

Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Rooftop Air Conditioners



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Energy and Transportation Science Division

**ALTERNATIVE REFRIGERANT EVALUATION FOR HIGH-AMBIENT-
TEMPERATURE ENVIRONMENTS: R-22 AND R-410A ALTERNATIVES
FOR ROOFTOP AIR CONDITIONERS**

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TABLE OF CONTENTS

LIST OF FIGURES	ix
LIST OF TABLES.....	x
ACRONYMS	xii
EXECUTIVE SUMMARY	xv
R-22 UNIT RESULTS.....	xvi
R-410A UNIT RESULTS.....	xvii
SUMMARY.....	xix
1. INTRODUCTION	1
1.1 PURPOSE/OBJECTIVES	1
1.2 SCOPE AND COVERAGE.....	2
1.3 PARTICIPANTS	2
1.3.1 Oak Ridge National Laboratory (ORNL)	2
1.3.2 Industry	4
1.3.3 International Expert Panel.....	4
2. SELECTION OF ALTERNATIVES AND TESTING CONDITIONS	4
2.1 ALTERNATIVE REFRIGERANTS SELECTION	4
2.2 TESTING CONDITIONS.....	5
3. EXPERIMENTAL FACILITIES AND EQUIPMENT.....	6
3.1 ROOFTOP AIR-CONDITIONING UNITS	6
3.2 ALTERNATIVE REFRIGERANTS	6
3.3 EXPERIMENTAL FACILITIES.....	7
3.4 EXPERIMENTAL SETUP AND INSTRUMENTATION.....	9
3.5 ALTERNATIVE REFRIGERANT EVALUATION EXPERIMENTAL DESIGN	9
4. EXPERIMENTAL PROCEDURE	10
4.1 OVERALL PROCEDURE	10
4.2 PREPARATION FOR DROP-IN TESTING.....	11
4.3 PROCESS FOR CHANGING REFRIGERANTS AND THE LUBRICANTS	12
5. RESULTS AND DISCUSSION	12
5.1 RESULTS FOR THE R-22 UNIT	12
5.1.1 COP and Cooling Capacity Performance.....	14
5.1.2 Performance Relative to Baseline	16
5.1.3 Performance by Refrigerant.....	18
5.2 RESULTS FOR THE R-410A UNIT	19
5.2.1 COP and Cooling Capacity Performance.....	20
5.2.2 Performance Relative to Baseline	22
5.2.3 Performance by Refrigerant.....	24
5.3 ERROR ANALYSIS	25
5.3.1 Uncertainty Analysis.....	25
5.3.2 Energy Balance	25
6. CONCLUSIONS	25
7. REFERENCES	27
APPENDIX A. EXPERT PANEL - BIOGRAPHIES	A-1
APPENDIX B. OTHER HIGH-AMBIENT-TEMPERATURE TESTING PROGRAMS	B-1
APPENDIX C. EXPERIMENTAL TEST SETUP.....	C-1
APPENDIX D. DETAILED R-22 TEST DATA.....	D-1
APPENDIX E. DETAILED R-410A TEST DATA	E-1
APPENDIX F. DATA REDUCTION METHODOLOGY	F-1
APPENDIX G. DISCLOSURES OF INTEREST	G-1

LIST OF FIGURES

Figure 1. Baseline equipment designed for high-ambient-temperature conditions.....	6
Figure 2. Multi-zone environmental chambers	8
Figure 3. ORNL's large environmental chambers - outdoor chamber.....	9
Figure 4. COP for R-22 and its alternatives at each test condition.	15
Figure 5. Cooling capacity for R-22 and its alternatives at each test condition.....	15
Figure 6. Performance of alternative refrigerants compared with R-22 (mineral oil) at all conditions.....	16
Figure 7. Compressor discharge temperature of the R-22 alternative refrigerants, with differences compared to the baseline.....	17
Figure 8. Performance of alternative refrigerants compared with R-22 (mineral oil) at all conditions.....	18
Figure 9. COP for R-410A and its alternatives at each test condition.	21
Figure 10. Cooling capacity for R-410A and its alternatives at each test condition.....	21
Figure 11. Performance of alternative refrigerants compared with R-410A at each test condition.....	22
Figure 12. Compressor discharge temperature of the R-410A alternative refrigerants, with differences compared to the baseline.	23
Figure 13. Performance of alternative refrigerants compared with R-22 (mineral oil) at all conditions.....	24
Figure C.1. As installed R-22 indoor unit.....	C-3
Figure C.2. As installed R-410A unit.	C-4
Figure F.1. LabView® display of room temperature and fan flow rate.....	F-3
Figure F.2. LabView® display of various monitored parameters.....	F-3
Figure F.3. LabView® display of built-in REFPROP calculation.....	F-4

LIST OF TABLES

Table ES.1. ORNL test plan summary.....	xv
Table ES.2. Baseline and lower-GWP alternative refrigerant characteristics for the R-22 unit.....	xvi
Table ES.3. ORNL test result for the R-22 unit at AHRI and T3 conditions (performance change from baseline in parentheses) ^{a,b}	xvi
Table ES.4. ORNL test results for the R-22 unit at Hot conditions (performance change from baseline in parentheses) ^{a,b}	xvii
Table ES.5. Baseline and lower-GWP alternative refrigerant characteristics for the R-410A unit	xvii
Table ES.6. ORNL test results for the R-410A unit at AHRI and T3 conditions (performance change from baseline in parentheses) ^{a,b}	xviii
Table ES.7. ORNL test results for the R-410A unit at Hot and Extreme conditions (performance change from baseline in parentheses) ^{a,b}	xviii
Table 1. Test conditions.....	5
Table 2. Baseline and alternative refrigerant data for the R-22 unit.....	7
Table 3. Baseline and alternative refrigerant data for the R-410A unit	7
Table 4. ORNL test plan summary	10
Table 5. Additional tests conducted (not included in original schedule)	10
Table 6. Optimized refrigerant charge masses for the R-22 unit	13
Table 7. Test results for R-22 and its alternatives at moderate ambient temperatures (performance change from baseline in parentheses) ^{a,b}	13
Table 8. Test results for R-22 and its alternatives at high ambient temperatures (performance change from baseline in parentheses) ^{a,b}	14
Table 9. Optimized refrigerant charge masses for the R-410A unit	19
Table 10. Test results for R-410A and its alternatives at moderate ambient temperatures (performance change from baseline in parentheses) ^{a,b}	19
Table 11. Test results for R-410A and its alternatives at high ambient temperatures (performance change from baseline in parentheses) ^{a,b}	20
Table 12. Energy balance with baseline refrigerants	25
Table B.1. EGYPRA (UNEP, UNIDO, Egypt) high-ambient-temperature testing programs	B-3
Table C.1. R-22 unit experimental setup instrumentation	C-5
Table C.2. R-410A unit experimental setup instrumentation	C-6
Table D.1. Complete test data for the R-22 unit	D-4
Table E.1. Complete test data for the R-410A unit.....	E-4
Table F.1. Data reduction methodology symbols	F-4
Table F.2. Data reduction methodology subscripts.....	F-5

ACRONYMS

AC	Air conditioner
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
BEE	Bureau of Energy Efficiency
BIS	Bureau of Indian Standards
BTRIC	ORNL's Building Technologies Research and Integration Center
CAP	Compliance Assistance Programme at UNEP's Regional Office for West Asia
CFC	Chlorofluorocarbon
CFD	Computational fluid dynamics
CFM	Cubic feet per minute
COP	Coefficient of performance
DOE	US Department of Energy
EER	Energy efficiency ratio
EGYPRA	Egyptian Program for Promoting Low-GWP Refrigerants' Alternatives
EPA	US Environmental Protection Agency
EOS	Egyptian Organization for Standardization and Quality
EXV	Electronic Expansion Valve
GHG	Green House Gases
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	hydrofluoroolefin (unsaturated HFC)
HP	heat pump
HPDM	ORNL's Heat Pump Design Model
IIR	International Institute of Refrigeration
ISO	International Organization for Standardization
ITH	Integration Time Horizon (for GWP calculations)
LCCP	Life cycle climate performance
MBH	1,000 British thermal units per hour
MLF	Multilateral Fund for the Implementation of the Montreal Protocol
NSCL	National Superconducting Cyclotron Laboratory
ODS	Ozone-depleting substance
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
POE	Polyolester (oil)
PRAHA	Promoting Low-GWP Alternative Refrigerants in the Air-Conditioning Industry for High Ambient Conditions
R&D	research and development
RAMA	Refrigeration & Air-Conditioning Manufacturers Association
RTOC	Refrigeration and Air Conditioning Technical Options Committee of UNEP (also referred to as the UNEP Technical Options Committee on Refrigeration, Air-Conditioning, and Heat Pumps)
TEAP	Technology and Economics Assessment Panel
TEWI	Total Equivalent Warming Impact
TR	Refrigeration tons
TXV	Thermal Expansion Valve
UN	United Nations

UNEP	United Nations Environmental Programme
UNIDO	United Nations Industrial Development Organization
VRF	Variable refrigerant flow

EXECUTIVE SUMMARY

The Oak Ridge National Laboratory (ORNL) High-Ambient-Temperature Evaluation Program for Low-Global Warming Potential (Low-GWP) Refrigerants aims to develop an understanding of the performance of low-GWP alternative refrigerants relative to hydrochlorofluorocarbon (HCFC) and hydrofluorocarbon (HFC) refrigerants in packaged or Rooftop Unit (RTU) air conditioners under high-ambient-temperature conditions. This final report describes the parties involved, the alternative refrigerants selection process, the test procedures, and the final results.

ORNL designed a matrix of 52 tests. Table ES.1 shows the refrigerants identified for testing by ORNL with guidance from a panel of international experts (expert panel).^{*} The expert panel is composed of members from various nations, as well as United Nations Environment Programme (UNEP) and United Nations Industrial Development Organization (UNIDO) personnel. Guided by input from the expert panel, ORNL selected the alternative refrigerants based on their GWP, commercial availability and physical properties, also considering whether information about the characteristics of the refrigerants is readily available. ORNL conducted tests on two units designed for high-ambient conditions, including one RTU provided by S.K.M. Air Conditioning LLC (27.2 kW_{th} [7.7 Refrigeration tons (TR)]), which is designed to operate with R-22, and one unit provided by Petra (38.7 kW_{th} [11 TR]), which was designed to operate with R-410A.^{†,‡}

Table ES.1. ORNL test plan summary

Unit:	Base – Mineral Oil	Base – POE Oil	L-20A (R-444B)	ARM-20b	DR-7 (R-454A)	ARM-20a	DR-55 (R-452B)	L41z (R-447B)	ARM-71a	R-32	Base – re-run	Total Tests
R-22	X (baseline)	X	X	X	X						X	28
R-410A		X (baseline)					X	X	X	X	X	24

Testing was conducted in ORNL's Multi-Zone Environmental Chambers for the R-22 unit, and the ORNL Large Environmental Chambers for the R-410A unit. The test procedure involved drop-in testing. ORNL used the same drop-in test procedure as defined in the Air Conditioning, Heating, and Refrigeration Institute (AHRI) Low GWP Alternative Refrigerants Evaluation Program (AREP), which allows for only minor, if any, modifications to the equipment. ORNL completed testing on each of the R-22 alternative refrigerants at three different environmental testing conditions, and completed testing on the R-410A alternatives at four different test conditions. Operation of the R-22 unit was attempted, but not completed, at the fourth and highest-ambient temperature condition due to actuation of the refrigerant high-pressure cut-off at those conditions.

For all refrigerants, including the baseline refrigerants, R-22 and R-410A, efficiency degraded with increased ambient temperature. Further, when evaluating the results, it is important to keep in mind that the test units were not designed specifically for the alternative refrigerants. As a result, the alternative

^{*} Additional tests beyond the original test plan were performed; for details, see Section 3.5.

[†] Drop-in tests are conducted on production units that have undergone limited, if any, modifications such as refrigerant charge optimization, lubricant change, and flow control device changes to run with a different refrigerant. This is contrast with soft-optimization or full-optimization, where more substantial changes and/or engineering work is done to optimize performance with a specific refrigerant. For details, see Section 1.2.

[‡] Capacity specifications are determined at ISO 5051 T1 conditions (indoor dry-bulb temperature at 27°C [80.6°F] and wet-bulb temperature at 19°C [66.2°F]).

refrigerants should not be expected to perform as well as they would if the system designs were fully optimized for them.

Due to the differences in design and in baseline efficiency, it is not possible to directly compare the test results for the R-22 unit and the R-410A unit; thus, their results are not directly comparable and presented separately.

R-22 UNIT RESULTS

Table ES.2 lists the characteristics of the alternative refrigerants evaluated in the R-22 unit.*

Table ES.2. Baseline and lower-GWP alternative refrigerant characteristics for the R-22 unit

Refrigerant	Manufacturer	ASHRAE Safety Class	GWP _{AR4^a}	GWP _{AR5^a}
R-22 (Baseline)	-	A1	1,810	1,760
L-20A (R-444B)	Honeywell	A2L	295	295
ARM-20b	Arkema	A2L	251	251
DR-7 (R-454A)	Chemours	A2L	239	238
ARM-20a	Arkema	A2L	139	139

* Evaluated as weighted average values of the GWP of the refrigerant blend components provided by the refrigerant manufacturers and the reported GWP values of those components in IPCC AR4, 2007 [1] and IPCC AR5, 2013 [2] respectively. GWPs are based on a 100 year integration time horizon (ITH).

Table ES.3 summarizes the test results at AHRI Standard 340/360[†] Standard Rating Conditions (AHRI or AHRI Conditions, 35.0°C [95°F] outdoor temperature) and ISO T3 conditions (46.0°C [114.8°F] outdoor temperature). At AHRI Standard Rating Conditions, the results from the R-22 unit showed that all the alternative refrigerants performed within approximately ±6% of the baseline for coefficient of performance (COP) and about -3 to +7% for cooling capacity. At these performance levels, most deficiencies can be overcome with limited engineering optimization, with the potential for performance improvements for all alternative refrigerants. At ISO T3 conditions, performance change was slightly more widespread than at AHRI conditions, with COP ranging from approximately -10 to -2% relative to the baseline and cooling capacity within ±10% of the baseline.

Table ES.3. ORNL test result for the R-22 unit at AHRI and T3 conditions (performance change from baseline in parentheses)^{a,b}

	AHRI Standard Rating Conditions Outdoor: 35.0°C (95°F) Indoor: 26.7°C (80.0°F)		ISO T3 Outdoor: 46.0°C (114.8°F) Indoor: 29.0°C (84.2°F)	
	COP	Cooling Capacity, kW _{th} .	COP	Cooling Capacity, kW _{th} .
R-22 (Baseline)	3.04	25.27	2.23	21.84
L-20A (R-444B)	2.94 (-3.3%)	25.46 (+0.7%)	2.10 (-5.8%)	21.67 (-0.8%)
ARM-20b	2.85 (-6.2%)	26.29 (+4.0%)	2.19 (-1.7%)	24.03 (+10%)
DR-7 (R-454A)	2.86 (-6.2%)	27.15 (+7.4%)	2.00 (-9.9%)	22.76 (+4.2%)
ARM-20a	3.21 (+5.5%)	24.58 (-2.8%)	2.18 (-2.3%)	19.58 (-10.4%)

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation; orange: >10% degradation

^b 5% losses may be nullified by soft optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

* Hydrocarbons were excluded from testing due to potential safety concerns.

† http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_340-360_2015.pdf

Table ES.4 summarizes the results at Hot conditions (52.0°C [125.6°F] outdoor temperature). Using ARM-20a, the system operated at a COP approximately 1% higher than the baseline with approximately a 7% drop in cooling capacity. The other three alternative refrigerants all showed cooling capacities about 1-2% above the baseline, with COPs ranging from about 5 to 14% below the baseline.

Table ES.4. ORNL test results for the R-22 unit at Hot conditions (performance change from baseline in parentheses)^{a,b}

	Hot Ambient		Extreme Ambient	
	Outdoor: 52°C (125.6° F)	Indoor: 29.0°C (84.2°F)	Outdoor: 55°C (131°F)	Indoor: 29.0°C (84.2°F)
	COP	Cooling Capacity, kW _{th}	COP	Cooling Capacity, kW _{th}
R-22 (Baseline)	1.84	19.82	Unavailable due to triggering of the unit's high-pressure cutoff switch, which prevented operation at these conditions	
L-20A (R-444B)	1.74 (-5.3%)	20.17 (+1.8%)		
ARM-20b	1.65 (-10.5%)	20.05 (+1.2%)		
DR-7 (R-454A)	1.58 (-14%)	19.95 (+0.6%)		
ARM-20a	1.86 (+0.8%)	18.48 (-6.8%)		

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation; orange: >10% degradation

^b 5% losses may be nullified by soft optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

ORNL's uncertainty analysis shows an air-side capacity uncertainty of $\pm 2.75\%$ and an air-side COP uncertainty of $\pm 2.75\%$. Considering these uncertainties and the potential for further performance enhancements, refrigerants with performance values within 5% of the baseline may be expected to match the performance of R-22 with further engineering optimization. Furthermore, values within 10% of the baseline indicate an acceptable match that requires additional engineering design to reach parity with R-22 performance. For performance losses greater than 10%, significant redesign of the unit would likely be necessary to match the performance of the baseline. This suggests that, at high ambient temperatures, at least a few alternative refrigerants could be expected to perform at least as well as R-22, if not better, with additional optimization, while others might require additional engineering to overcome COP losses.

Section 5.1 of this report provides detailed results for the R-22 alternatives.

R-410A UNIT RESULTS

Table ES.5 lists the alternative refrigerants evaluated in the R-410A unit and their characteristics.

Table ES.5. Baseline and lower-GWP alternative refrigerant characteristics for the R-410A unit

Refrigerant	Manufacturer	ASHRAE Safety Class	GWP _{AR4} ^a	GWP _{AR5} ^a
R-410A (Baseline)	-	A1	2088	1924
DR-55	Chemours	A2L	698	676
L41z (R-447B)	Honeywell	A2L	740	714
ARM-71a	Arkema	A2L	460	461
R-32	Daikin	A2L	675	677

^a Evaluated as weighted average values of the 100-year ITH GWP of the refrigerant blend components provided by the refrigerant manufacturers and the reported GWP values of those components in IPCC AR4, 2007 [1] and IPCC AR5, 2013 [2] respectively.

Table ES.6 summarizes the test results at AHRI Standard Rating Conditions and ISO T3 conditions. At these conditions, the R-410A alternatives closely matched the baseline performance. All the alternatives exceeded the baseline's COP by approximately 1-4% except for R-32 at the ISO T3 condition (-1%). Cooling capacities for three of the alternatives were approximately 0-4% lower than the baseline. R-32 exceeded the baseline's cooling capacity by 7% at AHRI and about 4% at ISO T3 conditions.

Table ES.6. ORNL test results for the R-410A unit at AHRI and T3 conditions (performance change from baseline in parentheses)^{a,b}

	AHRI Standard Rating Conditions		ISO T3	
	Outdoor: 35.0°C (95°F)	Indoor: 26.7°C (80.0°F)	Outdoor: 46.0°C (114.8°F)	Indoor: 29.0°C (84.2°F)
	COP	Cooling Capacity, kW _{th}	COP	Cooling Capacity, kW _{th}
R-410A (Baseline)	3.06	39.37	2.26	34.32
DR-55	3.15 (+3.0%)	39.35 (-0.1%)	2.29 (+1.4%)	34.04 (-0.8%)
L41z (R-447B)	3.16 (+3.4%)	37.96 (-3.6%)	2.33 (+3.5%)	33.08 (-3.6%)
ARM-71a	3.16 (+3.2%)	38.49 (-2.2%)	2.31 (+2.2%)	33.38 (-2.7%)
R-32	3.12 (+2.0%)	42.12 (+7.0%)	2.23 (-1.0%)	35.64 (+3.9%)

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation; orange: >10% degradation

^b 5% losses may be nullified by soft optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

Table ES.7 summarizes the results at high ambient temperatures (Hot and Extreme). At these conditions, the R-410A alternatives exceeded the baseline performance. All the alternatives exceeded the baseline's COP by about 2-9%, with the exception of R-32 at Extreme conditions only, which showed a COP approximately 3% lower than the baseline. Each of the alternative refrigerants exhibited cooling capacities approximately 1 to 8% better than the baseline.

