: Overview of test conditions and refrigerants

Refrigerants:	R-134a					
	R-1234yf					
	Opteon™ XP10					
	R-1234ze(E)					
	N13a					
Test type:	ASHRAE 72				Full Pull-Down	Half Pull-Down
Test cell temperature °C (°F):	23.9 (75)	23.9 (75)	26.7 (80)	26.7 (80)	32.2 (90)	32.2 (90)
Test cell relative humidity:	55%	55%	55%	55%	65%	65%
Bottle cooler setpoint, °C (°F):	5.6 (38)	-3.3 (22)	5.6 (38)	-3.3 (22)	5.6 (38)	5.6 (38)

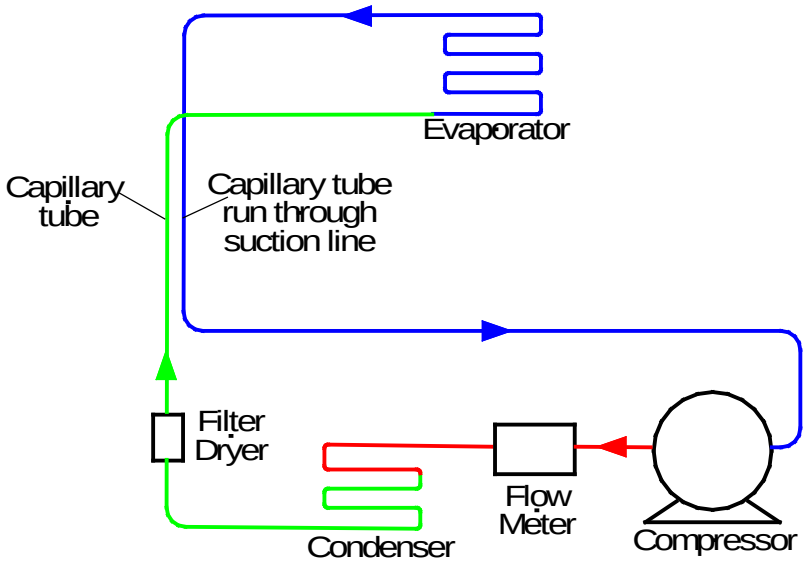

Fig 3. Flow diagram of refrigerant circuit

Tests were conducted in Test Cell No. 11 at the Hussmann R&D Lab in Bridgeton, MO, USA. The following data were recorded:

- Compressor suction and discharge pressures
- Refrigerant mass flow rate
- Refrigerant pressure drops through evaporator, condenser, and refrigerant flow meter
- Compressor suction and discharge temperatures

- Evaporator refrigerant outlet temperature
- Condenser air inlet and outlet temperatures
- Condenser refrigerant inlet and outlet temperatures
- Discharge air temperatures, 5 cm from left end, center, and 5 cm from right end of discharge air duct
- Return air temperatures, 5 cm from left end, center, and 5 cm from right end of return air duct
- Test cell ambient dry and wet bulb temperatures
- Test unit voltage, current, and power
- Compressor current and power
- Evaporator fan power (checked once, not recorded continuously)

A PC-based Data Acquisition System was used to record measurements. Temperatures were recorded every 60 seconds. Power, pressure, and differential pressure values were recorded every 10 seconds. Data was summarized in spreadsheets in accordance with the corresponding test standard. Refrigerant properties were obtained using REFPROP Database 23, Version 8.0

3. Results

Table 2
Low GWP AREP system drop-in test data form

Manufacturer: Hussmann Corporation Manufacturer's Notation: ARV-570

Basic Information	
Alternative Refrigerants (If not proprietary, composition as Charged, % wt)	Please refer to Table 1
Baseline Refrigerant and Lubricant	R-134a/POE
Make and Model of System	Hussmann ARV-570
Nominal Capacity W	350
Mode	Cooling
Compressor Type	Hermetic Reciprocating
Compressor Displacement cm^3	10.61
Nominal motor speed, rpm	Approx. 3500
Actual motor speed	Not Measured
Expansion Device Type	Capillary Tube
Lubricant type	POE, ISO10
Refrigerant composition at compressor inlet	Please refer to Table 1

Note: The above basic information is the same for all tests, and therefore is included here only.

3.1 ASHRAE 72 Tests

Tables 3 through 6 show averaged data over the duration of each test run. To make it easier to review the tables, each row has a number value and each column has a Test ID number.

Table 3 shows results at 23.9°C/55% relative humidity ambient conditions with the 3.3°C bottler cooler setpoint. Beginning with the left side of Table 3, three sets of baseline tests were conducted, Test ID Nos. 1, 2 and 3. Note the completion dates were 10/12/10, 2/16/11, and 5/09/11. These tests were conducted with R134a at the beginning, middle, and end of the overall program to verify that the baseline performance was repeatable. For example, if something had gone wrong with the compressor or instrumentation, large changes would likely have been seen between these three tests.

As shown in Table 3, there were some modest differences among the three baseline measurements. For example, in Rows 11 and 12, the compressor mass flow dropped slightly from 6.37 kg/hr to 6.24 kg/hr and then further to 6.16 kg/hr, for Tests 1, 2, and 3, respectively. Thus, the mass flow was 3.4% lower in Test 3 versus Test 1. On the other hand, there was almost no difference in the compressor power (Row 66) for these three tests, with 116 W, 118 W and again 118 W for Tests 1, 2, and 3, respectively. One possible cause of these changes is slightly different refrigerant charge. Beginning in 2011, an improved scale was used to charge the system. The new scale had +/-1 gram (+/-0.036 ounce) precision versus the old scale, which had +/- 7 gram (+/- 0.25 ounce) precision.

Keeping in mind the three sets of baseline results, some main results in Table 3 are:

- Rows 9 and 10: The suction and discharge pressure, 205 kPa and 558 kPa, respectively of R-1234ze(E) were considerably lower than the other refrigerants.
- Row 11 and 12: The mass flow rate of R-1234yf (Test 4) was 13.9% higher than the first baseline test (Test 1).
- Rows 23 through 25: The discharge air temperatures were nearly identical for all tests. We would expect this result since discharge air temperature was the basis for cycling the compressor on/off.
- Rows 66 and 67: The compressor power was within +/- 2.7% for all tests.
- Rows 69 and 70: The compressor run time for R-1234ze(E) (Test 6) was 21.5% higher than the first baseline test.
- Rows 79 and 80: The average cooling capacity for R-1234yf, XP10, R-1234ze, and N13a were 8.5%, 7.8%, 7.9%, and 5.2% lower, respectively
- Rows 80.1 and 80.2: The average COP for R-1234yf, XP10, R-1234ze, and N13a were 10.9%, 9.7%, 5.7%, and again 5.7% lower, respectively

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Table 3

Results at 23.9°C (75°F)/55% relative humidity ambient conditions,
3.3°C (38°F) bottle cooler set point

Row 0	Refrigerant	R134a	R134a	R134a	R-1234yf	Opteon™ XP10	R-1234ze	N13a
1	Test type	ASHRAE	ASHRAE (repeat)	ASHRAE (repeat)	ASHRAE	ASHRAE	ASHRAE	ASHRAE
2	Test ID no.	1	2	3	4	5	6	7
4	Test cell temperature setpoint db °C	23.9	23.9	23.9	23.9	23.9	23.9	23.9
4.1	Test cell temperature setpoint wb °C	17.8	17.8	17.8	17.8	17.8	17.8	17.8
5	Test cell relative humidity setpoint, %	55	55	55	55	55	55	55
6	Bottle cooler setpoint °C	3.3	3.3	3.3	3.3	3.3	3.3	3.3
8	Completion date	10/12/10	02/16/11	05/09/11	11/28/10	01/11/11	03/01/11	03/27/11
9	Suction pressure kPa	285	283	279	303	305	205	264
10	Discharge pressure kPa	702	704	704	730	727	558	674
11	Refrigerant flow rate kg/hr	6.37	6.24	6.16	7.26	6.58	6.50	6.53
12	Difference %	0%	-2.1%	-3.4%	**13.9%**	3.3%	2.0%	2.5%
13	Refrigerant pressure drop evaporator kPa	1.39	1.83	1.67	1.36	1.70	2.97	2.90
14	Refrigerant pressure drop condenser kPa	1.43	1.53	1.43	1.53	1.58	1.21	1.50
15	Refrigerant pressure drop flow meter kPa	26.78	27.33	27.89	26.76	27.01	29.89	28.46
16	Compressor suction temperature °C	19.4	20.2	20.4	20.1	21.0	18.2	20.4
17	Compressor discharge temperature °C	40.0	40.9	41.3	41.3	40.9	40.0	41.6
18	Evaporator outlet temperature °C	-0.2	0.7	1.0	1.3	1.9	0.0	0.9
19	Condenser air inlet temperature °C	23.9	24.0	24.2	24.1	24.2	24.0	24.4
20	Condenser air outlet temperature °C	25.8	26.0	26.2	26.0	26.1	25.7	26.3
21	Condenser refrigerant inlet temperature °C	32.1	31.9	32.2	32.8	32.9	32.0	32.8
22	Condenser refrigerant outlet temp °C	27.7	27.6	27.8	27.7	27.9	27.6	28.0
23	Refrigerated air discharge temperature 5 cm from left wall °C	2.5	2.5	2.5	2.4	2.5	2.5	2.4
24	Refrigerated air discharge temperature center °C	2.6	2.6	2.6	2.6	2.7	2.6	2.6
25	Refrigerated air dischrage temperature 5 cm from right wall °C	2.4	2.4	2.3	2.4	2.5	2.4	2.4
26	Refrigerated air return temperature 5 cm from left wall °C	3.8	3.9	3.9	3.8	3.9	3.8	3.8
27	Refrigerated air return temperature center °C	4.1	4.2	4.1	4.1	4.2	4.2	4.2
28	Refrigerated air return temperature 5 cm from right wall °C	4.1	4.3	4.3	4.2	4.3	4.3	4.3
29	Test cell dry bulb (1 of 2) °C	23.9	23.9	23.8	24.0	24.1	23.9	24.2
30	Test cell dry bulb (2 of 2) °C	23.4	23.6	23.5	23.7	23.8	23.7	24.0
31	Test cell wet bulb °C	17.6	18.1	18.2	18.1	18.3	17.8	18.2
40	Test cell relative humidity %	54.5%	57.4%	58.1%	56.1%	57.6%	55.0%	55.6%
50	**Product simulator temperatures**							
51	Integrated average product simulator temperature °C	4.0	4.0	4.1	4.0	4.0	4.0	4.1
52	{CTS} Integrated coldest product simulator. temperature °C	3.4	3.4	3.4	3.3	3.1	3.4	3.4
54	{WTS} Integrated warmest product simulator temperature °C	4.4	4.6	4.5	4.5	4.6	4.5	4.6
59	Refrigerant charge g	322+/-7	322 +/-1	322 +/-1	322+/-7	322 +/-1	322 +/-1	322 +/-1
61	Supply voltage	118	120	121	120	122	121	120
66	Compressor power W	116	118	118	120	119	114	117
67	Difference %	0%	**1.1%**	**1.3%**	2.7%	2.1%	-2.3%	0.6%
69	Compressor run time, %	35.1%	35.1%	35.9%	35.0%	35.0%	42.6%	37.0%
70	Difference %	0%	0.0%	2.4%	-0.2%	-0.2%	**21.5%**	**5.5%**
71	Evaporator fan power W (checked once, not recorded continuously)	58	58	58	58	58	58	58
73	Evaporating temperature (avg. of dew and bubble) °C	-0.8	-0.9	-1.3	-0.9	-1.5	-1.3	-1.8
74	Condensing temperature (avg. of dew and bubble) °C	26.8	26.9	26.9	27.9	27.8	28.8	27.2
75	Superheat at compressor inlet °K	20.1	21.1	21.7	21.0	22.5	19.4	22.2
79	Average cooling capacity W*	317	311	307	290	292	292	301
80	Difference %	0%	-1.9%	-3.0%	**-8.5%**	**-7.8%**	**-7.9%**	**-5.2%**
80.1	Average COP (W/W)	2.72	2.64	2.60	2.43	2.46	2.57	2.57
80.2	Difference %	0.0%	-3.0%	-4.3%	**-10.9%**	**-9.7%**	**-5.7%**	**-5.7%**
	*Assumes saturated liquid at inlet of expansion device							