Table ES.7. ORNL test results for the R-410A unit at Hot and Extreme conditions (performance change from baseline in parentheses)^{a,b}

	Hot Ambient		Extreme Ambient	
	Outdoor: 52°C (125.6°F)	Indoor: 29.0°C (84.2°F)	Outdoor: 55°C (131°F)	Indoor: 29.0°C (84.2°F)
	COP	Cooling Capacity, kW _{th}	COP	Cooling Capacity, kW _{th}
R-410A (Baseline)	1.85	31.01	1.74	30.37
DR-55	1.94 (+4.9%)	31.93 (+3.0%)	1.77 (+2.1%)	30.60 (+0.8%)
L41z (R-447B)	2.01 (+8.9%)	31.56 (+1.8%)	1.86 (+7.1%)	30.61 (+0.8%)
ARM-71a	1.99 (+8.1%)	31.96 (+3.1%)	1.86 (+7.1%)	31.14 (+2.6%)
R-32	1.91 (+3.6%)	33.58 (+8.3%)	1.69 (-2.9%)	31.42 (+3.5%)

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation; orange: >10% degradation

^b 5% losses may be nullified by soft optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

ORNL's uncertainty analysis shows an air-side capacity uncertainty of $\pm 3.5\%$ and an air-side COP uncertainty of $\pm 3.5\%$. Considering these uncertainties and the potential for further performance enhancements, refrigerants with performance values within 5% of the baseline may be expected to match the performance of R-410A with further engineering optimization. Furthermore, values within 10% of the

baseline indicate an acceptable match that requires additional engineering design to reach parity with R-410A performance. This suggests that, at high ambient temperatures, all of the alternatives to R-410A tested could deliver performance better than the baseline. In most cases, achieving such performance would not require further optimization or redesign; however, further engineering may still be required to ensure safe and reliable operation.

Section 5.2 of this report provides detailed results for all R-410A alternatives.

SUMMARY

The test results from this evaluation program demonstrate that there are several viable alternatives to both R-22 and R-410A in RTUs at high ambient temperatures. In many cases there was an improvement in the performance of RTUs using the alternatives versus the baseline, both in terms of COP and cooling capacity. In other cases, the performance of the alternatives fell within 10% of the baseline, which suggests that parity with baseline performance would likely be possible through soft optimization.

The R-410A alternative refrigerants showed very promising results; three of the four alternative refrigerants exhibited COPs at all testing conditions that exceeded those measured with the baseline R-410A. At high ambient temperatures (Hot and Extreme conditions), L41z (R-447B) and ARM-71a both exceeded the COP of the baseline by more than 7%, with cooling capacities within +3% of the baseline. All the R-410A alternative refrigerants exhibited higher compressor discharge temperatures than the baseline, which may negatively impact compressor reliability. Conversely, the reduction in compressor discharge temperatures exhibited by the R-22 alternatives can improve compressor reliability.

The R-22 alternative refrigerants also showed promising results. Three alternative refrigerants closely matched or exceeded the baseline cooling capacity at all test conditions. Their COP results were mixed; two refrigerants, ARM-20a and L-20A (R-444B), exhibited results within ~6% of the baseline at all test conditions. At Hot ambient conditions, ARM-20a exhibited a COP that was 0.8% better than the baseline and L-20A (R-444B) exhibited a cooling capacity 1.8% better than the baseline.

The efficiency and capacity of the alternative refrigerants would be expected to improve through design modifications that manufacturers would conduct prior to introducing a new product to market. However, given that the scope of this study only covered drop-in testing, no detailed assessment can be made as to the extent of potential improvements through design changes. The limited changes made to the units for this testing likely indicate that these are conservative results that could improve through further optimization. Improved heat transfer circuiting, proper compressor sizing and selection, and other system improvements would likely yield better performance results for all of the alternative refrigerants.

Losses in cooling capacity are typically easier to recover through engineering optimization compared to losses in COP. The primary practical limit to improvements in capacity is the physical size of the unit, but that is not expected to be a significant concern in this case based on the magnitude of the observed cooling capacity losses. Thus, the COP losses and the increase in compressor discharge temperature for the R-410A alternatives are particularly important results of this testing program, in that these variables will be the primary focus of future optimization efforts.

This performance evaluation shows that viable replacements exist for both R-22 and R-410A at high-ambient temperatures. Multiple alternatives for R-22 performed well, and many R-410A alternatives performed as well as, and often better than, R-410A, making them prime candidate refrigerants. Prior to commercialization, manufacturers' engineering optimization can address performance loss, the increase in compressor discharge temperature that the R-410A alternatives exhibited, and any safety concerns for flammable alternatives.

1. INTRODUCTION

Hydrofluorocarbon (HFC) refrigerants are non-ozone-depleting fluids that are used as working fluids in air conditioning and refrigeration equipment as substitutes for ozone-depleting substances (ODS) which have been or are being phased out under the Montreal Protocol.* However, some of the HFCs have high global warming potential (GWP), which introduces uncertainty about their use in the future due to their impact on the climate. HFCs currently account for only 1% of greenhouse gas emissions, but their use is growing rapidly by as much as 10 to 15% per year, primarily due to their use as replacements for ODS and the increasing use of air conditioners globally. [3] Therefore, there is potential for significant reduction in direct greenhouse gas (GHG) emissions through the substitution of high-GWP HFCs with lower-GWP alternatives.

While progress toward widespread application of low-GWP refrigerants continues, only limited information regarding the performance of the most commonly proposed low-GWP refrigerants is available. A particular concern is that low-GWP refrigerants might experience performance degradation at high-ambient-temperature conditions. In order to address this issue, the US Department of Energy (DOE), in cooperation with Oak Ridge National Laboratory (ORNL), established an evaluation program to assess the performance of several candidate low-GWP alternative refrigerants under high-ambient-temperature conditions. The program evaluated the performance of packaged or rooftop air conditioners (RTU) under high-ambient-temperature conditions using low-GWP refrigerants. The objective was to assess whether it is possible to achieve similar or better energy efficiency and cooling capacity with lower-GWP refrigerants compared with current baseline refrigerants R-22 and R-410A in existing production units available in hot climate markets such as the Middle East. This program was guided by a panel of international experts consisting of members of government, academia, and industry from interested countries.

Other evaluation programs aimed at understanding the performance of low-GWP refrigerants at high ambient temperatures are currently under way. The United Nations Environment Programme (UNEP) and the United Nations Industrial Development Organization (UNIDO) are sponsoring two separate programs funded by the Multilateral Fund for the Implementation of the Montreal Protocol (MLF): Promoting Low-GWP Alternative Refrigerants in the Air-Conditioning Industry for High-Ambient Conditions (PRAHA), which recently completed testing, and the Egyptian Program for Promoting Low-GWP Refrigerants' Alternatives (EGYPRA), which is targeted for completion in late 2016. [4][5] In addition to those efforts, participants in the Air-Conditioning, Heating, and Refrigeration Institute's (AHRI) Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP) are conducting high-ambient-temperature testing with a variety of heating, ventilation, and air conditioning (HVAC) equipment. [6] Due to the different scopes of each program, the specific results of each are not directly comparable; instead, together they provide a comprehensive picture of the viability of low-GWP refrigerants. For additional details on the other programs, see APPENDIX B.

1.1 PURPOSE/OBJECTIVES

The objective of this program was to evaluate the performance and help determine the viability of several lower-GWP refrigerants as replacements for the baseline refrigerants (R-22 and R-410A) in packaged RTUs under high-ambient temperatures.

This is the second phase of a larger effort to evaluate alternative refrigerants in high-ambient conditions. The first phase tested mini-split (ductless) air conditioners and the results are documented in a report

* UNEP provides additional information on the Montreal Protocol at: <http://ozone.unep.org/en/treaties-and-decisions/montreal-protocol-substances-deplete-ozone-layer>

titled “*Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners*” by Omar Abdelaziz et. al. (hereafter “The High Ambient Phase I Study”). The report is available at:

http://energy.gov/sites/prod/files/2015/10/f27/bto_pub59157_101515.pdf.

1.2 SCOPE AND COVERAGE

The program experimentally evaluated the performance of rooftop air-conditioning units originally designed to use R-22 (an HCFC with GWP=1,760) or R-410A (a blend of two HFCs with GWP=1,924), both when using the baseline refrigerants and when using low-GWP alternatives.* The primary objective of the evaluation was to determine whether it is possible, using the lower-GWP alternatives, to achieve comparable or better performance than with R-22 and R-410A. Low-GWP alternatives may or may not reduce indirect GHG emissions and overall total equivalent warming impact (TEWI) or life cycle climate performance (LCCP) depending on whether or not system energy efficiency is improved. RTUs were chosen as the equipment to be evaluated because they are a common type of air conditioner used in light commercial applications in most high-ambient-temperature regions and are therefore a natural follow-up research focus after The High Ambient Phase I study in 2015.

ORNL in Oak Ridge, Tennessee, USA, performed the evaluation using a range of fluorinated low-GWP refrigerants, which are tested and compared with two baselines – R-22 and R-410A. There is currently a global effort to transition away from R-22, as agreed under the Montreal Protocol.† Many nations are also transitioning away from R-410A due to its high GWP. The Parties to the Montreal Protocol have recently agreed to manage HFCs under the Montreal Protocol. The pace of the transition away from these HFCs will depend on control schedules under discussion by the Parties. These transitions are at various stages in different regions of the world, so including both refrigerants as baselines can provide a point of reference regardless of where particular countries stand in the transition process.

Testing of the baseline refrigerants was first carried out on the original equipment provided by the manufacturer. ORNL tested the alternative refrigerants as “drop-in” replacements. This is a change from the phase I evaluation of mini split units, as documented in The High Ambient Phase I Report, where the units were soft-optimized for each alternative refrigerant. Drop-in tests allow only minor adjustments to the equipment (as defined by Low-GWP AREP ‡), which differentiates it from soft-optimized testing, which can be modified with standard production line components, and from purpose-built prototype testing where units are custom-designed to work with a specific alternative refrigerant. Drop-in tests are the simplest to conduct, while purpose-built prototypes are the most complex. Therefore, both soft-optimized equipment and purpose-built prototypes have the potential to achieve higher efficiency levels than simple drop in-tests like those reported here.

1.3 PARTICIPANTS

1.3.1 Oak Ridge National Laboratory (ORNL)

ORNL has been involved in the research and development (R&D) of space-conditioning equipment and appliances for nearly 40 years.§ The Building Technologies Research and Integration Center (BTRIC)

* IPCC AR5 GWP values. [2] See Section 3.2 for discussion of refrigerants and GWP values (and sources).

† UNEP provides additional information on the Montreal Protocol at: <http://ozone.unep.org/en/treaties-and-decisions/montreal-protocol-substances-deplete-ozone-layer>

‡ Details on Low-GWP AREP are available via the AHRI website: <http://www.ahrinet.org/arep.aspx>

§ ORNL’s website includes detailed information on their history of work in space conditioning and appliances; available at: <http://web.ornl.gov/sci/buildings/>

partnerships with industry have resulted in successful introduction of products such as high-efficiency refrigerator-freezers, heat pump water heaters, high-efficiency supermarket refrigeration systems, and hybrid desiccant/vapor compression air-conditioning systems.* Nine of these products have won the prestigious R&D 100 Award.

The BTRIC User Facility at ORNL is the premier US DOE research facility devoted to the development of technologies that improve the energy efficiency and environmental compatibility of residential and commercial HVAC building equipment. BTRIC's mission is to identify, develop, and deploy energy-efficient technologies by forming partnerships between DOE and industry for technology development and analysis, well-characterized laboratory and field experiments, and market outreach. The experimental facilities for building equipment research are ISO14001 certified for environmental compliance.

BTRIC is a leading center for the development of innovative air conditioners, heat pumps, water heaters, and appliances. The public domain ORNL Heat Pump Design Model (HPDM) is one of the most frequently used heat pump models and is currently being used by several original equipment manufacturers (OEMs) in their sizing and selection software tools.^{†‡} Furthermore, ORNL plays an active role in the development in the U.S. of integrated heat pumps (air source and ground source) as well as heat-pump water heaters. [7][8]

BTRIC also has decades of experience in the research, design, and development of advanced heat exchangers. Its expertise in this area includes the measurement of heat transfer coefficients for zeotropic refrigerant mixtures and methods for improvement; evaluation of microchannel heat exchangers; and computational fluid dynamics (CFD) modeling to improve the performance of heat exchangers in heating, ventilation, and air-conditioning equipment by reducing maldistribution of air across the heat exchanger and of refrigerant inside the heat exchanger. In addition, ORNL has recently been involved in the application of rotating heat exchangers for refrigeration applications.[§]

Finally, BTRIC has decades of experience in alternative refrigerant evaluation programs. User facilities and flagship modeling capabilities were used during the CFC-to-HCFC transition, the HCFC-to-HFC transition, and are currently being leveraged as part of the transition from high-GWP HFCs to lower GWP refrigerants. This work has produced numerous publications in this field. In addition to the High Ambient Phase I Report (see section 1.1), other select examples include:

- *CFC Phase-out* – a strategy development project concerned with containing existing refrigerant and retrofitting or replacing CFC-based chillers with alternative refrigerants [9]
- *Global Warming Impacts of Ozone-Safe Refrigerants and Refrigeration, Heating, and Air-Conditioning Technologies* – an analysis of the contributions of various refrigerants in major applications to global warming [10]
- *Development of Low Global Warming Potential Refrigerant Solutions for Commercial Refrigeration Systems Using a Life Cycle Climate Performance (LCCP) Design Tool* – an LCCP analysis of the performance of typical commercial refrigeration systems with alternative refrigerants and minor system modifications [11]
- *Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies* – a comparative analysis of the global warming impacts of alternative technologies using total equivalent warming impact (TEWI) [12]

* For more information on BTRIC, see the website at: <http://www.ornl.gov/user-facilities/btric>

† For more information on ORNL's HPDM, see their website at: <http://web.ornl.gov/~wlj/hpdm/MarkVII.shtml>

‡ For a list of relevant reports on HPDM, see http://web.ornl.gov/~wlj/hpdm/Related_Reports.html

§ For a list of capabilities, see ORNL's Experimental Capabilities and Apparatus Directory at:

http://web.ornl.gov/sci/buildings/docs/buildings_catalog.pdf

1.3.2 Industry

As part of this program, major refrigerant producers such as Arkema, Chemours (formerly DuPont), and Honeywell provided sample prototype refrigerants with a lower GWP compared with existing refrigerants. They supplied ORNL with refrigerants that are being considered as alternatives to R-22 and R-410A. RTU manufacturers SKM and Petra donated equipment for testing, including both RTUs specially designed for the high-ambient-temperature conditions. One unit is designed for R-22 and the other for R-410A.

1.3.3 International Expert Panel

A group of HVAC experts was assembled to provide input and guidance to the evaluation program, including design of the program and review of the test results and the final report. For biographies of the panel members, refer to APPENDIX A. The investigators conducting the testing recognized that, given the international implications of the results of the evaluation program, it was essential that this panel consist of individuals from various nations, especially countries with hot climates. Accordingly, a number of governments were contacted to recommend experienced technical personnel who, whether from government, academia, or industry, would act independently, on their own behalf (i.e., not formally representing a government or an industrial entity) in providing guidance for this effort. In addition, representatives from UNEP and UNIDO were also asked to join the panel, given the significant involvement of both these UN organizations in projects aimed at developing solutions for the replacements of HCFC and high-GWP HFC refrigerants in the air-conditioning sector in high ambient temperature countries. The panel met three times via teleconference:

- March 29, 2016 – presentation of test plans and selection of alternative refrigerants
- May 15, 2016 – status update
- August 9, 2016 – review of preliminary results

The panel was tasked with providing technical input for this study, including recommending alternative refrigerants to be tested, commenting on appropriate test procedures, assessing results, and reviewing the final report. This panel, aside from two newly-added members, also provided technical input for The High Ambient Phase I Report.

2. SELECTION OF ALTERNATIVES AND TESTING CONDITIONS

2.1 ALTERNATIVE REFRIGERANTS SELECTION

Guided by input from the expert panel, the investigators decided on a set of criteria (in no particular order) for consideration when selecting alternative refrigerants for testing. The alternative refrigerants shall:

- Have a lower GWP than the refrigerants being replaced. No strict upper limit on the GWP of alternative refrigerants was specified.
- Be relatively close to commercial availability, or already commercially available (as determined by the expert panel).
- Have properties that are a relatively close match to the baseline refrigerant that they are replacing. It is notable that temperature glide is an especially important property, in addition to capacity and coefficient of performance (COP).
- Have readily available information about their characteristics.
- Be able to meet the safety constraints of the ORNL laboratory where the units will be tested.

In addition, it was decided that this program should not consider flammability as one of the selection criteria. ASHRAE Standard 34* defines flammability and toxicity classes. The flammability classes are: 1, 2, 2L, and 3, where higher numbers indicate higher flammability. Class 2L is a subgroup of mildly flammable class 2 refrigerants with a maximum burning velocity of 10 cm/sec. The toxicity classes are A and B, with A being nontoxic. As discussed in Section 3.2, this evaluation program only tested class A2L refrigerants, but the universe of candidate refrigerants also included refrigerants from classes A1 and A3. There is significant ongoing research and discussion on the safe use of flammable refrigerants, such as in the JRAIA International Symposium on New Refrigerants and Environmental Technology 2014 (Kobe, 2014) and the 4th Symposium on Alternative Refrigerants for High-Ambient Countries (Dubai, 2014).†‡

Given the uncertainties in Life Cycle Climate Performance (LCCP) models, the panel could not come to a consensus on whether to use LCCP as a selection criterion, and therefore recommended that LCCP not be used as a selection criterion. While the concept of LCCP is generally accepted as a metric for evaluating alternative refrigerants, there is considerable disagreement about accurate LCCP values, largely due to uncertainties related to assumptions about refrigerant leakage rates and electric emissions factors.

2.2 TESTING CONDITIONS

ORNL conducted testing of all refrigerants in the R-410A unit at each of the environmental conditions described in Table 1. They completed testing of all refrigerants in the R-22 unit at only the AHRI Standard Rating Conditions, ISO T3, and Hot conditions because the unit's refrigerant high-pressure cutout controls prevented operation at the Extreme test conditions.

Table 1. Test conditions

Test Condition	Outdoor^a		Indoor		
	Dry-Bulb Temp.	Dry-Bulb Temp.	Wet-Bulb Temp.	Dew Point Temp. ^b	Relative Humidity ^b
	°C (°F)	°C (°F)	°C (°F)	°C (°F)	%
AHRI Standard Rating Conditions^c	35.0 (95)	26.7 (80.0)	19.4 (67)	15.8 (60.4)	50.9
ISO T3	46 (114.8)	29 (84.2)	19 (66.2)	13.7 (56.6)	39
Hot	52 (125.6)	29 (84.2)	19 (66.2)	13.7 (56.6)	39
Extreme	55 (131)	29 (84.2)	19 (66.2)	13.7 (56.6)	39

^aThere is no specification for the outdoor relative humidity as it has no impact on the performance.

^bDew-point temperature and relative humidity evaluated at 0.973 atm (14.3 psi)

^cPer AHRI Standard 340/360

* ASHRAE Standard 34 information: <https://www.ashrae.org/resources-publications/bookstore/standards-15-34>

† For details on the JRAIA International Symposium on New Refrigerants and Environmental Technology 2014, refer to: <http://www.jraia.or.jp/english/symposium/index.html>

‡ For details on the 4th Symposium on Alternative Refrigerants for High-Ambient Countries, refer to: <http://4th-highambient.com/index.html>

3. EXPERIMENTAL FACILITIES AND EQUIPMENT

3.1 ROOFTOP AIR-CONDITIONING UNITS

ORNL performed drop-in tests for two baseline RTUs:^{*}

- R-22 unit: 27.2 kW_{th} (7.7 TR) R-22 system from SKM; PACL Series, model number PACL-51095Y (380/415V, 3 Phase, 50 Hz)
- R-410A unit: 38.7 kW_{th} (11 TR) R-410A system from Petra; PPH Series, model PPH4 115 (460V, 3 Phase, 60 Hz); 3.12 COP (10.66 energy efficiency ratio [EER])[†]

Figure 1 shows the two units (left: SKM PACL Series; Right: Petra PPH Series).



Figure 1. Baseline equipment designed for high-ambient-temperature conditions.

Due to the differences in design and in baseline efficiency, it is not possible to compare the test results for the R-22 unit and the R-410A unit directly. Thus, results in Sections 5.1 and 5.2 for each unit are not directly comparable.

3.2 ALTERNATIVE REFRIGERANTS

The panel selected four alternative refrigerants for testing in the R-22 unit and four different alternative refrigerants for testing in the R-410A unit. Table 2 and Table 3 show the details for each of the alternative and baseline refrigerants for the R-22 and R-410A RTUs, respectively.[‡] All the selected alternatives for both units are ASHRAE safety class A2L (nontoxic, mildly flammable, low burning velocity). The expert panel expressed interest in including hydrocarbons (safety class A3), but ORNL ultimately excluded them from testing due to potential safety concerns that they could not sufficiently mitigate in the tight

* Capacity specifications are determined at ISO 5051 T1 conditions (indoor dry-bulb temperature at 27°C [80.6°F] and wet-bulb temperature at 19°C [66.2°F]).

† EER is an efficiency metric commonly used in the U.S. for cooling performance of air conditioning equipment. COP is given in W/W, while EER is in Btu/W-h.