Table 4 shows results at 23.9°C/55% relative humidity ambient conditions with the -5.6°C bottle cooler setpoint. Some main results in this table are:

- Rows 9 and 10: The suction and discharge pressures, 132 kPa and 592 kPa, respectively of R-1234ze(E) (Test 11) were considerably lower than the other refrigerants.
- Rows 11 and 12: The mass flow rate of R-1234yf (Test 9) was 19.6% higher than the baseline.
- Rows 23 through 25: The discharge air temperatures were nearly identical for all tests. Again, we would expect this result since discharge air temperature was the basis for cycling the compressor on/off.
- Rows 66 and 67: Compared to the baseline, the compressor power values were 8.0% higher, 6.5% higher, 4.4% lower, and 1.4% higher for R-1234yf, XP10, R-1234ze(E), and N13a, respectively.
- Rows 69 and 70: The compressor run time for R-1234ze(E) (Test 11) was 18.1% higher than the baseline.
- Rows 79 and 80: The average cooling capacity for R-1234yf, R-1234ze, and N13a were 5.5%, 14.3%, and 6.5% lower, respectively
- Rows 80.1 and 80.2: The average COP for R-1234yf, XP10, R-1234ze, and N13a were 12.5%, 9.5%, 10.3%, and 7.8% lower, respectively

Table 5 shows results at 26.7°C/55% relative humidity ambient conditions with the 3.3°C bottle cooler setpoint. Some main results in this table are:

- Rows 9 and 10: The suction and discharge pressures, 201 kPa and 612 kPa, respectively of R-1234ze(E) (Test 16) were considerably lower than the other refrigerants.
- Rows 11 and 12: The mass flow rate of R-1234yf (Test 14) was 14.8% higher than the baseline.
- Rows 23 through 25: As with the other test conditions, the discharge air temperatures were nearly identical for all tests.
- Rows 66 and 67: With the exception of R-1234ze(E) (Test 16), the compressor power values were within +/- 2.5% of the baseline. R-1234ze(E) had 4.3% lower power than the baseline.
- Rows 69 and 70: The compressor run time for R-1234ze(E) (Test 16) was 20.0% higher than the baseline.
- Rows 79 and 80: The average cooling capacity for R-1234yf and R-1234ze were 5.1% and 5.3% lower, respectively
- Rows 80.1 and 80.2: The average COP for R-1234yf was 6.3% lower

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Table 4

Results at 23.9°C (75°F)/55% relative humidity ambient conditions, -5.6°C (22°F) bottle cooler setpoint

Row 0	Refrigerant	R-134a	R-1234yf	Opteon™ XP10	R-1234ze	N13a
1	Test type	ASHRAE	ASHRAE	ASHRAE	ASHRAE	ASHRAE
2	Test ID no.	8	9	10	11	12
4	Test cell temperature setpoint db °C	23.9	23.9	23.9	23.9	23.9
4.1	Test cell temperature setpoint wb °C	17.8	17.8	17.8	17.8	17.8
5	Test cell relative humidity setpoint, %	55	55	55	55	55
6	Bottle cooler setpoint °C	-5.6	-5.6	-5.6	-5.6	-5.6
8	Completion date	10/07/10	11/21/10	01/09/11	03/06/11	03/29/11
9	Suction pressure kPa	189	205	209	132	175
10	Discharge pressure kPa	796	822	829	592	749
11	Refrigerant flow rate kg/hr	8.06	9.64	8.68	7.41	8.04
12	Difference %	0.0%	**19.6%**	**7.7%**	**-8.2%**	-0.3%
13	Refrigerant pressure drop evaporator kPa	2.90	4.13	3.89	3.29	4.51
14	Refrigerant pressure drop condenser kPa	1.41	2.29	1.92	1.62	1.68
15	Refrigerant pressure drop flow meter kPa	27.16	26.36	22.04	22.67	24.36
16	Compressor suction temperature °C	9.5	10.8	14.9	12.4	13.1
17	Compressor discharge temperature °C	47.7	47.7	49.7	47.9	49.8
18	Evaporator outlet temperature °C	-10.2	-10.4	-9.3	-10.4	-9.9
19	Condenser air inlet temperature °C	23.6	24.2	24.1	23.4	24.1
20	Condenser air outlet temperature °C	25.6	26.3	26.1	25.2	26.1
21	Condenser refrigerant inlet temperature °C	36.8	38.3	39.1	36.6	38.6
22	Condenser refrigerant outlet temp °C	28.9	30.0	29.4	28.2	29.2
23	Refrigerated air discharge temperature 5 cm from left wall °C	-6.4	-6.5	-6.4	-6.6	-6.6
24	Refrigerated air discharge temperature center °C	-6.5	-6.6	-6.4	-6.7	-6.6
25	Refrigerated air dischrage temperature 5 cm from right wall °C	-6.7	-6.8	-6.6	-6.9	-6.8
26	Refrigerated air return temperature 5 cm from left wall °C	-4.8	-4.8	-4.7	-5.0	-4.8
27	Refrigerated air return temperature center °C	-4.3	-4.3	-4.2	-4.5	-4.3
28	Refrigerated air return temperature 5 cm from right wall °C	-4.3	-4.2	-4.0	-4.3	-4.2
29	Test cell dry bulb (1 of 2) °C	23.9	24.5	24.3	23.8	24.1
30	Test cell dry bulb (2 of 2) °C	23.4	24.1	24.0	23.7	24.1
31	Test cell wet bulb °C	17.6	18.3	18.4	18.5	18.2
40	Test cell relative humidity %	53.9%	55.1%	56.7%	60.0%	56.6%
50	**Product simulator temperatures**					
51	Integrated average product simulator temperature °C	-4.6	-4.6	-4.5	-4.7	-4.5
52	{CTS} Integrated coldest product simulator. temperature °C	-5.5	-5.5	-5.4	-5.6	-5.6
54	{WTS} Integrated warmest product simulator temperature °C	-4.0	-3.9	-3.7	-3.9	-3.8
59	Refrigerant charge g	322+/-7	322+/-7	322 +/-1	322 +/-1	322 +/-1
61	Supply voltage	118	119	121	120	120
66	Compressor power W	165	178	176	158	168
67	Difference %	0%	**8.0%**	**6.5%**	-4.4%	1.4%
69	Compressor run time, %	60.6%	59.7%	55.1%	71.6%	61.0%
70	Difference %	0%	-1.5%	**-9.0%**	**18.1%**	0.7%
71	Evaporator fan power W (checked once, not recorded continuously)	58	58	58	58	58
73	Evaporating temperature (avg. of dew and bubble) °C	-11.5	-11.8	-11.7	-12.6	-12.6
74	Condensing temperature (avg. of dew and bubble) °C	31.2	32.4	32.7	30.8	30.9
75	Superheat at compressor inlet °K	21.0	22.6	26.6	25.0	25.7
79	Average cooling capacity W*	372	352	359	319	348
80	Difference %	0%	**-5.5%**	-3.6%	**-14.3%**	**-6.5%**
80.1	Average COP (W/W)	2.25	1.97	2.04	2.02	2.08
80.2	Difference %	0.0%	**-12.5%**	**-9.5%**	**-10.3%**	**-7.8%**
	*Assumes saturated liquid at inlet of expansion device					

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Table 5

Results at 26.7°C (80°F)/55% relative humidity ambient conditions, 3.3°C (38°F) bottle cooler setpoint

Row 0	Refrigerant	R134a	R-1234yf	Opteon™ XP10	R-1234ze	N13a
1	Test type	ASHRAE	ASHRAE	ASHRAE	ASHRAE	ASHRAE
2	Test ID no.	13	14	15	16	17
4	Test cell temperature setpoint db °C	26.7	26.7	26.7	26.7	26.7
4.1	Test cell temperature setpoint wb °C	20.1	20.1	20.1	20.1	20.1
5	Test cell relative humidity setpoint, %	55	55	55	55	55
6	Bottle cooler setpoint °C	3.3	3.3	3.3	3.3	3.3
8	Completion date	10/19/10	12/02/10	01/03/11	03/13/11	04/06/11
9	Suction pressure kPa	281	299	302	201	259
10	Discharge pressure kPa	766	783	792	612	727
11	Refrigerant flow rate kg/hr	6.88	7.90	7.39	7.04	7.06
12	Difference %	0%	**14.8%**	**7.3%**	2.3%	2.5%
13	Refrigerant pressure drop evaporator kPa	1.58	1.68	1.85	3.46	3.09
14	Refrigerant pressure drop condenser kPa	1.43	1.59	1.87	1.26	1.77
15	Refrigerant pressure drop flow meter kPa	26.60	28.57	26.12	30.87	29.68
16	Compressor suction temperature °C	21.1	21.9	22.7	20.2	22.1
17	Compressor discharge temperature °C	44.7	44.8	46.2	44.4	46.0
18	Evaporator outlet temperature °C	-0.6	1.2	1.4	-0.4	0.8
19	Condenser air inlet temperature °C	26.5	26.4	26.6	26.5	26.6
20	Condenser air outlet temperature °C	28.6	28.5	28.7	28.3	28.8
21	Condenser refrigerant inlet temperature °C	36.0	36.4	36.8	35.7	36.3
22	Condenser refrigerant outlet temp °C	30.7	30.6	30.9	30.5	30.6
23	Refrigerated air discharge temperature 5 cm from left wall °C	2.3	2.4	2.3	2.4	2.3
24	Refrigerated air discharge temperature center °C	2.4	2.5	2.5	2.5	2.5
25	Refrigerated air dischrage temperature 5 cm from right wall °C	2.2	2.3	2.3	2.3	2.2
26	Refrigerated air return temperature 5 cm from left wall °C	3.8	3.9	3.8	3.8	3.8
27	Refrigerated air return temperature center °C	4.1	4.2	4.2	4.2	4.2
28	Refrigerated air return temperature 5 cm from right wall °C	4.1	4.3	4.3	4.3	4.4
29	Test cell dry bulb (1 of 2) °C	26.8	26.6	26.7	26.8	26.8
30	Test cell dry bulb (2 of 2) °C	26.2	26.1	26.3	26.4	26.3
31	Test cell wet bulb °C	20.0	20.3	20.0	19.9	20.3
40	Test cell relative humidity %	53.3%	56.4%	54.1%	52.9%	54.9%
50	**Product simulator temperatures**					
51	Integrated average product simulator temperature °C	4.0	4.0	4.0	4.1	4.1
52	{CTS} Integrated coldest product simulator. temperature °C	3.3	3.3	3.3	3.4	3.4
54	{WTS} Integrated warmest product simulator temperature °C	4.5	4.6	4.6	4.6	4.7
59	Refrigerant charge g	322+/-7	322+/-7	322 +/-1	322 +/-1	322 +/-1
61	Supply voltage	119	121	121	121	120
66	Compressor power W	132	133	135	126	130
67	Difference %	0%	1.3%	2.5%	-4.3%	-1.1%
69	Compressor run time, %	39.0%	37.7%	38.1%	46.8%	41.1%
70	Difference %	0%	-3.3%	-2.2%	**20.0%**	**5.4%**
71	Evaporator fan power W (checked once, not recorded continuously)	58	58	58	58	58
73	Evaporating temperature (avg. of dew and bubble) °C	-1.2	-1.3	-1.8	-1.9	-2.3
74	Condensing temperature (avg. of dew and bubble) °C	29.8	30.6	26.0	31.9	29.8
75	Superheat at compressor inlet °K	22.3	23.2	24.5	22.2	24.4
79	Average cooling capacity W*	328	312	336	311	321
80	Difference %	0%	**-5.1%**	2.4%	**-5.3%**	-2.3%
80.1	Average COP (W/W)	2.50	2.34	2.50	2.47	2.47
80.2	Difference %	0.0%	**-6.3%**	-0.1%	-1.1%	-1.2%
	*Assumes saturated liquid at inlet of expansion device					