‡ For thermodynamic cycle calculations for the baseline refrigerants as well as many of the component refrigerants that make up the alternatives, refer to the *Low-GWP AREP Participants' Handbook* (April 17, 2015) by the Air-Conditioning, Heating and Refrigeration Institute. Available: http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Participants_Handbook2015-04-17.pdf

timeframe of the testing. The GWP values are weighted average values of the GWP of each of the refrigerant blend components, the composition of which was provided by the refrigerant manufacturers, and the reported GWP values of those components in IPCC AR4, 2007 [1] and IPCC AR5, 2013 [2] respectively. See Section 4 for discussion of the charge optimization process.

Table 2. Baseline and alternative refrigerant data for the R-22 unit

Refrigerant	Manufacturer	ASHRAE Safety Class	GWP _{AR4}	GWP _{AR5}
R-22 (Baseline)	-	A1	1,810	1,760
L-20A (R-444B)	Honeywell	A2L	295	295
ARM-20b	Arkema	A2L	251	251
DR-7 (R-454A)	Chemours	A2L	239	238
ARM-20a	Arkema	A2L	139	139

Table 3. Baseline and alternative refrigerant data for the R-410A unit

Refrigerant	Manufacturer	ASHRAE Safety Class	GWP _{AR4}	GWP _{AR5}
R-410A (Baseline)	-	A1	2088	1924
DR-55 (R-452B)	Chemours	A2L	698	676
L41z (R-447B)	Honeywell	A2L	740	714
ARM-71a	Arkema	A2L	460	461
R-32	Daikin	A2L	675	677

The panel did recommend re-testing each unit with the unit's intended refrigerant (i.e., the baseline) again upon completion of all the alternatives in order to ensure that each unit's operating conditions remain unchanged.

ORNL tested the R-22 unit with both mineral oil (46cSt), the OEM-specified lubricant for the unit, and with POE oil (3MAF), the lubricant used for all the R-22 alternative refrigerants. The expert panel's consensus recommendation was that R-22 with mineral oil should be the baseline since that is how the unit was designed and shipped by the manufacturer. (See APPENDIX D for results of R-22 with POE oil.) ORNL tested the R-410A unit using the manufacturer-specified POE oil for all refrigerants except R-32, which ORNL tested using a prototype POE oil as recommended by the compressor manufacturer.

3.3 EXPERIMENTAL FACILITIES

The ORNL team evaluated both the R-22 Unit and the R-410A unit in parallel. Performance evaluation was carried at the ORNL Multi-Zone Environmental Chambers for the R-22 unit, (Figure 2), and the ORNL Large Environmental Chambers (Figure 3) for the R-410A unit.

- The ORNL Multi-Zone Environmental Chambers are capable of characterizing the performance of multi-zone electric or gas HVAC systems for residential and light commercial use. The “outdoor” chamber is 6.1 × 4.6 m (20 × 15 ft.); the 8.5 m (28 ft.) square “indoor” chamber can be divided into up to four spaces controlled at different conditions to represent separate zones. Dry-bulb temperature can be controlled at -23 to 55°C (-10 to 131°F) and relative humidity at 30 to 90%. Utilities include 480 V, three-phase power at 225 A with step-down to 240, 208, and 120 V. In this project, the indoor side was split into two chambers, each 8.5×4.25 m such that two

systems can be evaluated in parallel. The chambers are equipped with two code testers—one that can supply and measure airflow up to 5,100 m³/hr. (3,000 cfm) and the other up to 11,900 m³/hr. (7,000 cfm). The code testers have the required duct mixers and temperature sampling trees.

- The Large Environmental Chambers can characterize the performance of commercial HVAC, supermarket refrigeration, and combined heat and power systems (up to 30 tons). It is accomplished using “outdoor” and “indoor” chambers of the same size at 6.1×6.1 m (20×20 ft.) with a 4.3 m (14 ft.) ceiling. Gas and electricity are supplied, with 480 V, 3-phase power at 225 Amps and stepped-down voltage at 240, 208, and 120 V. The chamber can control the dry bulb temperature setpoint from -18 to 65.6°C (0 to 150°F) and the relative humidity setpoint from 0 to 100%. The chambers are equipped with one code tester that can supply and measure airflow up to 11,900 m³/hr. (7000 cfm). The code tester has the required duct mixers and temperature sampling trees.

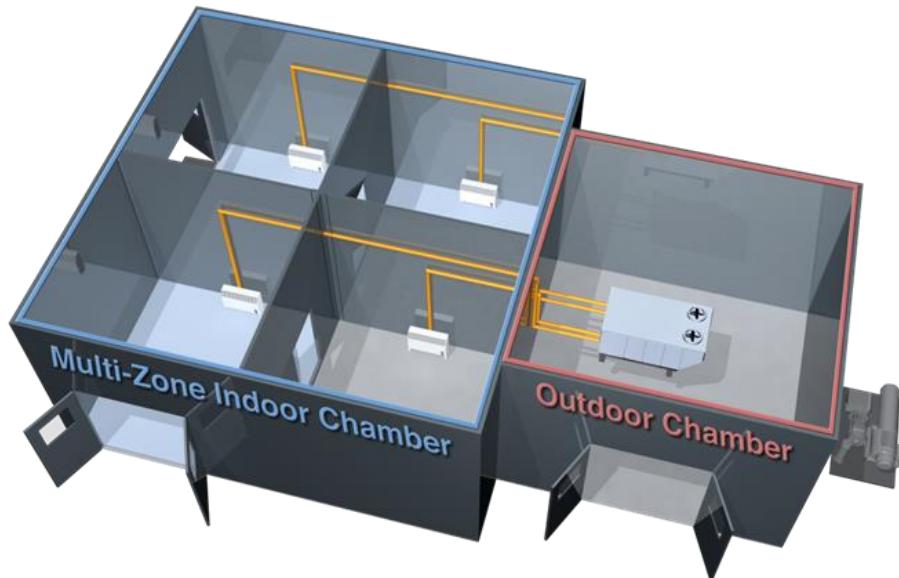


Figure 2. Multi-zone environmental chambers.

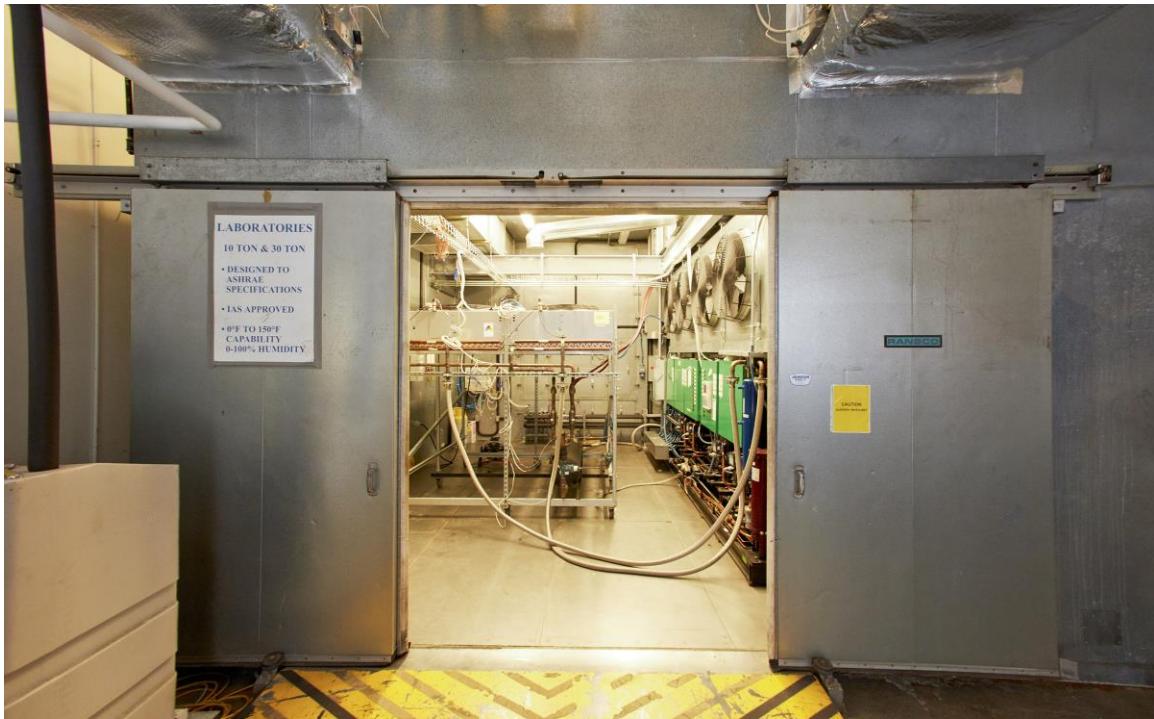


Figure 3. ORNL's large environmental chambers - outdoor chamber.

3.4 EXPERIMENTAL SETUP AND INSTRUMENTATION

A comprehensive experimental facility was designed and built to comply with ANSI/AHRI Standard 340/360 and ANSI/ASHRAE Standard 37. The Air Enthalpy method is used to evaluate the performance of the indoor unit, and the Refrigerant Enthalpy Method is used as a secondary means of evaluating the system performance in order to establish energy balance and assess measurement accuracy. For an overview of the experiment test setup, refer to APPENDIX C.

Table C.1 in APPENDIX C summarizes the instrumentation used for testing. All of the instrumentation provides better accuracy than required by ASHRAE Standard 37 (Table 2b). The data are collected to satisfy Table 3 of the ASHRAE Standard 37 for both the Indoor Air Enthalpy Method column and the Refrigerant Enthalpy Method column. Additional data were recorded to increase the level of understanding of the alternative refrigerants, including compressor shell temperature and additional surface thermocouples on the liquid line and the compressor suction line.

3.5 ALTERNATIVE REFRIGERANT EVALUATION EXPERIMENTAL DESIGN

ORNL evaluated the R-22 unit as baseline and with four alternative refrigerants at four different test conditions each, constituting 20 tests. In addition, ORNL tested R-22 with POE oil (as opposed to mineral oil, as used for the baseline tests) both before and after testing of all refrigerants, adding an additional 6 tests. ORNL evaluated the R-410A unit as baseline and with four alternative refrigerants at four different test conditions (see section 2.2 for discussion of test conditions) constituting 20 tests. In addition ORNL retested R-410A after testing all the refrigerants, adding an additional 4 tests. Consequently, the total number of tests was 52. Table 4 summarizes the test plan.

Table 4. ORNL test plan summary

Unit:	Base – Mineral Oil	Base – POE Oil	L-20A (R-444B)	ARM-20b	DR-7 (R-454A)	ARM-20a	DR-55 (R-452B)	L41z (R-447B)	ARM-71a	R-32	Base – re-run	Total Tests
R-22	X (baseline)	X	X	X	X						X	28
R-410A		X (baseline)					X	X	X	X	X	24

ORNL performed selected additional tests which were not initially planned.

Table 5 shows a summary of the additional tests and the section of the report where their results are presented. Considering the tests in both Table 4 and Table 5 the total number of tests performed by ORNL was 53.

Table 5. Additional tests conducted (not included in original schedule)

Purpose of test	RTU	Refrigerant	Test Conditions	Test Series ID ^a	Results Location
Increase superheat to 12°F	R-22	R-22	A, T3, Hot	T1	Appendix D
Increase superheat to 12°F w/smaller charge	R-22	R-444B	A, T3, Hot	T2	Appendix D
Increase superheat to 12°F	R-22	ARM-20b	A	T3	Appendix D
Increase superheat to 12°F	R-22	DR-7 (R454A)	A	T4	Appendix D
Increase superheat to 12°F	R-22	ARM-20a	A	T5	Appendix D
Increase superheat to 12°F w/ larger charge	R-22	ARM-20a	A	T6	Appendix D

^a Test Series ID is used here to identify the relevant results in Appendix D

4. EXPERIMENTAL PROCEDURE

4.1 OVERALL PROCEDURE

The following steps were taken to evaluate the equipment and refrigerant combinations.

1. Perform charge adjustment at AHRI Standard Rating Conditions.^{*} See Section 4.2.
2. Run the test matrix (each refrigerant at each test condition) as summarized in Table 4. Collect steady-state data for 30 minutes at each condition.[†]

^{*} ORNL performed charge adjustment at AHRI Standard Rating Conditions (35°C [95°F] outdoor and 26.7°C [80.0°F] indoor) because it is the closest of the test conditions in this study to manufacturers' reported rating conditions (ISO T1 conditions – 35°C [95°F] outdoor and 27°C [80.6°F] indoor). It is assumed that this is therefore also the condition for which manufacturers do their system design and analysis.

[†]Steady state is established when the average dry-bulb temperatures at the inlet of the indoor and outdoor heat exchangers are within 0.28°C (0.5°F) of the desired conditions, and the individual readings of each instrument at the inlet and outlet of each heat exchanger are within 0.56°C (1.0°F) of the average values of these quantities. Furthermore, the average wet-bulb temperature at the inlet of the indoor heat exchanger must be within 0.17°C (0.3°F) of the desired conditions with the individual readings within 0.56°C (1.0°F) of the average value, and the airflow rate must be within 1% of the desired value.

- To ensure system performance is maintained over the test period, the unit is retested with the baseline refrigerant to verify the system performance stability after finishing all alternative refrigerant tests.

4.2 PREPARATION FOR DROP-IN TESTING

ORNL used similar drop-in testing procedures as defined in the Low-GWP AREP. These procedures allow only minor modifications, if any, to the equipment. Minor modifications may include [13]:

- Adjustment of refrigerant charge quantity (by mass, the charge quantity may be different from the baseline refrigerant). It is strongly preferred to perform some type of charge optimization for each candidate refrigerant.
- Adjustment of expansion device (if adjustable).
- Adjustment of compressor speed to modify compressor flow rate, either mass flow or volumetric flow (if baseline equipment is variable-speed capable).

During the course of this program, ORNL replaced the mineral oil (46cSt) in the R-22 unit with compatible POE oil (3MAF) as recommended by the compressor manufacturer. The 3MAF POE oil was used for evaluating R-22 as well as all other alternative refrigerants. Furthermore, ORNL replaced the POE oil used in the R-410A unit with a prototype POE oil as recommended by the compressor manufacturer for the evaluation of R-32 only.

ORNL replaced the thermostatic expansion valves (TXV) on each unit with electronic expansion valves (EXV) with fixed opening control. The EXVs were used to impose the required superheat degree for the different alternative refrigerants as described in the following preparation procedure:^{*}

- Estimate refrigerant charge based on liquid density ratio at 26.7°C (80°F). The initial charge should not be higher than 85% of the estimated charge
- Evacuate the system overnight, and charge liquid refrigerant to the system liquid line as much as possible
- Start the system, and add liquid refrigerant to the system suction line until 85% of the estimated charge. Always use a charging orifice to flash the liquid refrigerant before it enters the system
- Add liquid refrigerant in discrete steps, and record 30 minutes data for each step to monitor system performance using the following guidelines:
 - Add 3 -5% refrigerant each step
 - At each step, TXV (TXV must be adjustable) should be adjusted for proper superheat
 - Superheat (dew) setting is based on baseline refrigerant superheat minus 80% of evaporator full glide divided by 2

$$\Delta T_{sup,dew} = \Delta T_{sup,baseline} - \frac{80\% \times Evaporator\ Full\ Glide}{2}$$

where the glide is the difference between the dew point temperature (T_{dew}) and the bubble point temperature (T_{bub}), evaluated based on just evaporator inlet pressure (or just outlet pressure)[†]

^{*} “Refrigerant Charge Guidelines”, Buffalo Research Laboratory, Honeywell, May 25th, 2016

[†]The dew point temperature is a measure of the temperature at which air reaches saturation given constant pressure and number of molecules. The bubble point temperature is a measure of the temperature at which vapor bubbles begin to form in a heated liquid at a given pressure.

- In case of EEV, either a new Pressure-Temp chart should be uploaded to the superheat controller or the opening of the valve must be set manually to match the superheat according to the above equation
 - Subcooling (bubble point) is not controlled, and it keeps increasing – Typically at the end of charge optimization, the optimum subcooling should be close to the baseline refrigerant subcooling minus condenser full glide divided by 2
5. The optimum refrigerant charge is at the highest efficiency region and above 95% of new refrigerant maximum capacity (determined during charge optimization)

4.3 PROCESS FOR CHANGING REFRIGERANTS AND THE LUBRICANTS

The following steps were followed to change refrigerants between sets of tests.

1. The refrigerant is reclaimed in empty cylinders.
2. The system is put under vacuum for an extended period of time (minimum of 3 hr.) to ensure all the refrigerant is dissolved from the oil; a vacuum gauge is used to ensure system is evacuated to 300 microns.
3. Refrigerant is slowly charged from the liquid port through the refrigerant suction line.

In the case of the R-22 unit, further modifications were required after baseline testing and prior to initiating testing of the alternative refrigerants:

1. Replace mineral oil with POE oil
2. Adjust the refrigerant charge to account for R-22 absorption in POE oil
3. Run tests at all test conditions
4. Evacuate system to 300 microns over the weekend (>24 hrs.) and proceed with the alternative refrigerant evaluation

Also for the case of evaluating R-32 in the R-410A unit, the baseline POE oil had to be replaced with prototype POE oil based on the compressor manufacturer recommendations:

1. Replace baseline POE oil with prototype POE oil
2. Adjust the refrigerant charge to account for different R-410A miscibility in the prototype POE oil
3. Run tests at all test conditions
4. Evacuate system to 300 microns overnight (>24 hrs.) and proceed with R-32 evaluation

5. RESULTS AND DISCUSSION

5.1 RESULTS FOR THE R-22 UNIT

This section describes the air-side performance results for R-22 and its alternatives at all test conditions (AHRI, ISO T3, and Hot, as defined in Table 1). The four alternative refrigerants (as discussed in Section 4.2) are: L-20A (R-444B), ARM-20b, DR-7 (R-454A), and ARM-20a. All the alternatives were tested

using POE oil as a lubricant. As discussed in Section 4.2.1, the expert panel recommended using R-22 with mineral oil as the baseline; all results in this section reflect this decision.

Table 6 shows the refrigerant charge masses used in the R-22 unit after the optimization process described in Section 5.2. The charges for the alternatives range from 14% lower (DR-7) to 17% lower (both ARM-20a and ARM-20b) than the baseline charge.

Table 6. Optimized refrigerant charge masses for the R-22 unit

Refrigerant	Manufacturer	ASHRAE Safety Class	Charge Mass kg (oz.)	Charge Increase vs. Baseline
R-22 (Baseline)	-	A1	10.170 (358)	N/A
L-20A (R-444B)	Honeywell	A2L	8.636 (304)	-15%
ARM-20b	Arkema	A2L	8.466 (298)	-17%
DR-7 (R-454A)	Chemours	A2L	8.722 (307)	-14%
ARM-20a	Arkema	A2L	8.438 (297)	-17%

Table 7 summarizes the results of testing the baseline refrigerant and alternatives in the R-22 unit at AHRI and T3 conditions. At these conditions, all alternatives exhibited COPs and cooling capacities within approximately $\pm 10\%$ of the baseline.

Table 7. Test results for R-22 and its alternatives at moderate ambient temperatures (performance change from baseline in parentheses)^{a,b}

	AHRI Standard Rating Conditions		ISO T3	
	Outdoor: 35.0°C (95°F)	Indoor: 26.7°C (80.0°F)	Outdoor: 46.0°C (114.8°F)	Indoor: 29.0°C (84.2°F)
	COP	Cooling Capacity, kW _{th}	COP	Cooling Capacity, kW _{th}
R-22 (Baseline)	3.04	25.27	2.23	21.84
L-20A (R-444B)	2.94 (-3.3%)	25.46 (+0.7%)	2.10 (-5.8%)	21.67 (-0.8%)
ARM-20b	2.85 (-6.2%)	26.29 (+4.0%)	2.19 (-1.7%)	24.03 (+10%)
DR-7 (R-454A)	2.86 (-6.2%)	27.15 (+7.4%)	2.00 (-9.9%)	22.76 (+4.2%)
ARM-20a	3.21 (+5.5%)	24.58 (-2.8%)	2.18 (-2.3%)	19.58 (-10.4%)

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation; orange: >10% degradation

^b 5% losses may be nullified by system optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

Table 8 summarizes the results of testing the baseline refrigerant and alternatives in the R-22 unit at high ambient temperatures. The results show a tradeoff between cooling capacity and unit efficiency; refrigerants that maintained roughly the same capacity had COP loss between -5 to 14% whereas ARM-20a showed similar COP compare with the baseline but at the cost of roughly 7% reduction in cooling capacity.

Table 8. Test results for R-22 and its alternatives at high ambient temperatures (performance change from baseline in parentheses)^{a,b}

	Hot Ambient		Extreme Ambient	
	COP	Cooling Capacity, kW _{th.}	COP	Cooling Capacity, kW _{th.}
R-22 (Baseline)	1.84	19.82	Results unavailable due to triggering of the unit's high-pressure cutoff switch, which prevented operation at these conditions	
L-20A (R-444B)	1.74 (-5.3%)	20.17 (+1.8%)		
ARM-20b	1.65 (-10.5%)	20.05 (+1.2%)		
DR-7 (R-454A)	1.58 (-14%)	19.95 (+0.6%)		
ARM-20a	1.86 (+0.8%)	18.48 (-6.8%)		

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation; orange: >10% degradation

^b 5% losses may be nullified by system optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

Some refrigerant mixtures result in high temperature glide (difference in saturation vapor and saturation liquid temperatures at a given saturation pressure). This results in unfavorable performance, since condensation and evaporation would no longer be constant-temperature processes. Unfortunately, evaporator temperature glide could not be calculated during testing because the evaporator inlet pressure could not be measured due to the long distribution lines between the expansion valve and the evaporator. Exact evaporator inlet and outlet pressures are required in order to accurately calculate the evaporator temperature glide.