Table 6 shows results at 26.7°C/55% relative humidity ambient conditions with the -5.6°C bottle cooler setpoint. Some main results in this table are:

- Rows 9 and 10: The suction and discharge pressures, 127 kPa and 644 kPa, respectively of R-1234ze(E) (Test 21) were considerably lower than the other refrigerants.
- Rows 11 and 12: The mass flow rate of R-1234yf (Test 19) was 22.3% higher than the baseline.
- Rows 23 through 25: The discharge air temperatures were nearly identical for all tests.
- Rows 66 and 67: The compressor power values were 5.8% higher, 6.3% higher, 4.8% lower and 2.0% lower for R-1234yf, XP10, R-1234ze(E), and N13a, respectively.
- Rows 69 and 70: The compressor run time for R-1234ze(E) (Test 21) was 18.2% higher than the baseline.
- Rows 79 and 80: The average cooling capacity for R-1234ze and N13a were 12.9%, and 5.6% lower, respectively
- Rows 80.1 and 80.2: The average COP for R-1234yf, XP10, and R-1234ze were 9.5%, 7.2%, and 8.6% lower, respectively

3.2 Full and half pull-down tests

Table 7 shows full pull-down results. Some main items in this table are:

- Rows 9 and 10: The suction and discharge pressures, 182 kPa and 789 kPa, respectively of R-1234ze(E) (Test 26) were considerably lower than the other refrigerants.
- Rows 11 and 12: The mass flow rate of R-1234yf (Test 24) was 19.9% higher than the baseline.
- Rows 23 through 25: The discharge air temperatures were nearly identical for all tests.
- Rows 66 and 67: The compressor power values were 4.8% higher, 2.4% higher, 11.2% lower and 2.9% lower for R-1234yf, XP10, R-1234ze(E), and N13a, respectively.
- Rows 69 and 70: The compressor run times were within +/- 2.2% with the exception of R-1234ze(E) (Test 26), which was 12.5% higher than the baseline.
- Rows 79 and 80: The average cooling capacity for R-1234yf, XP10, R-1234ze, and N13a were 6.2%, 6.0%, 9.9%, and 1.1% lower, respectively
- Rows 80.1 and 80.2: The average COP for R-1234yf and XP10 were 10.5% lower and 8.1%, respectively
- Rows 108 and 109: The amount of time until compressor started cycling was within +/- 5.2% with the exception of R-1234ze(E) (Test 26), which took 31.3% longer.

The compressor was relatively undersized for use with R-1234ze(E). In the pull-down test, we saw a main disadvantage of an undersized compressor – longer pull-down time.

Table 6

Results at 26.7°C (80°F)/55% relative humidity ambient conditions, -5.6°C (22°F) bottle cooler setpoint