Based on the uncertainty analysis described in Section 5.3.1, the air-side capacity has an uncertainty of $\pm 2.75\%$ and the air-side COP has an uncertainty of $\pm 2.75\%$. Considering these uncertainties and the potential for performance enhancements through system optimization, refrigerants with performance values within 5% of the baseline may be expected to match the performance of R-22 with optimization; whereas refrigerants within 10% of the baseline may require only additional engineering to achieve the same performance as the baseline refrigerant. For performance losses greater than 10%, significant design changes would likely be necessary to match the performance of the baseline.

5.1.1 COP and Cooling Capacity Performance

Figure 4 shows the COP for each refrigerant at each test condition. For all refrigerants, including R-22, the efficiency degraded with the increase in ambient temperature. The percentage of efficiency degradation associated with increasing ambient temperature was roughly consistent for both the R-22 baseline and all the alternatives; the COP degraded approximately 40% to 45% as the ambient temperature increased from AHRI to Hot conditions. The system COP was highest using ARM-20a at AHRI conditions (about 5.5% better than the baseline) and Hot conditions (about 0.8% better than the baseline). At T3 conditions, the baseline R-22 exhibited the highest COP, with both ARM-20a and ARM-20b showing COPs within approximately 2%.

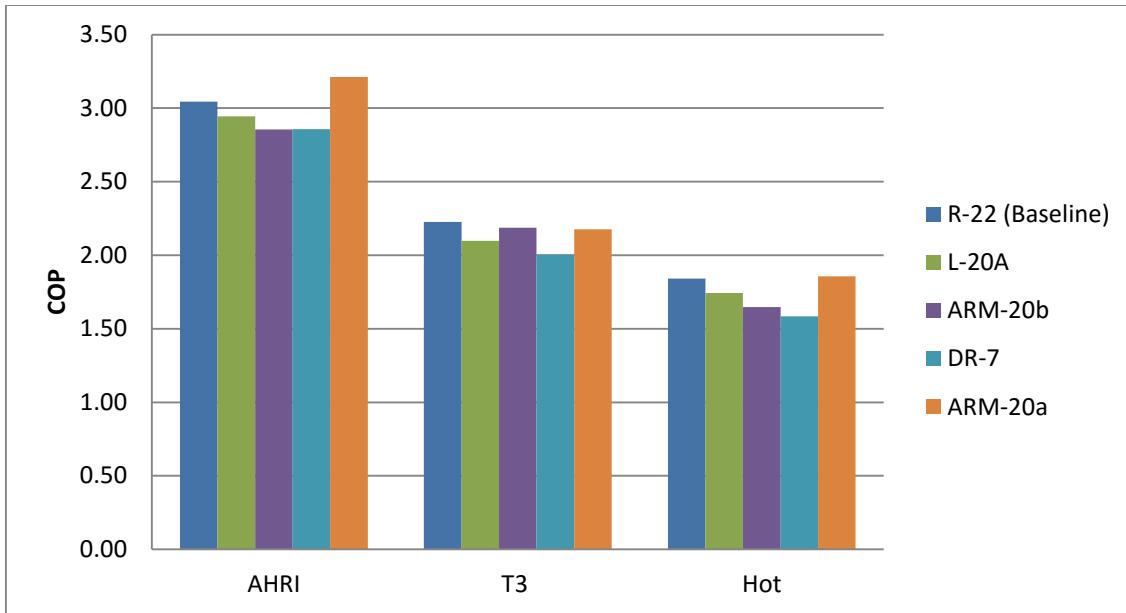


Figure 4. COP for R-22 and its alternatives at each test condition.

Figure 5 shows the cooling capacity for each refrigerant at each test condition. For all tested refrigerants, including R-22, the cooling capacity degraded as the ambient temperature increased. The amount of capacity degradation varied by refrigerant, with R-22 showing the least degradation (39%) from AHRI to Hot conditions. The other refrigerants exhibited between 41% (L-20A) to 45% (DR-7) degradation from AHRI to Hot conditions. Two refrigerants, ARM-20b and DR-7, exhibited cooling capacities that were better than the baseline at all three test conditions. A third refrigerant, L-20A had higher cooling capacity than the baseline at both AHRI and Hot conditions.

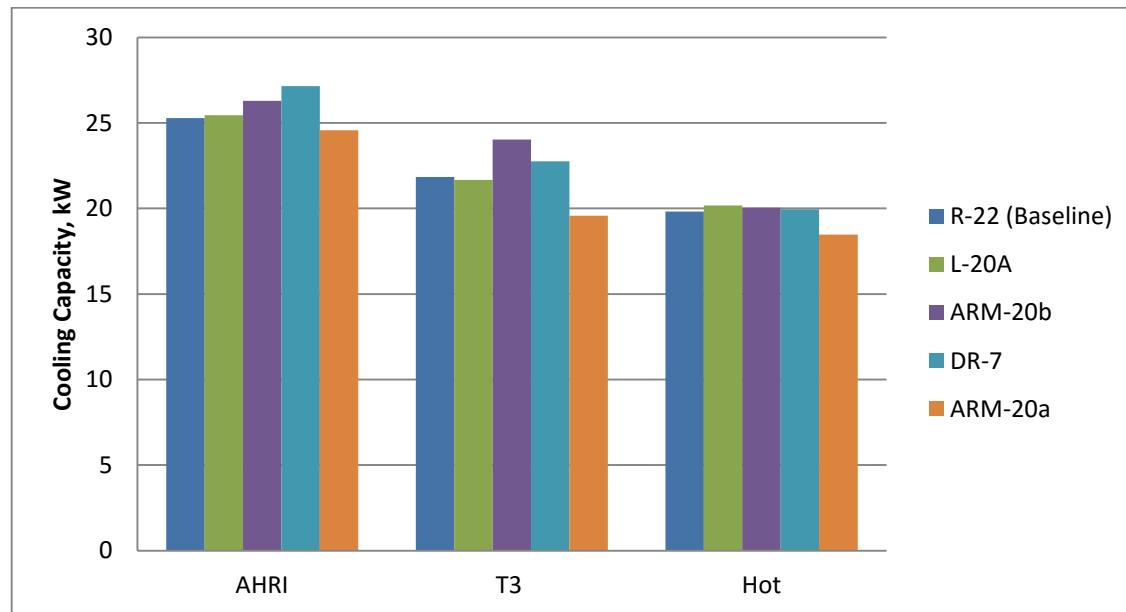


Figure 5. Cooling capacity for R-22 and its alternatives at each test condition.

5.1.2 Performance Relative to Baseline

Another way to visualize the system performance using the alternative refrigerants is to normalize the COP and cooling capacity using the corresponding COP and cooling capacity of the baseline system at the same test conditions. Figure 6 compares the COP and capacity of the alternative refrigerants with the baseline under each of the test conditions.

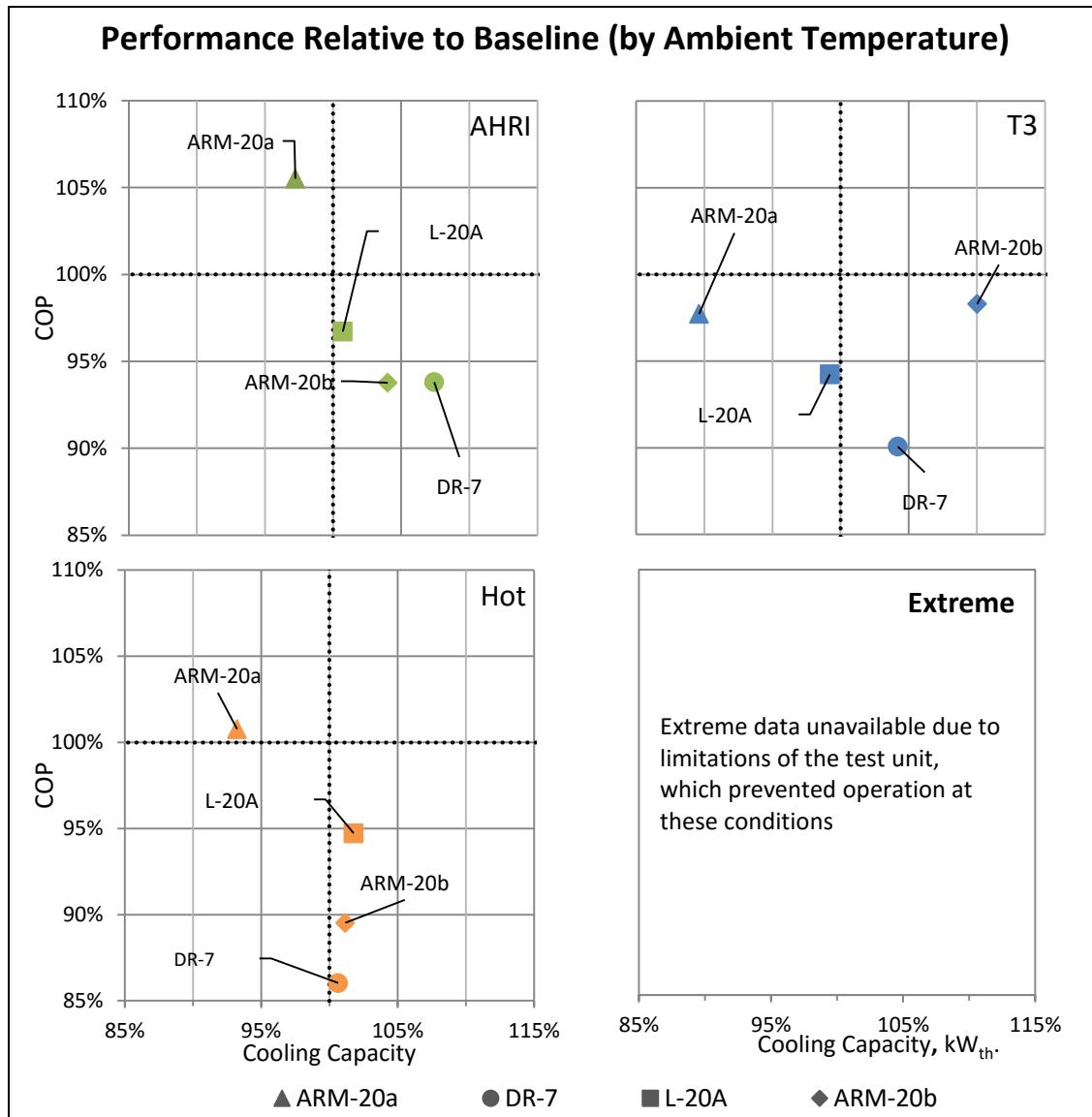


Figure 6. Performance of alternative refrigerants compared with R-22 (mineral oil) at all conditions.

At AHRI conditions, the alternative refrigerants present a tradeoff between either improved COP or improved cooling capacity, but not both. ARM-20a resulted in a COP more than 5% better than the baseline, but with a 2.8% lower cooling capacity. The other three alternatives performed with between approximately 3 and 6% lower COP, but between approximately 1 and 7% better cooling capacity than the baseline.

At ISO T3 conditions, ARM-20a and ARM-20b showed COPs within approximately 2% of the baseline; however, ARM-20b showed a 10% improvement in cooling capacity while ARM-20a had a 10% loss in cooling capacity. L-20A closely matched the baseline in cooling capacity, but had an approximately 6% lower COP. The normalized performance of all refrigerants (relative to the baseline) except ARM-20b decreased from AHRI conditions to ISO T3 conditions for both COP and cooling capacity. The performance of ARM-20b relative to the baseline in both COP and cooling capacity improved approximately 5% from AHRI conditions.

Test results at the Hot test conditions also exhibited a tradeoff between either improved COP or improved cooling capacity. ARM-20a closely matched the baseline for COP with a decrease in cooling capacity of 6.8%. L-20A, ARM-20b, and DR-7 all showed slight (1-2%) improvements in cooling capacity, but showed decreases in COP ranging from -5.3% for L-20A to -14% for DR-7. The relative performance of ARM-20a and L-20A at Hot conditions relative to the baseline improved compared to the ISO T3 results for both COP and cooling capacity. The relative performance of DR-7 versus the baseline continued to decrease from ISO T3 to Hot conditions. ARM-20b, the only refrigerant to show a relative improvement versus the baseline at ISO T3, also showed a decrease in relative performance at Hot conditions.

As discussed in Section 2.2, above, there are no test data available at Extreme test conditions for the R-22 unit.

Figure 7 shows the difference between the compressor discharge temperatures of each refrigerant compared to the baseline, at each test condition. This result is to be expected from the selected alternative refrigerants because the compressor discharge temperature is largely driven by the thermophysical properties of the alternative refrigerants. In this case the selected R-22 alternative refrigerants have lower heat capacities and therefore run at higher mass flow rates through the compressor compared to the baseline, which results in the same heat input from the compressor dissipating faster than would occur with R-22. The reduction in compressor discharge temperatures exhibited by the R-22 alternatives is beneficial and can improve compressor reliability and longevity.

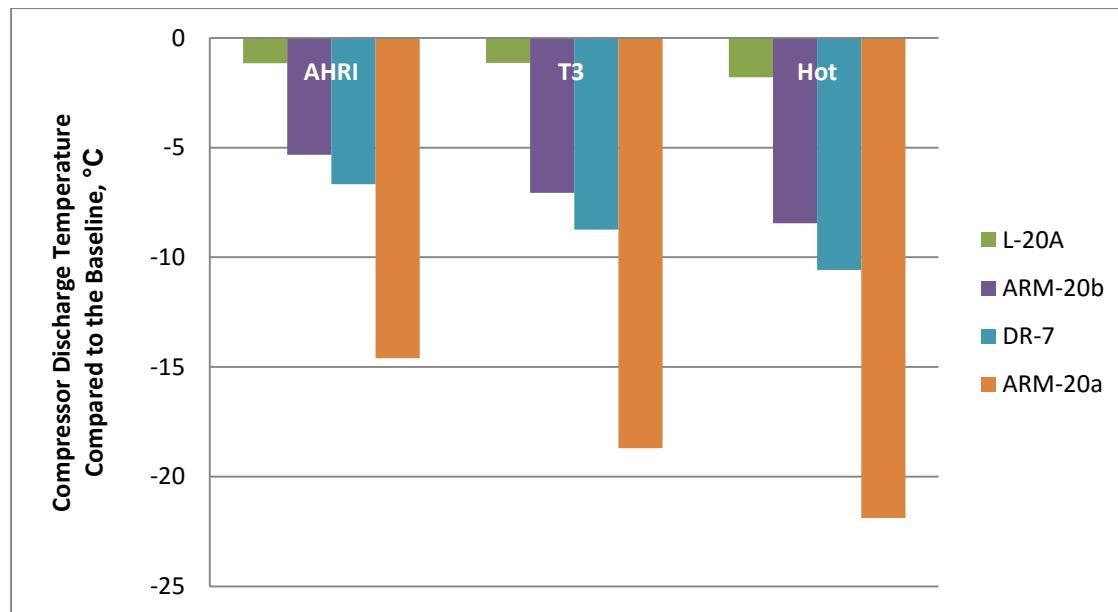


Figure 7. Compressor discharge temperature of the R-22 alternative refrigerants, with differences compared to the baseline.

5.1.3 Performance by Refrigerant

Figure 8 compares the COP and capacity of the R-22 alternative refrigerants with the baseline under each of the test conditions, organized by refrigerant.

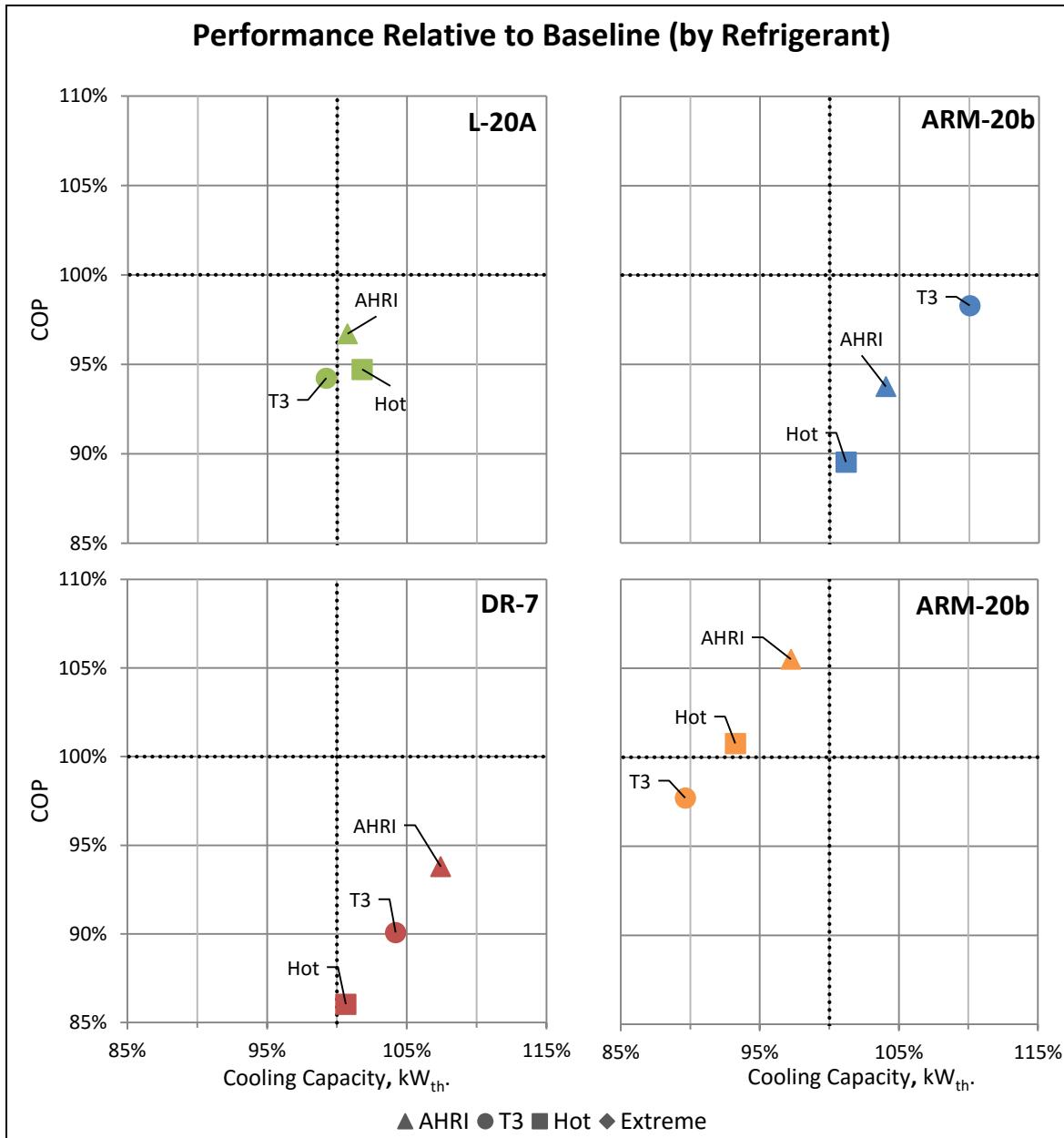


Figure 8. Performance of alternative refrigerants compared with R-22 (mineral oil) at all conditions.

The re-run of the unit with R-22 at the end of the testing (detailed results in APPENDIX D), compared with the R-22 runs at the beginning of testing showed that the unit performed within $\pm 1\%$ for both COP and capacity. These results suggest that the extended testing with all the alternative refrigerants resulted in limited performance change and that the system reliability was not affected by the use of the alternative refrigerants.

See APPENDIX D for comprehensive results, including detailed data tables.

5.2 RESULTS FOR THE R-410A UNIT

This section presents the air-side performance results for R-410A and its alternatives at all test conditions (AHRI, ISO T3, Hot, and Extreme as defined in Table 1). The four alternative refrigerants (as discussed in Section 3.2) are: DR-55 (R-452B), L41z (R-447B), ARM-71a, and R-32. All use POE oil as a lubricant.

Table 9 shows the refrigerant charge masses used in the R-410A unit after the optimization process described in Section 5.2. The charges for the alternatives range from 8% (both L41z and ARM-71a) to 17% lower (R-32) than the baseline charge.