Row 0	Refrigerant	R134a	R-1234yf	Opteon™ XP10	R-1234ze	N13a
1	Test type	ASHRAE	ASHRAE	ASHRAE	ASHRAE	ASHRAE
2	Test ID no.	18	19	20	21	22
4	Test cell temperature setpoint db °C	26.7	26.7	26.7	26.7	26.7
4.1	Test cell temperature setpoint wb °C	20.1	20.1	20.1	20.1	20.1
5	Test cell relative humidity setpoint, %	55	55	55	55	55
6	Bottle cooler setpoint °C	-5.6	-5.6	-5.6	-5.6	-5.6
8	Completion date	10/24/10	12/06/10	01/05/11	03/10/11	04/03/11
9	Suction pressure kPa	187	204	205	127	172
10	Discharge pressure kPa	836	863	894	644	795
11	Refrigerant flow rate kg/hr	8.19	10.01	9.29	7.80	8.35
12	Difference %	0%	**22.3%**	**13.5%**	-4.8%	2.0%
13	Refrigerant pressure drop evaporator kPa	3.67	4.42	3.86	3.13	4.37
14	Refrigerant pressure drop condenser kPa	1.59	2.52	2.23	1.84	1.97
15	Refrigerant pressure drop flow meter kPa	17.57	24.21	21.85	20.70	19.43
16	Compressor suction temperature °C	14.6	13.9	16.6	15.2	16.1
17	Compressor discharge temperature °C	52.5	52.3	54.1	53.6	53.6
18	Evaporator outlet temperature °C	-10.6	-10.4	-9.7	-10.9	-10.0
19	Condenser air inlet temperature °C	26.1	26.2	26.3	26.0	26.2
20	Condenser air outlet temperature °C	28.2	28.3	28.4	27.9	28.4
21	Condenser refrigerant inlet temperature °C	41.0	41.9	42.9	41.5	42.3
22	Condenser refrigerant outlet temp °C	31.6	32.1	32.1	31.3	31.8
23	Refrigerated air discharge temperature 5 cm from left wall °C	-6.4	-6.4	-6.4	-6.8	-6.5
24	Refrigerated air discharge temperature center °C	-6.5	-6.5	-6.5	-6.9	-6.6
25	Refrigerated air dischrage temperature 5 cm from right wall °C	-6.7	-6.8	-6.7	-7.2	-6.9
26	Refrigerated air return temperature 5 cm from left wall °C	-4.6	-4.6	-4.6	-5.1	-4.7
27	Refrigerated air return temperature center °C	-4.0	-4.1	-4.0	-4.5	-4.1
28	Refrigerated air return temperature 5 cm from right wall °C	-4.0	-4.0	-3.9	-4.4	-4.0
29	Test cell dry bulb (1 of 2) °C	26.6	26.6	26.7	26.8	26.6
30	Test cell dry bulb (2 of 2) °C	26.1	26.2	26.3	26.5	26.4
31	Test cell wet bulb °C	20.0	20.3	20.1	21.3	20.3
40	Test cell relative humidity %	54.4%	56.4%	54.5%	61.4%	55.8%
50	**Product simulator temperatures**					
51	Integrated average product simulator temperature °C	-4.3	-4.4	-4.3	-4.8	-4.4
52	{CTS} Integrated coldest product simulator. temperature °C	-5.5	-5.4	-5.3	-5.7	-5.5
54	{WTS} Integrated warmest product simulator temperature °C	-3.4	-3.5	-3.5	-3.9	-3.6
59	Refrigerant charge g	322+/-7	322+/-7	322 +/-1	322 +/-1	322 +/-1
61	Supply voltage	118	120	122	120	119
66	Compressor power W	181	192	192	172	177
67	Difference %	0%	**5.8%**	**6.3%**	-4.8%	-2.0%
69	Compressor run time, %	66.2%	62.6%	62.3%	78.2%	65.8%
70	Difference %	0%	**-5.5%**	**-5.9%**	**18.2%**	-0.5%
71	Evaporator fan power W (checked once, not recorded continuously)	58	58	58	58	58
73	Evaporating temperature (avg. of dew and bubble) °C	-11.7	-12.1	-12.2	-13.6	-13.0
74	Condensing temperature (avg. of dew and bubble) °C	32.9	34.2	35.6	33.7	33.0
75	Superheat at compressor inlet °K	26.2	26.1	28.8	28.8	29.1
79	Average cooling capacity W*	382	366	377	333	361
80	Difference %	0%	-4.2%	-1.4%	**-12.9%**	**-5.6%**
80.1	Average COP (W/W)	2.11	1.91	1.96	1.93	2.03
80.2	Difference %	0.0%	**-9.5%**	**-7.2%**	**-8.6%**	-3.7%
	*Assumes saturated liquid at inlet of expansion device					