Table 9. Optimized refrigerant charge masses for the R-410A unit

Refrigerant	Manufacturer	ASHRAE Safety Class	Charge Mass kg (oz.)	Charge Increase vs. Baseline
R-410A (Baseline)	-	A1	12.02 (424)	N/A
DR-55 (R-452B)	Chemours	A2L	10.89 (384)	-9%
L41z (R-447B)	Honeywell	A2L	11.11 (392)	-8%
ARM-71a	Arkema	A2L	11.11 (392)	-8%
R-32	Daikin	A2L	9.98 (352)	-17%

Table 10 summarizes the results of testing the baseline refrigerant and alternatives in the R-410A unit at moderate ambient temperatures (AHRI and ISO T3 conditions). At these test conditions, all the alternatives performed between about -4 and +7% of the baseline for both COP and cooling capacity.

Table 10. Test results for R-410A and its alternatives at moderate ambient temperatures (performance change from baseline in parentheses)^{a,b}

	AHRI Standard Rating Conditions		ISO T3	
	Outdoor: 35.0°C (95°F)	Indoor: 26.7°C (80.0°F)	Outdoor: 46.0°C (114.8°F)	Indoor: 29.0°C (84.2°F)
	COP	Cooling Capacity, kW _{th}	COP	Cooling Capacity, kW _{th}
R-410A (Baseline)	3.06	39.37	2.26	34.32
DR-55 (R-452B)	3.15 (+3.0%)	39.35 (-0.1%)	2.29 (+1.4%)	34.04 (-0.8%)
L41z (R-447B)	3.16 (+3.4%)	37.96 (-3.6%)	2.33 (+3.5%)	33.08 (-3.6%)
ARM-71a	3.16 (+3.2%)	38.49 (-2.2%)	2.31 (+2.2%)	33.38 (-2.7%)
R-32	3.12 (+2.0%)	42.12 (+7.0%)	2.23 (-1.0%)	35.64 (+3.9%)

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation; orange: >10% degradation

^b 5% losses may be nullified by optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

Table 11 summarizes the results of testing the baseline refrigerant and alternatives in the R-410A unit at high ambient temperatures. At these test conditions, all the alternatives either closely matched or exceeded the performance of the baseline.

Table 11. Test results for R-410A and its alternatives at high ambient temperatures (performance change from baseline in parentheses)^{a,b}

	Hot Ambient		Extreme Ambient	
	Outdoor: 52°C (125.6°F)	Indoor: 29.0°C (84.2°F)	Outdoor: 55°C (131°F)	Indoor: 29.0°C (84.2°F)
	COP	Cooling Capacity, kW _{th} .	COP	Cooling Capacity, kW _{th} .
R-410A (Baseline)	1.85	31.01	1.74	30.37
DR-55 (R-452B)	1.94 (+4.9%)	31.93 (+3.0%)	1.77 (+2.1%)	30.60 (+0.8%)
L41z (R-447B)	2.01 (+8.9%)	31.56 (+1.8%)	1.86 (+7.1%)	30.61 (+0.8%)
ARM-71a	1.99 (+8.1%)	31.96 (+3.1%)	1.86 (+7.1%)	31.14 (+2.6%)
R-32	1.91 (+3.6%)	33.58 (+8.3%)	1.69 (-2.9%)	31.42 (+3.5%)

^a Shading – green: performance improvement; blank: 0-5% degradation; yellow: 5-10% degradation

^b 5% losses may be nullified by optimization, while 10% losses may require additional engineering and losses greater than 10% may require complete redesign of the unit

Based on the uncertainty analysis described in Section 5.3.1, the air-side capacity has an uncertainty of $\pm 3.5\%$ and the air-side COP has an uncertainty of $\pm 3.5\%$. Considering these uncertainties and the potential for performance enhancements through system optimization, refrigerants with performance values within 5% of the baseline may be expected to match the performance of R-410A with optimization.

5.2.1 COP and Cooling Capacity Performance

Figure 9 shows the COP for each refrigerant at each test condition. For all refrigerants, including R-410A, the efficiency degraded with the increase in ambient temperature. The percentage of efficiency degradation associated with increasing ambient temperature was roughly consistent for both the R-410A baseline and all the alternatives; the COP degraded approximately 40% to 45% as the ambient temperature increased from AHRI to Extreme conditions. The system COP was highest using L41z at AHRI conditions (3.4% better than the baseline), ISO T3 conditions (3.5% better than the baseline), and Hot conditions (8.9% better than the baseline). For Extreme conditions, L41z and ARM-71a both exhibited the highest COP, performing 7.1% higher than the baseline.

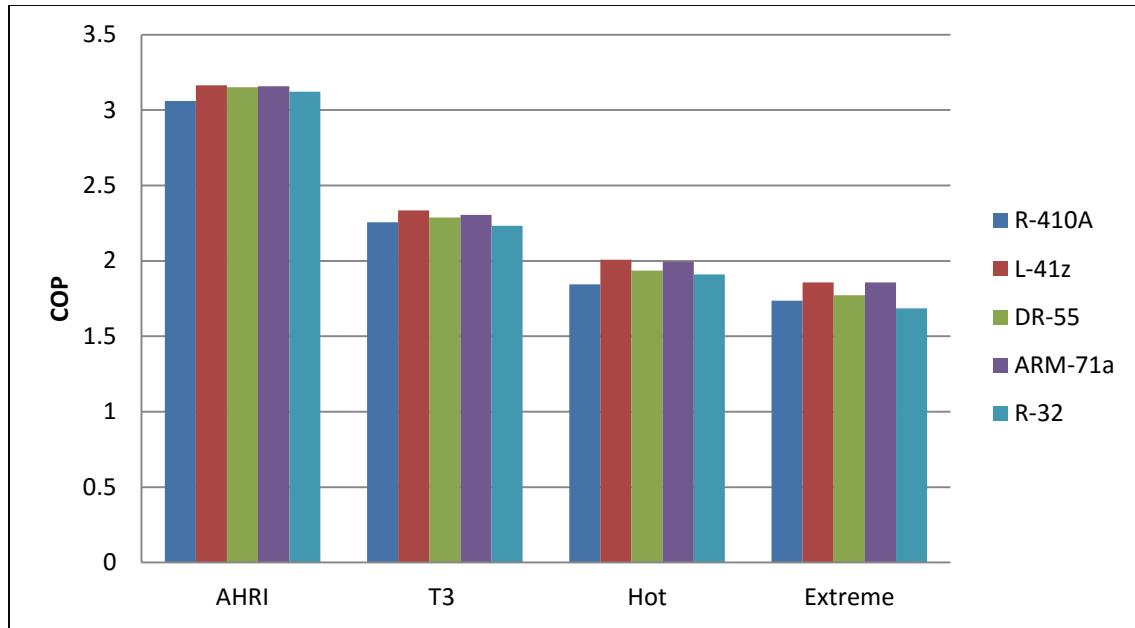


Figure 9. COP for R-410A and its alternatives at each test condition.

Figure 10 shows the cooling capacity for each refrigerant at each test condition. For all tested refrigerants, including R-410A, the cooling capacity degraded as the ambient temperature increased. The amount of capacity degradation varied by refrigerant, with ARM-71a and L41z showing the least degradation (approximately 19%) from AHRI to Extreme conditions. The other refrigerants exhibited between 22% (DR-55) and 25% (R-32) degradation from AHRI to Extreme conditions. Each of the alternative refrigerants exhibited cooling capacities that closely matched or outperformed the baseline at both Hot and Extreme conditions.

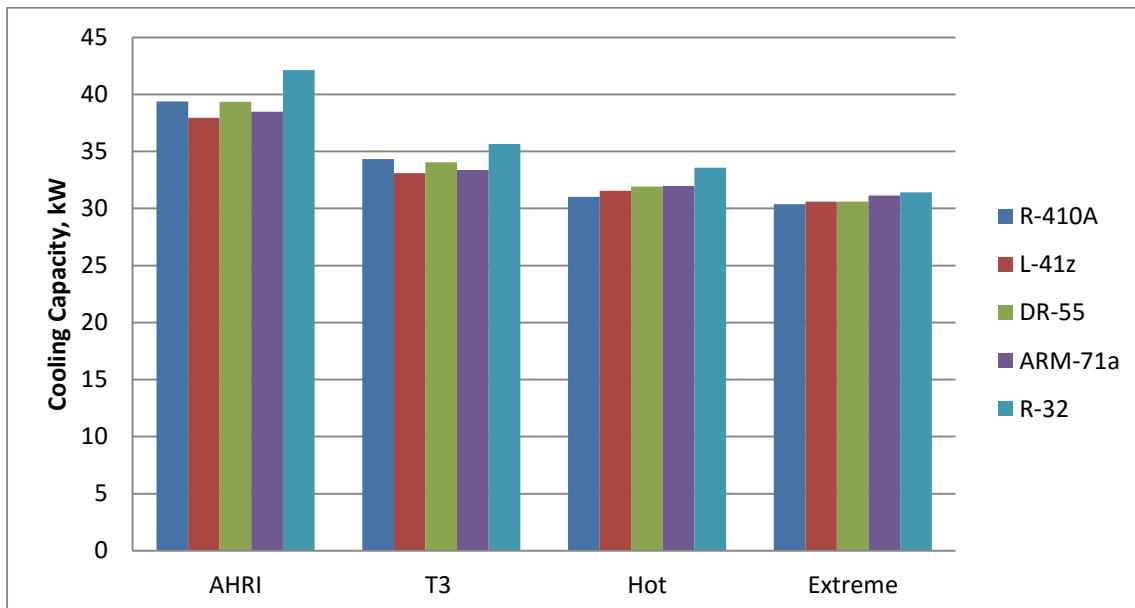


Figure 10. Cooling capacity for R-410A and its alternatives at each test condition.

5.2.2 Performance Relative to Baseline

Another way to visualize the system performance using the alternative refrigerant is to normalize the COP and cooling capacity using the corresponding COP and cooling capacity of the baseline system at the same test conditions. Figure 11 compares the COP and capacity of the alternative refrigerants with the baseline under the each of the test conditions.

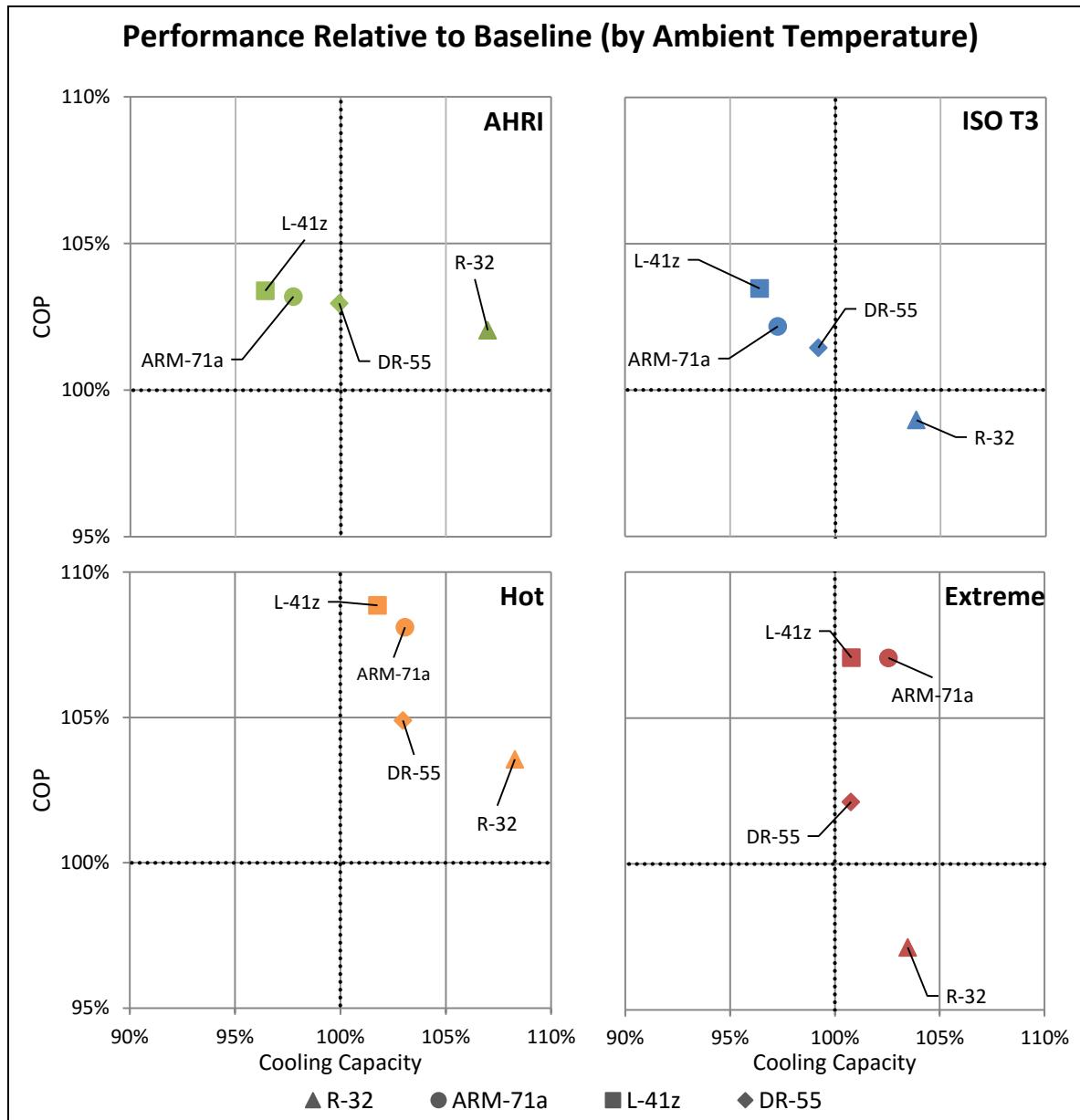


Figure 11. Performance of alternative refrigerants compared with R-410A at each test condition.

At AHRI test conditions, each of the alternative refrigerants resulted in a COP approximately 3% better than the baseline. Cooling capacity results showed varying levels of degradation (within 3.6% of the baseline) for each of the refrigerants except R-32, for which capacity increased approximately 7%.

At ISO T3 test conditions, L41z showed the highest COP, approximately 4% higher than the baseline, while ARM-71a and DR-55 experienced COPs approximately 1-2% higher than the baseline. R-32 was the only alternative refrigerant with a COP lower than the baseline (1% lower). The relative performance at ISO T3 (compared to the baseline) of all refrigerants except L41z decreases compared to the AHRI results for both COP and cooling capacity. The performance of L41z relative to the baseline in both COP and cooling capacity is higher at ISO T3 than at AHRI conditions.

At the Hot test conditions, the results for all the alternatives showed improvement in both COP (4-9%) and capacity (2-8%) relative to the baseline. The relative performance of each of the alternative refrigerants versus the baseline at Hot conditions improved compared to the ISO T3 results for both COP and cooling capacity.

At Extreme test conditions, as seen at Hot conditions, the results for ARM-71a and DR-55 show an improved COP (7.1% and 2.1% better, respectively) and improved cooling capacity (2.6% and 0.8% better, respectively) relative to the baseline. R-32 exceeded baseline cooling capacity by 3.5% but shows a COP approximately 3% lower than the baseline. The performance of all refrigerants at Extreme conditions relative to the baseline decreases compared to the Hot COP and cooling capacity results.

Figure 12 shows the difference between the compressor discharge temperatures of each refrigerant compared to the baseline, at each test condition. This result is to be expected from the selected alternative refrigerants because the compressor discharge temperature is largely driven by the thermophysical properties of the alternative refrigerants. In this case the selected R-410A alternatives have high heat capacities and therefore run at lower mass flow rates through the compressor compared to the baseline, which results in the same heat input from the compressor dissipating slower than would occur with R-410A. The increase in compressor discharge temperatures may impact the compressor reliability and longevity.

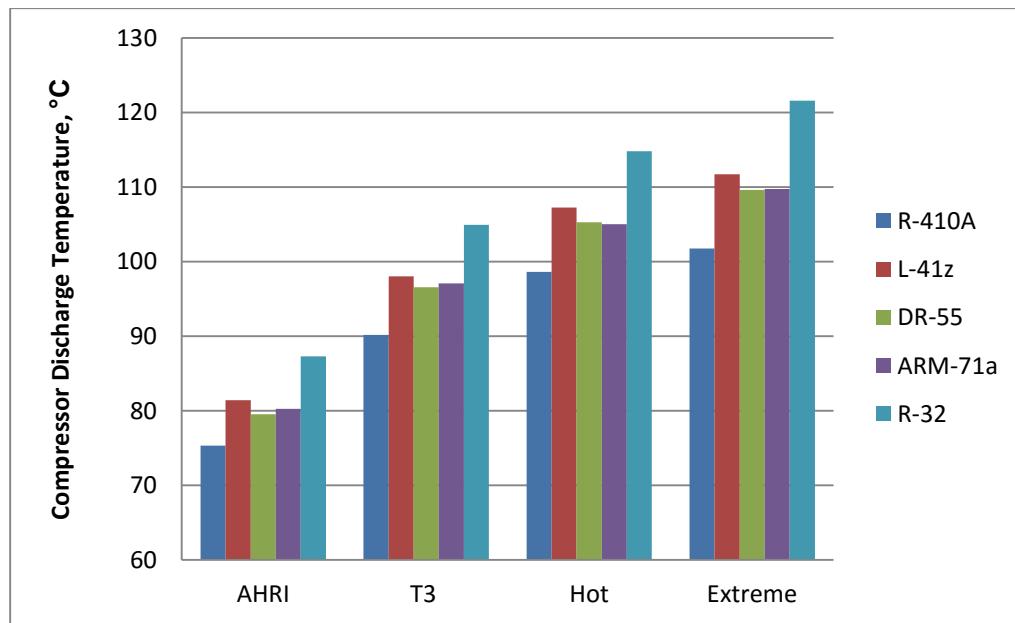


Figure 12. Compressor discharge temperature of the R-410A alternative refrigerants, with differences compared to the baseline.

5.2.3 Performance by Refrigerant

Figure 13 compares the COP and capacity of the alternative refrigerants with the baseline under each of the test conditions, organized by refrigerant.

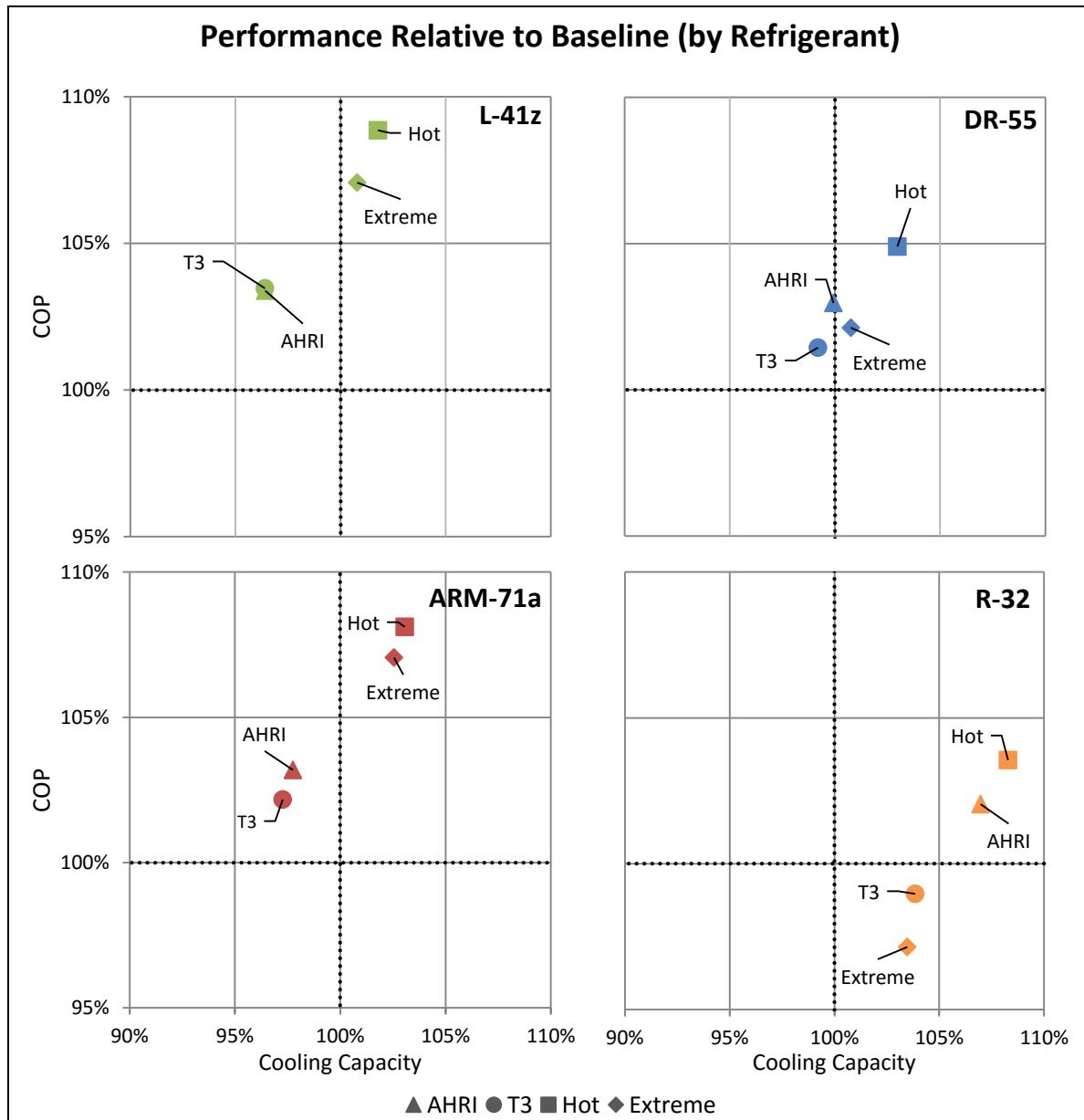


Figure 13. Performance of alternative refrigerants compared with R-22 (mineral oil) at all conditions.

The re-run of the unit with R-410A at the end of the testing (detailed results in APPENDIX E) compared with the R-410A runs at the beginning of testing showed that the unit performed within $\pm 1\%$ for both COP and capacity. These results suggest that the extended testing with all the alternative refrigerants resulted in limited performance change and that the system reliability was not affected by the use of the alternative refrigerants.

See APPENDIX E for comprehensive results, including detailed data tables.

5.3 ERROR ANALYSIS

5.3.1 Uncertainty Analysis

The experimental uncertainty was calculated based on the uncertainties of each of the measured variables which are propagated into the value of the calculated quantity. The method for determining this uncertainty propagation is described in NIST Technical Note 1297. [14] Assuming the individual measurements are uncorrelated and random, the uncertainty in the calculated quantity can be determined as

$$U_Y = \sqrt{\sum_i \left(\frac{\partial Y}{\partial X_i} \right)^2 U_{X_i}^2}$$

where Y is the calculated quantity, X_i is the measured variable and U_{X_i} is the uncertainty in the measured variable.

The uncertainty analysis, based on the instrument accuracies listed in Table C.1 and C.2, resulted in measurement uncertainty of $\pm 2.75\%$ for both air-side capacity and COP for the R-22 unit and $\pm 3.5\%$ for both air-side capacity and COP for the R-410A unit.

5.3.2 Energy Balance

ANSI/ASHRAE Standard 37^{*} requires that the cooling capacity be evaluated both from the air side and the refrigerant side in order to establish trustworthy results by analyzing the energy balance on the system.[†] The investigators evaluated the airside cooling capacity using the air enthalpy method and the refrigerant side capacity was evaluated using refrigerant mass flow measurements and thermodynamic property evaluation using appropriate independent measured properties (e.g. single phase temperature and pressure). It was important to establish proper energy balance using the baseline refrigerants since for these refrigerants the thermodynamic property evaluations are established and well characterized. Table 12 shows the energy balance for both the R-22 unit and the R-410A unit at the AHRI conditions for the baseline refrigerants.

Table 12. Energy balance with baseline refrigerants

Equipment	Energy Balance at AHRI Conditions
R-22 unit with R-22 (mineral oil)	-5.37%
R-410A unit with R-410A (POE oil)	4.66%

6. CONCLUSIONS

This report documents the performance evaluation of two RTUs designed to operate in high ambient environments. The first unit is designed for R-22 with a rated cooling capacity of 27.2 kWth (7.7 TR) and the second unit is designed for R-410A with a rated cooling capacity of 38.7 kWth (11 TR). The

* ASHRAE standards information available at: <https://www.ashrae.org/standards-research--technology/standards-guidelines/titles-purposes-and-scopes>

[†] The energy balance is defined as the difference between the refrigerant-side cooling capacity and the air-side cooling capacity, divided by the air-side cooling capacity.

experimental facility followed the ANSI/ASHRAE Standard 37 and exhibited air-side capacity and COP measurement uncertainties of $\pm 2.75\%$ and $\pm 2.75\%$ for the R-22 unit, respectively, and ± 3.5 and $\pm 3.5\%$ for the R-410A unit, respectively. As expected, under all testing conditions, the units' performance degraded as the outdoor temperature increased.

The R-22 alternative refrigerants showed promising results; most alternatives performed within $\pm 10\%$ of the baseline. At all test conditions, L-20A (R-444B), ARM-20b, and DR-7 (R-454A) all had cooling capacities ranging from 1% below and 10% higher than the baseline. At Hot ambient conditions, ARM-20a most closely matched the COP performance of the baseline, while the other alternatives had mixed performance. All the R-22 alternative refrigerants exhibited lower compressor discharged temperatures than the baseline.

The R-410A alternative refrigerants also showed very promising results, with all refrigerants but one exhibiting COPs that exceeded the baseline at all test conditions. At high ambient temperatures (Hot and Extreme conditions), both L41z (R-447B) and ARM-71a both exceeded the COP of the baseline by more than 7%. While R-32 experienced an improved COP relative to baseline at AHRI and Hot conditions, its ISO T3 and Extreme ambient COPs were approximately 1 to 3% lower than the baseline. Cooling capacity of all the alternatives except R-32 was within $\pm 3.6\%$ of the baseline at all conditions. For R-32, cooling capacity was between about 3.5% and 8.3% higher than the baseline at all conditions. All the R-410A alternative refrigerants exhibited higher compressor discharged temperatures than the baseline.

The efficiency and capacity of the alternative refrigerants would be expected to improve further through optimization and design modifications that manufacturers would conduct before introducing a new product to market. However, given that the scope of this study covered only drop-in testing, no detailed assessment can be made as to the extent of potential improvements through design changes. The fact that the units tested for this report did not include any optimization to account for the different performance characteristics of the alternative refrigerants likely indicates that the data presented here are conservative results that could improve through further optimization. Additional optimization, including heat transfer circuiting and proper compressor sizing and selection, would likely yield better performance results for all of the alternative refrigerants.

Losses in cooling capacity are typically easier to recover through engineering optimization compared to losses in COP. The primary practical limit to improvements in capacity is the physical size of the unit, but that is not expected to be a significant concern in this case based on the magnitude of the capacity losses exhibited in this evaluation program, where such losses were observed. Thus, the COP losses and the increase in compressor discharge temperature are particularly important results of this testing program, in that these variables will be the primary focus of future optimization efforts.

This performance evaluation shows that viable replacements exist for RTUs using either R-22 or R-410A at high-ambient temperatures. Multiple alternatives for R-22 performed well, and all R-410A alternatives closely matched or exceeded the performance of R-410A. These may be considered as prime-candidate lower-GWP refrigerants for high-ambient-temperature environments. Before commercialization, engineering optimization by manufacturers can address any performance losses, the increase in compressor discharge temperature that the R-410A alternatives exhibited, and any safety concerns associated with mildly flammable alternatives.

7. REFERENCES

- [1] IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; section 2.10.2: Direct Global Warming Potentials. Available:
https://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html
- [2] IPCC, 2013. Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Available: https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf.
- [3] Xu Y., Zaelke D., Velders G. J. M., & Ramanathan V. (2013) *The role of HFCs in mitigating 21st century climate change*, ATMOS. CHEM. PHYS. 13:6083-6089; see also Hare B. et al. (2012) *CLOSING THE 2020 EMISSIONS GAP: ISSUES, OPTIONS AND STRATEGIES*; and Ramanathan V. & Xu Y. (2010) *The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues*, PROC. NAT'L ACAD. SCI. U.S.A. 107:8055-8062
- [4] UNEP & UNIDO Presentation, *EGYPRA – Testing Low-GWP Refrigerants for Air Conditioning in Egypt*, June 2015.
- [5] El-Talouny, A. & Nielsen, O. (2014) *Promoting Low-GWP Refrigerants for Air-Conditioning Sectors in High-Ambient Temperature Countries (PRAHA)*, UNEP and UNIDO, OzonAction Fact Sheet - November 2014, available at
[http://www.unep.org/ozonaction/Portals/105/documents/events/MOP26/Fact%20Sheet%20Promoting%20low-GWP%20Refrigerants%20for%20Air-Conditioning%20Sectors%20in%20High-Ambient%20Temperature%20Countries%20\(PRAHA\).pdf](http://www.unep.org/ozonaction/Portals/105/documents/events/MOP26/Fact%20Sheet%20Promoting%20low-GWP%20Refrigerants%20for%20Air-Conditioning%20Sectors%20in%20High-Ambient%20Temperature%20Countries%20(PRAHA).pdf)
- [6] AHRI, *Participants' Handbook: AHRI Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP)*, April 17, 2015; available:
http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Participants_Handbook2015-04-17.pdf
- [7] C. K. Rice, V. D. Baxter, S. A. Hern, T. P. McDowell, J. D. Munk, and B. Shen (2013) *Development of a Residential Ground-Source Integrated Heat Pump*, 2013 ASHRAE Winter Conference Paper, Dallas, TX
- [8] V. D. Baxter, J. J. Tomlinson, R. W. Murphy, B. G. Ashdown, M. V. Lapsa (2005) *Residential Heat Pump Water Heater (HPWH) Development Status – USA*, Proceedings of 8th International Energy Agency Heat Pump Conference, Las Vegas, NV
- [9] CFC project phase-out summary available: <http://homer.ornl.gov/seia/environment/ods/ornl.pdf>
- [10] Fischer et al. (1997) *Global Warming Impacts of Ozone-Safe Refrigerants and Refrigeration, Heating, and Air-Conditioning Technologies*, available: <http://www.osti.gov/scitech/biblio/555370>
- [11] Abdelaziz et al. (2012) *Development of Low Global Warming Potential Refrigerant Solutions for Commercial Refrigeration Systems using a Life Cycle Climate Performance Design Tool*, available: <http://docs.lib.psu.edu/cgi/viewcontent.cgi?article=2352&context=iracc>

- [12] Sand et al. (1997) report to US DOE, *Energy and Global Warming Impacts of HFC Refrigerants and Emerging Technologies*, available:
http://web.ornl.gov/sci/ees/etsd/btrc/eere_research_reports/electrically_driven_heat_pumps/fluids_development/cfc_and_hcfc_replacements/tewi_3/tewi_3.pdf
- [13] AHRI, *Participants' Handbook: AHRI Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP)*, April 17, 2015, pp24-25; available:
http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Participants_Handbook2015-04-17.pdf
- [14] Taylor B.N. and Kuyatt, C.E. (1994) *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results*, National Institute of Standards and Technology Technical Note 1297.

APPENDIX A. EXPERT PANEL - BIOGRAPHIES

APPENDIX A. EXPERT PANEL - BIOGRAPHIES

Brief biographies of the panel members are included below.



Dr. Radhey Agarwal (India)

Radhey Agarwal is a Mechanical Engineer and received his Ph.D. from the Indian Institute of Technology Delhi (India) in 1975. He specializes in refrigeration, air-conditioning, and alternative refrigerants to CFCs and HCFCs. He is a former Deputy Director (Faculty), Dean of Industrial Research & Development and Chairman, Department of Mechanical Engineering, IIT Delhi. He was the Co-Chair, UNEP Technical Options Committee on Refrigeration, Air-conditioning and Heat Pumps (ROTC) and a member of the Technology and Economics Assessment Panel (1996–2008) of the Montreal Protocol. He has been actively contributing towards efforts to protect the ozone layer as part of the Technology and Economics Assessment Panel (UNEP TEAP) since 1989. He is the recipient of the 1998 US Environmental Protection Agency (EPA) Stratospheric Ozone Protection Award for Technical Leadership in CFC-Free Refrigeration and the 2007 US EPA Stratospheric Ozone Protection Award Best of the BEST. Dr. Agarwal was the Vice-President of IIR, Commission-B2 and member of the scientific committee of the IIR. He is a member of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the Indian Society of Heating, Refrigerating, and Air-Conditioning Engineers (ISHRAE).



Dr. Fotouh Al-Raqom (Kuwait)

Fotouh Al-Raqom is a Manager of the Energy Efficiency Technologies Program and a research scientist at the Energy and Building Research Center (EBRC) of the Kuwait Institute for Scientific Research (KISR). She obtained her B.Sc. from Kuwait University in Mechanical engineering, M.Sc. in mechanical engineering from Northeastern University, Boston, Massachusetts, M.Sc. in aerospace engineering and PhD in mechanical engineering from University of Florida. She is a certified energy manager (CEM) since 2001 and a Certified Sustainable Development Professional (CSDP) since 2007. She obtained several awards including the 2008 Emirates Energy Award. She is a founder of Kuwait's local chapter for the Association of Energy Engineers (AEE) and currently holding the President position. Her research interests include air-conditioning, solar fuels, hydrogen production, energy auditing, and energy efficiency. She is a member of several professional organizations including ASHRAE, ASME, AEE, and SWE. She served on Kuwait's national ozone committee from: 1998 – 2006.



Dr. Karim Amrane (USA)

Karim Amrane is Senior Vice President of Regulatory and International Policy at the Air-Conditioning, Heating, and Refrigeration Institute (AHRI). He manages the industry's cooperative research program and is responsible for the development and implementation of AHRI's regulatory and international policy. He holds a Ph.D. in Mechanical Engineering from the University of Maryland at College Park (Maryland, USA) where he currently is a part-time faculty member. Dr. Amrane has over 25 years of experience in the air-conditioning and refrigeration industry. He is a member of (ASHRAE), the International Institute of Refrigeration (IIR), and the American Society of Mechanical Engineers (ASME).



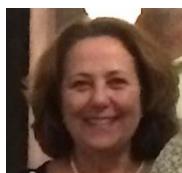
Dr. Enio Bandarra (Brazil)

Enio P. Bandarra Filho is an associate professor of mechanical engineering from the Federal University of Uberlandia (Brazil). He received his BS degree from the State University of Sao Paulo (Brazil) in 1994, and his MS and Ph.D. degrees from the University of Sao Paulo, in thermal sciences, in 1997 and 2002, respectively. In 2007–2008 he was a visiting professor in the heat and mass transfer laboratory at the Ecole Polytechnique Federale de Lausanne, Switzerland, working with oil-refrigerant mixtures in two-phase flow. Currently, he has 1 postdoc, 8 Ph.D., and 4 M.S. students in different areas, such as refrigeration and air-conditioning, heat transfer of nanofluids, heat exchangers, single-phase flow, control in refrigeration systems, and related topics. He published more than 260 papers in journals, book chapters, and conferences, including some awards received by the best-presented papers.



Dr. Jitendra M. Bhambure (India)

Jitendra Bhambure, who is presently the Executive Vice President - R&D and Technology at Blue Star, received a degree in Electrical Engineering in 1979 from Bombay University (India) and a Post-Graduate degree in Management Studies from Mumbai University (India) in 1983. He joined Rallis India Ltd. in 1979 as a trainee engineer and worked there for 13 years. He was head of R&D before he left Rallis India. He joined Blue Star in 1992, and worked in various operations, before taking charge of R&D in 2000. He has trained in the United States, London Business School, IIM-A'bad, and at Tel Aviv University. Dr. Bhambure was the founder and President of ISHRAE Thane Sub Chapter, which over the course of 3 years has become an independent chapter. He is a member of the ISHRAE Technical Committee and an active member of the Refrigeration & Air-Conditioning Manufacturers Association (RAMA) to represent Industry on Energy Efficiency and new refrigerants with Bureau of Energy Efficiency (BEE), Bureau of Indian Standards (BIS) and Ozone Cell under the Ministry of Environment & Forest. He is also the Chairperson of the ozone-depleting substances committee of RAMA.



Dr. Suely Machado Carvalho (co-chair; Brazil)

Suely Carvalho is a physicist and received her Ph.D. from Purdue University (USA). She was a postdoctoral researcher at the National Superconducting Cyclotron Laboratory (NSCL), Department of Energy (DOE), at Michigan State University, East Lansing, USA (1980). As former director of the Montreal Protocol Unit and Principal Technical Adviser for Chemicals for the United Nations Development Programme in New York (2002–2013), she led the implementation of projects in over 100 developing countries to replace ozone-depleting substances in several sectors. She was the UNEP TEAP co-chair for 10 years. As the former director of Technology Transfer at the São Paulo State Environment Protection Agency, CETESB (1985–1987), she established the Climate and Ozone Protection programs at the state level. She has been involved with the Montreal Protocol nationally and internationally for 25 years. Dr. Carvalho is currently adviser to the Superintendent at the Instituto de Pesquisas Energéticas e Nucleares, IPEN-CNEN, Ministry of Science, Technology and Innovation, MCTI, São Paulo, Brazil.



Mr. Ayman El-Talouny (UNEP)

Mr. Eltalouny holds a mechanical engineering degree from Cairo University, and specialized in the field of refrigeration and air-conditioning. Before joining the UN, he spent 10 years in the refrigeration industry and 4 years as Technical Advisor for the Egyptian Environmental Affairs Agency (EEAA) for the implementation of the Montreal Protocol. He has 20 years of experience with the Montreal Protocol at the industry, government and UN levels. Mr. Eltalouny joined UNEP in 2003 and is currently responsible for the implementation of phase-out plans of ODS in the West Asia region and is currently co-managing the UNEP-UNIDO PRAHA and EGYPRA projects for assessing low-GWP alternative refrigerants. Mr. Eltalouny is also a founding member and past president of the Bahrain ASHRAE Chapter, coordinator to the UNEP-ASHRAE and UNEP-AHRI partnerships as well as member of the drafting committees of the Arab and Egyptian Codes of refrigeration and air-conditioning.

Mr. Daniel Giguère*



Dr. Tingxun Li (China)

Tingxun Li received his Ph.D. from SHANGHAI JIAOTONG University (China). He has been engaged in alternative refrigerant activities since 1995. As an associate professor in Sun Yat-sen University, he teaches courses in refrigeration and conducts research on air-conditioning and cryogenics. He led the conversion from R-22-based to propane-based room air conditioner manufacturing at Guangdong Midea Group in a demonstration project that was funded by MLF of the Montreal Protocol. As a member of the Refrigeration and Air-Conditioning Technical Options Committee (RTOC) of UNEP, he is one of the authors of the 2014 RTOC report and the report of the task force. He is also a member of IEC SC61D and has been engaged in a revision of the standard IEC 60335-2-40 since 2013.



Dr. Samuel Yana Motta (Peru)

Samuel F. Yana Motta received his BS degree from the National Engineering University in his native Peru, and his Ph.D. from the Catholic University (Brazil), all in mechanical engineering. Following a guest researcher appointment at the National Institute of Standards (Thermal Machinery Group – Gaithersburg, MD, USA), he joined Honeywell as a scientist in the Buffalo Research Laboratory in 2000. At Honeywell, he participated in the development of new environment-friendly refrigerants such as HFO-1234yf and HFO-1234ze. He has also assumed positions of increasing responsibility and leadership in the development of such fluids. He now leads the Global R&D teams responsible for developing new heat transfer fluids.



Mr. Maher Mousa (Saudi Arabia)

Maher Mousa is currently an independent consultant in HVACR industry and environmental policy; offering consultancy services both to the private and public sectors. He has been the Director of Product Development and Regulations for United Technologies BIS, Middle East/Carrier Middle East from May 2013 until June 2015. He also had the lead role in managing the laboratories and testing services at Carrier Middle

*Biography for Mr. Daniel Giguère was unavailable at the time of publishing.

East with the objective of complying with international quality standards and laboratories accreditations. He is currently based in Jeddah, Saudi Arabia.

Maher Mousa started his career with Carrier Corporation in 2002. In 2011, he was working as the Product Development Manager. He led the technology transfer and development of high efficiency products with alternative refrigerants for high ambient applications in the Middle East. Prior to that, he has held several positions of increasing responsibility related to engineering and marketing.

Maher Mousa is also serving as a government advisor for energy and environmental regulations. He has contributed to the development of minimum energy efficiency regulations in Saudi Arabia and UAE. In 2013, Maher was an industry representative providing technical advisory to the regulatory authorities in KSA on Montreal Protocol implementation and impact on local HVAC industry. Currently, Maher Mousa is a member RTOC of UNEP under Montreal Protocol nominated by the Kingdom Saudi Arabia.

Maher has a Bachelor's degree and higher diploma in Mechanical Engineering from King Abdul Aziz University, Saudi Arabia, and is in the process of completing his MBA from Leicester University, UK.



Mr. Ole Nielsen (UNIDO)

Mr. Nielsen graduated from the Technical University of Copenhagen (Denmark) in 1988 as a mechanical engineer specializing in energetics and refrigeration. He worked in the Danish refrigeration industry until 1996. Afterwards, Mr. Nielsen worked as an independent technical consultant on the Montreal Protocol project formulation and implementation until 2003. He then returned to the private sector as sales manager for refrigeration equipment. He joined the UNIDO Montreal Protocol team in 2011.

Currently he is acting as Chief of the Montreal Protocol Unit. Mr. Nielsen has been involved with the Montreal Protocol since 1993 through consultancy, the private sector, and most recently through an implementing agency, with a specialty in the refrigeration and air-conditioning sectors.



Mr. Tetsuji Okada (Japan)

Tetsuji Okada received his BS degree from the University of Tokyo (Japan) and his MS degree from the University of California, Berkeley (USA), all in mechanical engineering. He joined Mitsubishi Electric Corporation in 1980. He was engaged in the design of domestic air conditioners and the development of finned tubed-type heat exchangers until 1995. From 1995 to 1998 he researched radiation air-conditioning in the company's laboratory. He was the department manager of heat pump hot water heater development using CO₂ refrigerant from 2000 to 2009. He was transferred to the commercial air conditioners factory in Scotland as the vice president (2010–2012). Mr. Okada was the general manager of the Brussels office of Mitsubishi Electric Europe from 2012–2014 and is now the president of the Japan Refrigeration and Air Conditioner Industry Association.