Table 7
Full pull-down test results

Row 0	Refrigerant	R134a	R-1234yf	Opteon™ XP10	R-1234ze	N13a
1	Test type	Pulldown	Pulldown	Pulldown	Pulldown	Pulldown
2	Test ID no.	23	24	25	26	27
4	Test cell temperature setpoint db °C	32.2	32.2	32.2	32.2	32.2
4.1	Test cell temperature setpoint wb °C	26.6	26.6	26.6	26.6	26.6
5	Test cell relative humidity setpoint, %	65	65	65	65	65
6	Bottle cooler setpoint °C	3.3	3.3	3.3	3.3	3.3
8	Completion date	10/28/10	12/14/10	01/18/11	03/16/11	05/04/11
9	Suction pressure kPa	251	271	268	182	238
10	Discharge pressure kPa	1043	1087	1081	789	979
11	Refrigerant flow rate kg/hr	9.96	11.94	10.80	9.77	10.40
12	Difference %	0%	**19.9%**	**8.4%**	-1.9%	4.4%
13	Refrigerant pressure drop evaporator kPa	2.64	2.46	3.23	4.00	4.00
14	Refrigerant pressure drop condenser kPa	2.12	2.45	2.36	2.26	2.15
15	Refrigerant pressure drop flow meter kPa	29.58	33.10	30.12	33.72	33.78
16	Compressor suction temperature °C	25.7	26.9	26.8	25.4	25.6
17	Compressor discharge temperature °C	63.3	64.1	65.2	60.2	63.1
18	Evaporator outlet temperature °C	-0.6	-0.6	1.4	0.3	-0.2
19	Condenser air inlet temperature °C	33.3	34.2	33.3	32.3	33.1
20	Condenser air outlet temperature °C	35.7	36.9	35.8	34.7	35.7
21	Condenser refrigerant inlet temperature °C	51.9	53.4	52.8	49.4	50.9
22	Condenser refrigerant outlet temp °C	39.9	41.6	40.3	38.7	39.8
23	Refrigerated air discharge temperature 5 cm from left wall °C	2.4	2.5	2.6	3.0	2.7
24	Refrigerated air discharge temperature center °C	2.5	2.5	2.7	3.2	2.8
25	Refrigerated air dischrage temperature 5 cm from right wall °C	2.2	2.3	2.3	2.9	2.5
26	Refrigerated air return temperature 5 cm from left wall °C	4.7	5.0	5.0	5.4	5.1
27	Refrigerated air return temperature center °C	5.8	5.9	6.0	6.5	6.0
28	Refrigerated air return temperature 5 cm from right wall °C	5.6	5.9	5.8	6.3	6.1
29	Test cell dry bulb (1 of 2) °C	34.0	35.1	33.9	33.2	33.8
30	Test cell dry bulb (2 of 2) °C	33.2	34.4	33.3	32.6	33.2
31	Test cell wet bulb °C	26.7	26.2	27.0	26.6	26.8
40	Test cell relative humidity %	56.4%	49.6%	58.6%	59.6%	58.0%
50	**Product simulator temperatures**					
51	Integrated average product simulator temperature °C	7.6	7.8	7.8	8.2	7.9
52	{CTS} Integrated coldest product simulator. temperature °C	2.6	2.6	2.5	2.7	2.7
54	{WTS} Integrated warmest product simulator temperature °C	32.9	32.8	32.5	32.7	32.8
59	Refrigerant charge g	322+/-7	322+/-7	322 +/-1	322 +/-1	322 +/-1
61	Supply voltage	119	121	121	120	121
66	Compressor power W	214	224	219	190	207
67	Difference %	0%	4.8%	2.4%	**-11.2%**	-2.9%
69	Compressor run time, %	61.0%	61.0%	59.7%	68.7%	61.9%
70	Difference %	0%	0.0%	-2.2%	**12.5%**	1.5%
71	Evaporator fan power W (checked once, not recorded continuously)	58	58	58	58	58
73	Evaporating temperature (avg. of dew and bubble) °C	-4.2	-4.2	-5.1	-4.7	-4.6
74	Condensing temperature (avg. of dew and bubble) °C	40.9	43.3	43.1	40.9	40.7
75	Superheat at compressor inlet °K	29.9	31.1	31.9	30.1	30.2
79	Average cooling capacity W*	455	427	428	410	451
80	Difference %	0%	**-6.2%**	**-6.0%**	**-9.9%**	-1.1%
80.1	Average COP (W/W)	2.13	1.91	1.96	2.16	2.17
80.2	Difference %	0.0%	**-10.5%**	**-8.1%**	1.4%	1.9%
	*Assumes saturated liquid at inlet of expansion device					
100	Maximum compressor discharge temperature** °C	88.8	85.5	87.1	77.5	84.5
101	Maximum compressor suction temperature** °C	37.1	36.0	36.7	36.0	36.3
108	Amount of time until compressor cycling starts minutes	291	291	306	382	305
109	Difference %	0%	0.0%	5.2%	**31.3%**	4.8%
	**Measured from start of test until the compressor first cycles off					
	72 hour minimum thermal soak time for pulldown and half pulldown tests					

Table 8 shows half pull-down results. Some main results in this table are:

- Rows 9 and 10: The suction and discharge pressures, 184 kPa and 756 kPa, respectively of R-1234ze(E) (Test 31) were considerably lower than the other refrigerants.
- Rows 11 and 12: The mass flow rate of R-1234yf (Test 29) was 17.4% higher than the baseline.
- Rows 23 through 25: The discharge air temperatures were nearly identical for all tests.
- Rows 66 and 67: The compressor power values were 2.7% higher, 4.2% higher, 5.2% lower and 0.5% lower for R-1234yf, XP10, R-1234ze(E), and N13a, respectively.
- Rows 69 and 70: The compressor run times were 0.8% higher, 8.2% higher, 20.0% higher and 11.3% higher for R-1234yf, XP10, R-1234ze(E), and N13a, respectively.
- Rows 79 and 80: The average cooling capacity for R-1234yf, XP10, R-1234ze, and N13a were 6.8%, 6.9%, 7.8%, and 6.5% lower, respectively
- Rows 80.1 and 80.2: The average COP for R-1234yf, XP10, and N13a were 9.3%, 10.7%, and 6.1% lower, respectively
- Rows 108 and 109: The amount of time until the compressor cycling started were 10% lower, 3.8% lower, 40.8% higher and 50.8% higher for R-1234yf, XP10, R-1234ze(E), and N13a, respectively. The time until compressor cycling started for the N13a blend seems inconsistent with the other values. Given the other results, we expected this value to be closer to the baseline. The cause of this unexpected result is not known.