Dr. Alaa Olama (Egypt)

Alaa Olama received his M.Sc. and Ph.D. from King's College, London University (England), in mechanical engineering, specializing in refrigeration and air-conditioning. He is the founder, board of directors' member, and past vice chair of the first district cooling company in Egypt, GasCool. He is a member of the RTOC of UNEP. Dr. Olama is the head of the committee writing the first District Cooling code for Egypt and a

member of the committee writing the Egyptian code of Air Conditions, Refrigeration & Automatic Control and the Arab Refrigeration and Air-Conditioning Code. He is the past president of the Board of Directors of ASHRAE Cairo Chapter 2002–2003 and general Chair, ASHRAE, of the Second Regional Conference of Refrigeration (ARC) Region-At-Large in Cairo, September 2003. He is a member of the international reviewers' panel of the low-GWP refrigerants testing program of PRAHA and the technical advisor of EGYPRA. Dr. Olama is an independent consultant.



Dr. Alessandro Giuliano Peru (Italy)

Dr. Peru was a researcher at the University Consortium CUEIM, where he co-authored several research papers and technical reports for the protection of the environment. He has worked for more than 15 years in the ozone protection field. He was in charge of national plans for the phase-out of ozone-depleting and high-GWP substances from 2000 to 2010. Starting in 2006, he was in charge, as financial expert, of the mobilization of financial resources and budget of the multi-environmental agreements and member of the executive committee of the MLF for the years 2006-2007 and 2014-2015. Dr. Peru has chaired and coordinated many technical working groups at both the European and international level.

In addition, he was in charge of several bilateral and multilateral cooperation programs. In 2014, he was President of the European Union for the Montreal Protocol during the Italian Presidency of the Council of the European Union. Dr. Peru is the author of several articles and publications on environmental issues and Former Professor of Economics and Management at the Faculty of Economics at the University "La Sapienza."



Dr. Patrick Phelan (co-chair; USA)

Patrick Phelan received his BS degree from Tulane University (New Orleans, Louisiana, USA), his MS degree from the Massachusetts Institute of Technology (USA), and his PhD from the University of California, Berkeley (USA), all in mechanical engineering. Following a 2 year postdoctoral fellowship at the Tokyo Institute of Technology (Japan), he started his academic career as an Assistant Professor at the University of Hawaii in 1992. In 1996 he moved to Arizona State University (USA), where he is a Professor of Mechanical & Aerospace Engineering and a Senior Sustainability Scientist. While on leave from Arizona State University, he served as the Director of the National Science Foundation Thermal Transport Processes Program from 2006 to 2008, and from 2012 – 2016 as the Program Manager for Emerging Technologies in the Building Technologies Office, Energy Efficiency and Renewable Energy, US DOE.

APPENDIX B. OTHER HIGH-AMBIENT-TEMPERATURE TESTING PROGRAMS

APPENDIX B. OTHER HIGH-AMBIENT-TEMPERATURE TESTING PROGRAMS

Comparison of high-ambient-temperature testing programs:

Table B.1, Table B.2, and Table B.3, summarize the EGYPRA, PRAHA, and AHRI's Low-GWP AREP test programs, respectively. Low-GWP AREP includes testing of a wide range of equipment; Table B.3 covers only a subset that is directly applicable to this report.

Table B.1. EGYPRA (UNEP, UNIDO, Egypt) high-ambient-temperature testing programs

Type of Test	Individual test prototypes, comparing with base units: R-22 and R-410A				
Number of Prototypes	36 prototypes, each specific to one capacity and one refrigerant, compared with base units: R-22, R-410A				
Equipment Categories (all 50 Hz)	Split 12 MBH	Split 18 MBH	Split 24 MBH	Central 120 MBH	Central micro Channel 120 MBH
Testing Conditions	EOS 4814 and 3795 (ISO 5151), T1 conditions plus one point in T3 conditions				
Prototypes Supplied & Tests Performed	Prototypes built at eight OEMs, test at NREA (Local test laboratory in Egypt)				
Refrigerants Tested	R-32, R-290, HFC/HFO blends (3 Types) vs. to R-22, HFC/HFO blends (3 Types) vs. to R-410A				
Expected Delivery Dates	Fall 2016				
Constraints	To build new prototypes with dedicated compressors for the selected refrigerants with the condition to meet the same design capacities of the selected models in comparison to the R-22 or R-410A designs				

Table B.2. PRAHA (UNEP, UNIDO, high-ambient-temperature countries)

Type of Test	Individual test prototypes, comparing with base units: R-22 and R-410A			
Number of Prototypes	14 prototypes each specific to one capacity and one refrigerant, compared with 9 additional base units using R-22 or R-410A			
Equipment Categories	Window 18 MBH (60 Hz)	Decorative Split 24 MBH (60 Hz)	Ducted 36 MBH (50 Hz)	Packaged 90 MBH (50 Hz)
Testing Conditions	ISO 5151 at T1, T3 and T3+ (50°C) and a continuity test for 2 hr at 52°C			
Prototypes Supplied & Tests Performed	Prototypes built at 6 OEMs; test at Intertek			
Refrigerants Tested	Comparison to R-22: R-290, R-444B (L-20), DR-3 Comparison to R-410A: R-32, R-447A (L-41)			
Expected Delivery Dates	Report published April 2016			
Constraints	To build new prototypes with dedicated compressors for the selected refrigerants with the condition to meet the same design capacities of the selected models in comparison to the R-22 or R-410A designs			
Other Components	The project includes other non-testing elements to assess relevant issues of EE standards, technology transfer and economics in addition to special reporting on the potential of District Cooling to reduce the use of high-GWP alternatives.			

Table B.3. Low-GWP AREP (AHRI)^a

Type of Test	Soft-optimization and drop-in tests. Baseline units vary by application.
Number of Prototypes	Data for 17 prototypes has been published so far; 18 reports with high-ambient-temperature tests are expected in total.
Equipment Categories (all 60 Hz)	<ul style="list-style-type: none">• 056: System Soft-optimization Tests of Refrigerant R-32, DR-5A, and DR-55 in a R-410A 4-ton Unitary Rooftop Heat Pump (Cooling Mode)• 055: System Soft-optimization Tests of Refrigerant R-32 in a 6-ton RTU• 053: System Drop-In Test of Refrigerant Blend DR-55 in a Five-Ton R-410A RTU• 047: System Drop-in Test of R-32 and Refrigerant Blends ARM-71a, HPR2A, L-41-2 and DR-5A in a Five-Ton R 410A RTU• 057: System Soft-optimization Tests of Refrigerant R-32 in a 2.5 ton Rooftop Heat Pump
Testing Conditions	Varies by test report; see reports for details at: http://www.ahrinet.org/Resources/Research/AHRI-Low-GWP-Alternative-Refrigerants-Evaluation-Program/Reports-by-Category.aspx#Ambient
Prototypes Supplied & Tests Performed	Units were manufactured or obtained by each party and tested at each party's facilities
Refrigerants Tested	For rooftop air-conditioning applications, the refrigerants included: DR-55, R-32, DR-5A, ARM-71a, HPR2A, L-41-2.
Expected Delivery Dates	Phase I results have already been published; Phase II results are currently being published on a rolling basis
Constraints	To conduct drop-in system tests and soft-optimized tests with any modifications clearly indicated in the test reports
Other Components	Compressor calorimeter tests are also performed

^a Only includes test results that are directly related to this report.

APPENDIX C. EXPERIMENTAL TEST SETUP

APPENDIX C. EXPERIMENTAL TEST SETUP

The code testers used for the airside flow measurement and the outdoor unit setup are shown in Figure C.1 for the R-22 unit and Figure C.2 for the R-410A unit.



Figure C.1. As installed R-22 indoor unit.

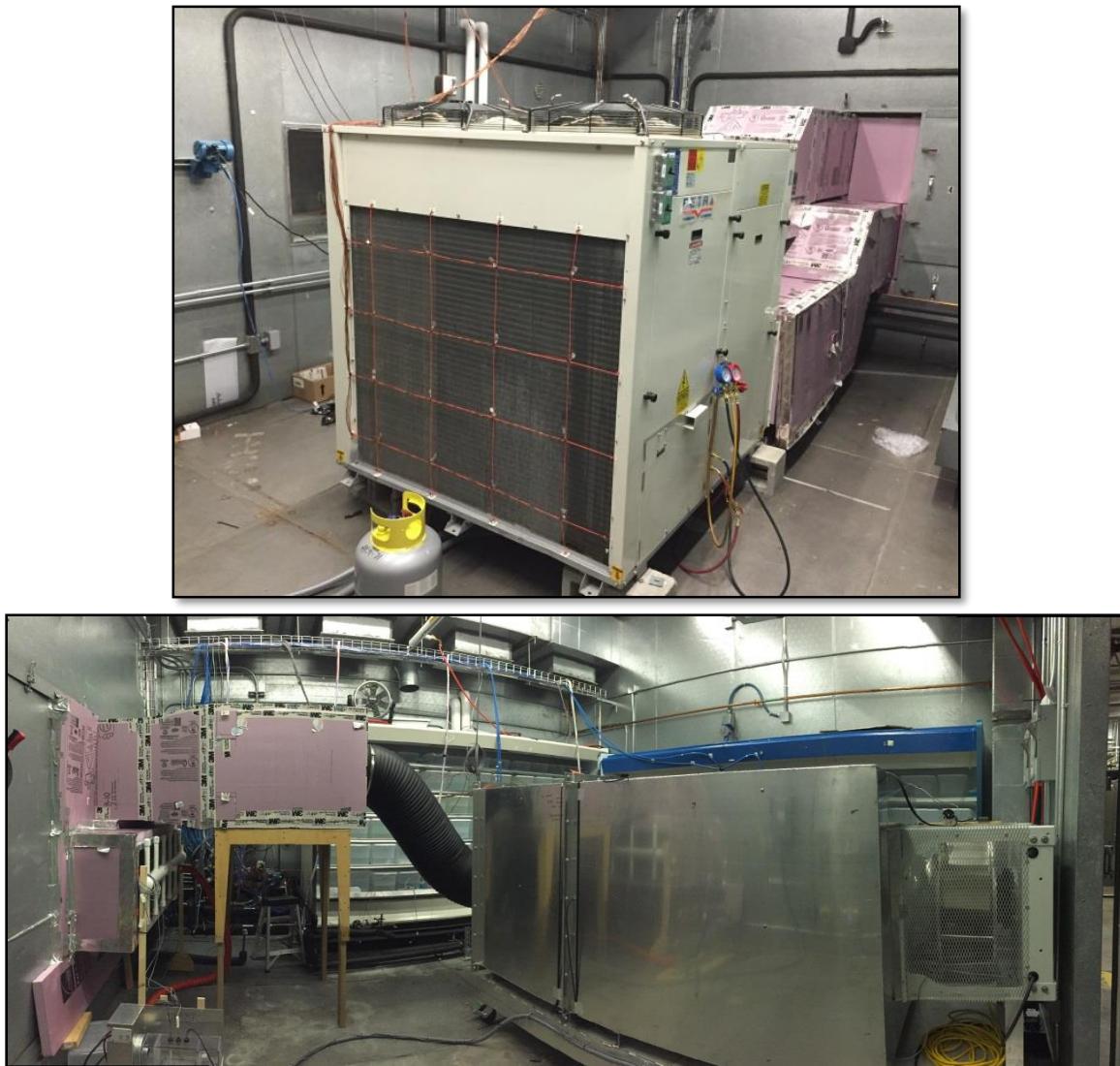


Figure C.2. As installed R-410A unit.

Table C.1 provides a summary of the instrumentation used for testing of the R-22 unit and Table C.2 provides a summary of the instrumentation used for testing of the R-410A unit.

Table C.1. R-22 unit experimental setup instrumentation

Data	Instrument	Range and Accuracy	Comments
Indoor unit air inlet temperature	Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	Using aspirated sampling temperature tree
Indoor unit air inlet wet bulb temperature	Wetted hygrometer with Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Indoor unit air outlet temperature	Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Indoor unit air outlet wet bulb temperature	Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Condensate rate	Sartorius Midrics electronic scale	0 to 30kg, 2 g readability	
Airflow rate	Code tester with two 203.2 mm nozzles and one 25.4 mm nozzle		Air mass flow rate measurement
Barometric pressure upstream of the nozzle	Setra model 278 barometric pressure sensor	800 to 1100 hPa/mb, $\pm 0.6 \text{ hPa/mb}$	
Temperature upstream of the nozzle	T-type thermocouple	1.7 to 79.4°C, $\pm 0.28^\circ\text{C}$	
Pressure drop across the nozzle	Setra Model 239 differential pressure sensor	0 to 2.5 in. H ₂ O, $\pm 0.073\% \text{ FS}$	
External static pressure	Setra 239	0 to 1 in. H ₂ O, $\pm 0.073\% \text{ FS}$	
Liquid line pressure	Omega Pressure Transducer PX409 absolute pressure sensor	0-750 psia, $\pm 0.05\% \text{ BSL}$	Used to evaluate evaporator inlet enthalpy
Liquid line temperature	In-stream Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
			Used to evaluate evaporator outlet enthalpy
		-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Evaporator outlet pressure	Omega Pressure Transducer PX409 absolute pressure sensor	0 to 250 psiA, $\pm 0.05\% \text{ BSL}$	
Evaporator outlet temperature	In-stream Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Refrigerant mass flow rate	Micro Motion Elite CMF025 Coriolis mass flow meter	0 to 0.19 kg/s, $\pm 0.1\% \text{ of rate}$	
Total power	Power meter	0 to 20 kW, $\pm 0.2\%$ reading	

Data	Instrument	Range and Accuracy	Comments
Compressor power	Power meter	0–15 kW, $\pm 0.2\%$ reading	
Outdoor fan power	Power meter	0–4 kW, $\pm 0.2\%$ reading	
Indoor unit power	Power meter	0–4 kW, $\pm 0.2\%$ reading	

Table C.2. R-410A unit experimental setup instrumentation

Data	Instrument	Range and Accuracy	Comments
Indoor unit air inlet temperature	Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	Using aspirated sampling temperature tree
Indoor unit air inlet wet bulb temperature	Wetted hygrometer with Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Indoor unit air outlet temperature	Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Indoor unit air outlet wet bulb temperature	Wetted hygrometer with Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Condensate rate	Sartorius Midrics electronic scale	0 to 30kg, 2 g readability	
Airflow rate	Code tester with three 203.2 mm nozzles		Air mass flow rate measurement
Barometric pressure upstream of the nozzle	Setra model 278 barometric pressure sensor	800 to 1100 hPa/mb, $\pm 0.6 \text{ hPa/mb}$	
Temperature upstream of the nozzle	T-type thermocouple	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Pressure drop across the nozzle	Setra Model 239 differential pressure sensor	0 to 2.5 in. H ₂ O, $\pm 0.073\% \text{ FS}$	
External static pressure	Setra 239	0 to 1 in. H ₂ O, $\pm 0.073\% \text{ FS}$	
Liquid line pressure	Omega Pressure Transducer PX409 absolute pressure sensor	0-750 psiA, $\pm 0.05\% \text{ BSL}$	Used to evaluate evaporator inlet enthalpy
Liquid line temperature	In-stream Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Evaporator inlet temperature	In-stream Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	
Evaporator outlet pressure	Omega Pressure Transducer PX409 absolute pressure sensor	0 to 250 psiA, $\pm 0.05\% \text{ BSL}$	

Data	Instrument	Range and Accuracy	Comments
Evaporator outlet temperature	In-stream Class-A RTD	-200 to 500°C $\pm 0.15 \pm 0.002 \times t \text{ } ^\circ\text{C}$	Used to evaluate evaporator outlet enthalpy
Refrigerant mass flow rate	Micro Motion Elite CMF50 Coriolis mass flow meter	0 to 0.4158 kg/s, $\pm 0.1\%$ of rate	
Total power	Power meter	0 to 10 kW, $\pm 0.2\%$ reading	
Compressor power	Power meter	0 to 10 kW, $\pm 0.2\%$ reading	
Outdoor fan power	Power meter	0 to 800 W, $\pm 0.2\%$ reading	
Indoor unit power	Power meter	0 to 2 kW, $\pm 0.2\%$ reading	

APPENDIX D. DETAILED R-22 TEST DATA

APPENDIX D. DETAILED R-22 TEST DATA

This appendix provides additional details of the testing documented in Section 5.1. ORNL conducted three sets of tests with R-22, one with mineral oil (the baseline), and one with POE oil, both before any other refrigerants were tested, and one with POE oil after all alternative refrigerants had been tested. By comparing the results before and after testing the alternative refrigerants, it is possible to establish the performance reliability using the alternative refrigerants. The results for the first R-22 (POE) run and the R-22 with POE oil re-run agree within 3.8% in terms of COP and within 3.1% in terms of cooling capacity for all test conditions. At Hot conditions, results agreed within 1.9% and 1.6% for cooling capacity and COP, respectively.

Table D.1 shows additional test data, including

- Air-side cooling capacity
- Air-side COP
- Condenser subcooling
- Evaporator superheat
- Compressor discharge temperature
- Liquid line temperature
- Liquid line pressure
- Evaporator inlet temperature
- Evaporator outlet temperature
- Airflow
- External static pressure
- Compressor suction temperature
- Liquid line saturation temperature
- Evaporator outlet saturation temperature
- Compressor discharge saturation temperature
- Refrigerant Mass flow rate
- Energy Balance
- Refrigerant charge

Table D.1. Complete test data for the R-22 unit

	Refrigerant	Test Conditions			Extreme
		AHRI	T3	Hot	
Cooling Capacity (air-side), kW_{th}	R-22/mineral oil	25.27	21.84	19.82	N/A
	R-22/POE	24.00	21.97	19.79	N/A
	L-20A (R-444B)	25.46	21.67	20.17	N/A
	ARM-20b	26.29	24.03	20.05	N/A
	DR-7 (R-454A)	27.15	22.76	19.95	N/A
	ARM-20a	24.58	19.58	18.48	N/A
	R-22/mineral oil Rerun	24.51	21.68	19.77	N/A
COP (air-side)	R-22/mineral oil	3.04	2.23	1.84	N/A
	R-22/POE	2.93	2.25	1.83	N/A
	L-20A (R-444B)	2.94	2.10	1.74	N/A
	ARM-20b	2.85	2.19	1.65	N/A
	DR-7 (R-454A)	2.86	2.00	1.58	N/A
	ARM-20a	3.21	2.18	1.86	N/A
	R-22/mineral oil Rerun	3.01	2.24	1.85	N/A
Condenser Subcooling, °C	R-22/mineral oil	4.33	4.64	4.46	N/A
	R-22/POE	5.20	6.75	7.26	N/A
	L-20A (R-444B)	5.86	5.99	6.08	N/A
	ARM-20b	5.64	5.60	5.58	N/A
	DR-7 (R-454A)	5.47	5.23	5.12	N/A
	ARM-20a	2.51	2.32	2.18	N/A
	R-22/mineral oil Rerun	3.95	4.19	4.11	N/A
Evaporator Superheat, °C	R-22/mineral oil	4.86	4.07	4.79	N/A
	R-22/POE	5.41	4.61	3.88	N/A
	L-20A (R-444B)	0.00	-0.11	-0.06	N/A
	ARM-20b	0.19	-0.03	0.01	N/A
	DR-7 (R-454A)	0.46	0.15	0.10	N/A
	ARM-20a	-0.07	-0.04	0.00	N/A
	R-22/mineral oil Rerun	2.97	2.15	1.49	N/A
Compressor Discharge Temperature, °C	R-22/mineral oil	80.6	97.2	107.4	N/A
	R-22/POE	77.5	95.6	106.6	N/A
	L-20A (R-444B)	79.5	96.1	105.6	N/A
	ARM-20b	75.3	90.1	98.9	N/A
	DR-7 (R-454A)	74.0	88.5	96.8	N/A
	ARM-20a	66.0	78.5	85.5	N/A
	R-22/mineral oil Rerun	79.3	95.7	104.9	N/A

Table D.1. (continued)