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Table 8

Half pull-down test results

Row 0	Refrigerant	R134a	R-1234yf	Opteon™ XP10	R-1234ze	N13a
1	Test type	Half-Pulldown	Half-Pulldown	Half-Pulldown	Half-Pulldown	Half-Pulldown
2	Test ID no.	28	29	30	31	32
4	Test cell temperature setpoint db °C	32.2	32.2	32.2	32.2	32.2
4.1	Test cell temperature setpoint wb °C	26.6	26.6	26.6	26.6	26.6
5	Test cell relative humidity setpoint, %	65	65	65	645	65
6	Bottle cooler setpoint °C	3.3	3.3	3.3	3.3	3.3
8	Completion date	11/08/10	12/21/10	02/09/11	03/21/11	04/19/11
9	Suction pressure kPa	258	276	263	184	229
10	Discharge pressure kPa	949	966	976	756	900
11	Refrigerant flow rate kg/hr	8.54	10.02	9.10	8.70	8.67
12	Difference %	0%	**17.4%**	**6.6%**	1.9%	1.6%
13	Refrigerant pressure drop evaporator kPa	2.86	2.30	3.32	4.44	0.63
14	Refrigerant pressure drop condenser kPa	1.97	1.85	2.22	2.00	0.34
15	Refrigerant pressure drop flow meter kPa	25.39	32.02	26.58	29.41	4.16
16	Compressor suction temperature °C	25.0	25.0	25.1	24.9	25.1
17	Compressor discharge temperature °C	57.8	57.5	60.4	57.4	59.7
18	Evaporator outlet temperature °C	-0.8	0.3	1.7	-0.9	1.2
19	Condenser air inlet temperature °C	32.1	32.0	31.5	32.3	89.5
20	Condenser air outlet temperature °C	34.4	34.5	33.9	34.6	93.6
21	Condenser refrigerant inlet temperature °C	47.1	47.1	48.1	46.8	117.4
22	Condenser refrigerant outlet temp °C	37.7	38.0	37.1	38.0	99.2
23	Refrigerated air discharge temperature 5 cm from left wall °C	2.0	1.9	2.2	2.1	2.2
24	Refrigerated air discharge temperature center °C	2.0	2.0	2.4	2.1	2.3
25	Refrigerated air dischrage temperature 5 cm from right wall °C	1.8	1.7	1.9	1.9	1.9
26	Refrigerated air return temperature 5 cm from left wall °C	3.9	3.8	4.0	4.0	39.5
27	Refrigerated air return temperature center °C	4.3	4.3	4.5	4.5	40.3
28	Refrigerated air return temperature 5 cm from right wall °C	4.5	4.4	4.7	4.7	40.6
29	Test cell dry bulb (1 of 2) °C	32.4	32.5	32.3	33.2	90.8
30	Test cell dry bulb (2 of 2) °C	32.0	31.9	31.8	32.6	89.8
31	Test cell wet bulb °C	26.5	25.8	27.1	26.7	79.0
40	Test cell relative humidity %	62.8%	58.8%	67.4%	60.2%	59.5%
50	**Product simulator temperatures**					
51	Integrated average product simulator temperature °C	5.6	5.5	5.7	5.7	5.8
52	{CTS} Integrated coldest product simulator. temperature °C	3.2	3.1	3.3	3.2	37.8
54	{WTS} Integrated warmest product simulator temperature °C	32.3	32.4	32.6	32.7	90.8
59	Refrigerant charge g	322+/-7	322+/-7	322 +/-1	322 +/-1	322 +/-1
61	Supply voltage	119	121	122	120	120
66	Compressor power W	179	184	187	170	178
67	Difference %	0%	2.7%	4.2%	**-5.2%**	-0.5%
69	Compressor run time, %	51.7%	52.1%	55.9%	62.0%	57.5%
70	Difference %	0%	0.8%	**8.2%**	**20.0%**	**11.3%**
71	Evaporator fan power W (checked once, not recorded continuously)	58	58	58	58	58
73	Evaporating temperature (avg. of dew and bubble) °C	-3.4	-3.6	-5.6	-4.2	-5.7
74	Condensing temperature (avg. of dew and bubble) °C	37.4	38.6	39.0	39.5	37.5
75	Superheat at compressor inlet °K	28.4	28.6	30.7	29.1	30.7
79	Average cooling capacity W*	401	373	373	370	375
80	Difference %	0%	**-6.8%**	**-6.9%**	**-7.8%**	**-6.5%**
80.1	Average COP (W/W)	2.24	2.03	2.00	2.18	2.10
80.2	Difference %	0.0%	**-9.3%**	**-10.7%**	-2.7%	**-6.1%**
	*Assumes saturated liquid at inlet of expansion device					
100	Maximum compressor discharge temperature** °C	81.1	79.7	80.2	73.9	77.7
101	Maximum compressor suction temperature** °C	32.5	32.5	32.3	33.6	32.0
108	Amount of time until compressor cycling starts minutes	130	117	125	183	196
109	Difference %	0%	**-10.0%**	-3.8%	**40.8%**	**50.8%**
	**Measured from start of test until the compressor first cycles off					
	72 hour minimum thermal soak time for pulldown and half pulldown tests					

4. Discussion and Conclusions

4.1 ASHRAE 72 Tests

All things being equal, we consider the COP values to be a main result for this series of tests. In nearly all cases, the COP of the test refrigerants was lower than the baseline.

As explained earlier, the same charge mass was used for each refrigerant. The test unit was a critically charged capillary tube system, and as is well known, critically charged systems are sensitive to the charge amount. Some of the test refrigerants may have had better performance if the charge were adjusted. For example, in Table 6, Row 75, it can be seen that the superheat at the compressor was 29.1°K for N13a versus 26.2°K for R134a. In this example, the N13a may have had a higher COP value if more refrigerant were used.

4.2 Full and half pull-down tests

With the full and half pull-down tests, the amount of time until the compressor cycling started is a main result. Because R-1234ze(E) has lower density, it required longer pull-down times. The pull-down times could be shorter if a larger displacement compressor were used.