	Refrigerant	Test Conditions			
		AHRI	T3	Hot	Extreme
Liquid Line Temperature, °C	R-22/mineral oil	40.7	51.4	57.4	N/A
	R-22/POE	39.8	50.0	55.7	N/A
	L-20A (R-444B)	38.4	49.3	55.2	N/A
	ARM-20b	39.2	49.9	55.7	N/A
	DR-7 (R-454A)	39.1	50.2	56.1	N/A
	ARM-20a	39.1	50.1	56.2	N/A
	R-22/mineral oil Rerun	40.8	51.7	57.8	N/A
Liquid Line Pressure, MPa (absolute)	R-22/mineral oil	1.73	2.23	2.53	N/A
	R-22/POE	1.73	2.26	2.59	N/A
	L-20A (R-444B)	1.93	2.48	2.82	N/A
	ARM-20b	2.08	2.64	2.99	N/A
	DR-7 (R-454A)	2.16	2.74	3.09	N/A
	ARM-20a	1.62	2.07	2.36	N/A
	R-22/mineral oil Rerun	1.72	2.22	2.53	N/A
Evaporator Inlet Temperature, °C	R-22/mineral oil	19.50	22.65	24.19	N/A
	R-22/POE	19.62	22.39	24.00	N/A
	L-20A (R-444B)	14.53	17.78	20.33	N/A
	ARM-20b	17.52	21.20	23.27	N/A
	DR-7 (R-454A)	18.25	22.25	24.54	N/A
	ARM-20a	19.90	24.75	27.93	N/A
	R-22/mineral oil Rerun	19.50	22.80	24.85	N/A
Evaporator Outlet Temperature, °C	R-22/mineral oil	10.51	10.59	11.90	N/A
	R-22/POE	11.03	11.06	11.29	N/A
	L-20A (R-444B)	9.74	10.28	11.80	N/A
	ARM-20b	8.29	9.06	9.95	N/A
	DR-7 (R-454A)	8.25	8.99	9.94	N/A
	ARM-20a	8.74	10.07	11.52	N/A
	R-22/mineral oil Rerun	8.46	8.57	8.85	N/A
ID Airflow, m³/s	R-22/mineral oil	1.519	1.522	1.521	N/A
	R-22/POE	1.519	1.524	1.527	N/A
	L-20A (R-444B)	1.519	1.522	1.596	N/A
	ARM-20b	1.514	1.521	1.560	N/A
	DR-7 (R-454A)	1.517	1.522	1.549	N/A
	ARM-20a	1.518	1.528	1.624	N/A
	R-22/mineral oil Rerun	1.517	1.521	1.558	N/A

Table D.1. (continued)

	Refrigerant	Test Conditions			Extreme
		AHRI	T3	Hot	
External Static Pressure, mm	R-22/mineral oil	6.37	6.82	7.25	N/A
	R-22/POE	6.28	6.84	7.36	N/A
	L-20A (R-444B)	6.05	6.83	6.48	N/A
	ARM-20b	5.93	6.71	6.32	N/A
	DR-7 (R-454A)	6.02	6.60	6.58	N/A
	ARM-20a	6.43	7.58	6.32	N/A
	R-22/mineral oil Rerun	6.04	6.60	6.25	N/A
Compressor Suction Temperature, °C	R-22/mineral oil	12.09	12.88	14.21	N/A
	R-22/POE	12.16	13.08	14.04	N/A
	L-20A (R-444B)	12.87	13.46	14.93	N/A
	ARM-20b	12.31	13.27	14.22	N/A
	DR-7 (R-454A)	11.96	13.14	14.19	N/A
	ARM-20a	12.62	14.13	15.44	N/A
	R-22/mineral oil Rerun	12.23	13.19	13.99	N/A
Saturation Temperature, Liquid Line, °C	R-22/mineral oil	45.0	56.0	61.9	N/A
	R-22/POE	45.0	56.7	62.9	N/A
	L-20A (R-444B)	44.3	55.3	61.3	N/A
	ARM-20b	44.8	55.5	61.3	N/A
	DR-7 (R-454A)	44.6	55.5	61.2	N/A
	ARM-20a	41.6	52.4	58.4	N/A
	R-22/mineral oil Rerun	44.7	55.9	61.9	N/A
Saturation Temperature, Evaporator Outlet, °C	R-22/mineral oil	5.65	6.52	7.11	N/A
	R-22/POE	5.62	6.45	7.32	N/A
	L-20A (R-444B)	9.74	10.38	11.87	N/A
	ARM-20b	8.11	9.08	9.94	N/A
	DR-7 (R-454A)	7.80	8.84	9.84	N/A
	ARM-20a	8.81	10.10	11.53	N/A
	R-22/mineral oil Rerun	5.49	6.41	7.36	N/A
Saturation Temperature, Compressor Discharge, °C	R-22/mineral oil	47.8	58.1	63.5	N/A
	R-22/POE	48.0	58.7	64.6	N/A
	L-20A (R-444B)	53.3	63.2	68.6	N/A
	ARM-20b	52.2	61.8	67.0	N/A
	DR-7 (R-454A)	52.3	61.9	66.9	N/A
	ARM-20a	50.4	60.1	65.6	N/A
	R-22/mineral oil Rerun	47.6	58.0	63.6	N/A

Table D.1. (continued)

	Refrigerant	Test Conditions			
		AHRI	T3	Hot	Extreme
Mass Flow Rate, kg/min	R-22/mineral oil	9.73	9.71	9.63	N/A
	R-22/POE	9.90	9.78	N/A	N/A
	L-20A (R-444B)	8.13	8.04	8.20	N/A
	ARM-20b	9.87	9.88	9.91	N/A
	DR-7 (R-454A)	10.88	10.93	11.03	N/A
	ARM-20a	9.47	9.70	10.02	N/A
	R-22/mineral oil Rerun	9.73	9.74	9.84	N/A
Energy Balance, %	R-22/mineral oil	-5.37	-4.67	-3.90	N/A
	R-22/POE	2.53	-2.69	-1.18	N/A
	L-20A (R-444B)	N/A	N/A	N/A	N/A
	ARM-20b	N/A	N/A	N/A	N/A
	DR-7 (R-454A)	N/A	N/A	N/A	N/A
	ARM-20a	N/A	N/A	N/A	N/A
	R-22/mineral oil Rerun	-3.49	-5.11	-3.72	N/A
Refrigerant Charge, kg	R-22/mineral oil	8.335			
	R-22/POE	8.335			
	L-20A (R-444B)	8.618			
	ARM-20b	8.448			
	DR-7 (R-454A)	8.703			
	ARM-20a	8.420			
	R-22/mineral oil Rerun	8.335			

Table D.2. Data for additional tests on R-22 unit (See Table 5 for Test ID)

	Test ID	Refrigerant	Test Conditions		
			AHRI	T3	Hot
Cooling Capacity (air-side), kW_{th}	T1	R-22/POE	24.50	21.94	19.96
	T2	L-20A (R-444B)	25.03	21.16	19.28
	T3	ARM-20b	26.04	Not tested	Not tested
	T4	DR-7 (R-454A)	25.70	Not tested	Not tested
	T5	ARM-20a	22.47	Not tested	Not tested
	T6	ARM-20a	20.74	Not tested	Not tested
COP (air-side)	T1	R-22/POE	3.04	2.28	1.86
	T2	L-20A (R-444B)	2.96	2.10	1.71
	T3	ARM-20b	2.86	Not tested	Not tested
	T4	DR-7 (R-454A)	2.74	Not tested	Not tested
	T5	ARM-20a	2.98	Not tested	Not tested
	T6	ARM-20a	2.74	Not tested	Not tested
Condenser Subcooling, °C	T1	R-22/POE	5.89	7.39	7.73
	T2	L-20A (R-444B)	5.92	5.47	5.40
	T3	ARM-20b	5.99	Not tested	Not tested
	T4	DR-7 (R-454A)	5.23	Not tested	Not tested
	T5	ARM-20a	3.27	Not tested	Not tested
	T6	ARM-20a	3.11	Not tested	Not tested
Evaporator Superheat, °C	T1	R-22/POE	4.25	3.32	2.37
	T2	L-20A (R-444B)	4.15	1.86	1.08
	T3	ARM-20b	3.57	Not tested	Not tested
	T4	DR-7 (R-454A)	3.49	Not tested	Not tested
	T5	ARM-20a	4.14	Not tested	Not tested
	T6	ARM-20a	4.05	Not tested	Not tested
Compressor Discharge Temperature, °C	T1	R-22/POE	77.57	96.39	106.59
	T2	L-20A (R-444B)	82.21	98.75	108.13
	T3	ARM-20b	77.77	Not tested	Not tested
	T4	DR-7 (R-454A)	76.13	Not tested	Not tested
	T5	ARM-20a	68.15	Not tested	Not tested
	T6	ARM-20a	68.52	Not tested	Not tested

Table D.2 (continued)

	Test ID	Refrigerant	Test Conditions		
			AHRI	T3	Hot
Liquid Line Temperature, °C	T1	R-22/POE	39.19	49.55	55.37
	T2	L-20A (R-444B)	37.82	49.23	55.29
	T3	ARM-20b	38.83	Not tested	Not tested
	T4	DR-7 (R-454A)	39.28	Not tested	Not tested
	T5	ARM-20a	38.13	Not tested	Not tested
	T6	ARM-20a	38.75	Not tested	Not tested
Liquid Line Pressure, MPa (absolute)	T1	R-22/POE	1.73	2.27	2.59
	T2	L-20A (R-444B)	1.91	2.45	2.79
	T3	ARM-20b	2.08	Not tested	Not tested
	T4	DR-7 (R-454A)	2.16	Not tested	Not tested
	T5	ARM-20a	1.61	Not tested	Not tested
	T6	ARM-20a	1.63	Not tested	Not tested
Evaporator Inlet Temperature, °C	T1	R-22/POE	19.47	22.18	24.11
	T2	L-20A (R-444B)	13.77	17.31	19.65
	T3	ARM-20b	16.98	Not tested	Not tested
	T4	DR-7 (R-454A)	17.81	Not tested	Not tested
	T5	ARM-20a	19.05	Not tested	Not tested
	T6	ARM-20a	19.44	Not tested	Not tested
Evaporator Outlet Temperature, °C	T1	R-22/POE	9.88	9.66	9.67
	T2	L-20A (R-444B)	13.37	11.88	12.41
	T3	ARM-20b	11.42	Not tested	Not tested
	T4	DR-7 (R-454A)	10.91	Not tested	Not tested
	T5	ARM-20a	12.57	Not tested	Not tested
	T6	ARM-20a	12.54	Not tested	Not tested
ID Airflow, m³/s	T1	R-22/POE	1.521	1.524	1.559
	T2	L-20A (R-444B)	1.517	1.520	1.582
	T3	ARM-20b	1.515	Not tested	Not tested
	T4	DR-7 (R-454A)	1.521	Not tested	Not tested
	T5	ARM-20a	1.518	Not tested	Not tested
	T6	ARM-20a	1.521	Not tested	Not tested

Table D.2 (continued)

	Test ID	Refrigerant	Test Conditions		
			AHRI	T3	Hot
External Static Pressure, mm	T1	R-22/POE	6.15	6.75	6.34
	T2	L-20A (R-444B)	6.35	7.10	6.42
	T3	ARM-20b	5.94	Not tested	Not tested
	T4	DR-7 (R-454A)	6.15	Not tested	Not tested
	T5	ARM-20a	6.46	Not tested	Not tested
	T6	ARM-20a	6.33	Not tested	Not tested
Compressor Suction Temperature, °C	T1	R-22/POE	12.37	13.17	13.98
	T2	L-20A (R-444B)	15.80	16.72	17.94
	T3	ARM-20b	14.50	Not tested	Not tested
	T4	DR-7 (R-454A)	14.08	Not tested	Not tested
	T5	ARM-20a	15.12	Not tested	Not tested
	T6	ARM-20a	15.11	Not tested	Not tested
Saturation Temperature, Liquid Line, °C	T1	R-22/POE	45.08	56.94	63.10
	T2	L-20A (R-444B)	43.75	54.70	60.69
	T3	ARM-20b	44.82	Not tested	Not tested
	T4	DR-7 (R-454A)	44.51	Not tested	Not tested
	T5	ARM-20a	41.40	Not tested	Not tested
	T6	ARM-20a	41.86	Not tested	Not tested
Saturation Temperature, Evaporator Outlet, °C	T1	R-22/POE	5.63	6.34	7.30
	T2	L-20A (R-444B)	9.22	10.02	11.32
	T3	ARM-20b	7.84	Not tested	Not tested
	T4	DR-7 (R-454A)	7.42	Not tested	Not tested
	T5	ARM-20a	8.43	Not tested	Not tested
	T6	ARM-20a	8.49	Not tested	Not tested
Saturation Temperature, Compressor Discharge, °C	T1	R-22/POE	48.19	59.05	64.93
	T2	L-20A (R-444B)	52.77	62.57	67.97
	T3	ARM-20b	52.09	Not tested	Not tested
	T4	DR-7 (R-454A)	52.10	Not tested	Not tested
	T5	ARM-20a	50.14	Not tested	Not tested
	T6	ARM-20a	50.54	Not tested	Not tested

Table D.2 (continued)

	Test ID	Refrigerant	Test Conditions		
			AHRI	T3	Hot
Mass Flow Rate, kg/min	T1	R-22/POE	9.91	9.73	9.79
	T2	L-20A (R-444B)	7.87	7.84	7.94
	T3	ARM-20b	9.65	Not tested	Not tested
	T4	DR-7 (R-454A)	10.62	Not tested	Not tested
	T5	ARM-20a	9.24	Not tested	Not tested
	T6	ARM-20a	9.26	Not tested	Not tested
Energy Balance, %	T1	R-22/POE	-0.49%	-4.41%	-2.91%
	T2	L-20A (R-444B)	-7.10%	-6.98%	-6.18%
	T3	ARM-20b	-4.82%	Not tested	Not tested
	T4	DR-7 (R-454A)	-5.77%	Not tested	Not tested
	T5	ARM-20a	-5.36%	Not tested	Not tested
	T6	ARM-20a	7.48%	Not tested	Not tested
Refrigerant Charge, kg	T1	R-22/POE	10.15	10.15	10.15
	T2	L-20A (R-444B)	8.33	8.33	8.33
	T3	ARM-20b	8.45	Not tested	Not tested
	T4	DR-7 (R-454A)	8.70	Not tested	Not tested
	T5	ARM-20a	8.42	Not tested	Not tested
	T6	ARM-20a	8.62	Not tested	Not tested

APPENDIX E. DETAILED R-410A TEST DATA

APPENDIX E. DETAILED R-410A TEST DATA

This appendix provides additional details of the testing documented in Section 5.2. ORNL conducted two sets of tests with R-410A: one set used as the baseline test result, and a set of “rerun” tests conducted after the alternatives had been tested in the unit. By comparing the results with before and after testing the alternative refrigerants, it is possible to establish the performance reliability using the alternative refrigerants. The maximum discrepancy between the first R-410A run and the rerun was approximately 2.5% both for COP and cooling capacity; this result is within the experimental uncertainty.

Table E.1 shows additional test data, including

- Air-side cooling capacity,
- Air-side COP,
- Condenser subcooling
- Evaporator superheat
- Compressor discharge temperature
- Liquid line temperature
- Liquid line pressure
- Evaporator inlet temperature
- Evaporator outlet temperature
- Airflow
- External static pressure
- Compressor suction temperature
- Liquid line saturation temperature
- Evaporator outlet saturation temperature
- Compressor discharge saturation temperature
- Refrigerant Mass flow rate
- Energy Balance
- Refrigerant charge

Table E.1. Complete test data for the R-410A unit

	Refrigerant	Test Conditions			
		AHRI	T3	Hot	Extreme
Cooling Capacity (air-side), kW_{th}	R-410A	39.37	34.32	31.01	30.37
	DR-55	39.35	34.04	31.93	30.60
	L41z (R-447B)	37.96	33.08	31.56	30.61
	ARM-71a	38.49	33.38	31.96	31.14
	R-32	42.12	35.64	33.58	31.42
	R-410A rerun	38.46	33.61	31.00	30.34
COP (air-side)	R-410A	3.06	2.26	1.85	1.74
	DR-55	3.15	2.29	1.94	1.77
	L41z (R-447B)	3.16	2.33	2.01	1.86
	ARM-71a	3.16	2.31	1.99	1.86
	R-32	3.12	2.23	1.91	1.69
	R-410A rerun	2.99	2.23	1.86	1.72
Condenser Subcooling, °C	R-410A	7.90	7.56	7.08	6.79
	DR-55	8.20	7.83	7.87	7.80
	L41z (R-447B)	7.92	7.73	7.50	7.52
	ARM-71a	8.70	8.50	8.31	8.29
	R-32	8.84	8.41	8.03	7.81
	R-410A rerun	7.54	7.04	6.28	6.00
Evaporator Superheat, °C	R-410A	5.85	5.66	5.71	5.60
	DR-55	5.06	5.28	4.76	4.55
	L41z (R-447B)	3.72	3.89	3.48	3.48
	ARM-71a	4.92	4.72	4.60	4.53
	R-32	5.80	6.23	5.25	5.25
	R-410A rerun	6.03	5.90	5.94	5.98
Compressor Discharge Temperature, °C	R-410A	75.3	90.2	98.6	101.8
	DR-55	79.5	96.5	105.3	109.6
	L41z (R-447B)	81.4	98.0	107.3	111.7
	ARM-71a	80.3	97.1	105.0	109.7
	R-32	87.3	104.9	114.8	121.6
	R-410A rerun	71.3	85.2	93.4	97.7
Liquid Line Temperature, °C	R-410A	39.2	49.4	55.1	57.4
	DR-55	38.4	49.4	54.8	57.3
	L41z (R-447B)	38.4	49.0	55.0	57.6
	ARM-71a	38.0	48.9	54.3	57.1
	R-32	39.0	49.5	54.9	57.9
	R-410A rerun	39.3	49.7	55.8	58.9

Table E.1. (continued)

	Refrigerant	Test Conditions			
		AHRI	T3	Hot	Extreme
Liquid Line Pressure, MPa (absolute)	R-410A	2.87	3.60	4.03	4.21
	DR-55	2.73	3.47	3.91	4.11
	L41z (R-447B)	2.59	3.28	3.71	3.91
	ARM-71a	2.66	3.38	3.79	4.01
	R-32	2.99	3.76	4.19	4.45
	R-410A rerun	2.85	3.57	4.02	4.27
Evaporator Inlet Temperature, °C	R-410A	16.1	18.6	20.3	21.0
	DR-55	14.5	16.8	18.9	19.5
	L41z (R-447B)	13.5	15.9	18.0	18.8
	ARM-71a	14.0	16.4	18.7	19.4
	R-32	13.2	15.0	16.2	16.6
	R-410A rerun	16.0	18.6	20.4	21.6
Evaporator Outlet Temperature, °C	R-410A	15.0	15.9	17.0	17.6
	DR-55	15.3	16.4	17.3	17.6
	L41z (R-447B)	16.2	17.4	18.4	19.0
	ARM-71a	15.8	16.6	18.2	18.6
	R-32	14.8	16.1	16.0	16.4
	R-410A rerun	15.2	16.1	17.4	18.3
Compressor Suction Temperature, °C	R-410A	15.6	16.5	17.6	18.1
	DR-55	15.9	16.9	18.0	18.3
	L41z (R-447B)	16.8	17.9	19.1	19.7
	ARM-71a	16.5	17.2	18.9	19.3
	R-32	15.1	16.3	16.6	16.9
	R-410A rerun	15.7	16.5	17.8	18.7
Saturation Temperature, Liquid Line, °C	R-410A	47.1	57.0	62.2	64.2
	DR-55	46.6	57.2	62.7	65.1
	L41z (R-447B)	46.3	56.8	62.6	65.1
	ARM-71a	46.7	57.4	62.6	65.3
	R-32	47.8	58.0	63.0	65.7
	R-410A rerun	46.8	56.7	62.1	64.9
Saturation Temperature, Evaporator Outlet, °C	R-410A	9.2	10.3	11.3	12.0
	DR-55	10.2	11.1	12.6	13.1
	L41z (R-447B)	12.4	13.5	15.0	15.6
	ARM-71a	10.9	11.8	13.6	14.1
	R-32	9.0	9.9	10.8	11.2
	R-410A rerun	9.2	10.2	11.5	12.3

Table E.1. (continued)

	Refrigerant	Test Conditions			
		AHRI	T3	Hot	Extreme
Saturation Temperature, Compressor Discharge, °C	R-410A	48.5	58.2	63.4	65.5
	DR-55	48.8	59.1	64.5	67.0
	L41z (R-447B)	50.5	60.4	65.8	68.2
	ARM-71a	49.6	59.8	64.9	67.5
	R-32	48.6	58.6	63.6	66.3
	R-410A rerun	48.1	57.7	63.1	65.9
Mass Flow Rate, kg/min	R-410A	15.29	15.42	15.54	15.64
	DR-55	12.49	12.48	12.74	12.71
	L41z (R-447B)	11.35	11.42	11.62	11.66
	ARM-71a	11.91	11.95	12.34	12.33
	R-32	10.72	10.64	10.55	10.34
	R-410A rerun	15.38	15.55	15.80	16.01
Energy Balance	R-410A	4.66%	6.77%	9.76%	10.24%
	DR-55	1.68%	4.53%	5.85%	8.15%
	L41z (R-447B)	0.98%	5.13%	6.54%	8.14%
	ARM-71a	2.61%	6.18%	7.34%	9.50%
	R-32	3.68%	10.90%	9.57%	10.88%
	R-410A rerun	7.84%	9.76%	10.57%	8.79%
Refrigerant Charge, kg	R-410A	12.020			
	DR-55	10.886			
	L41z (R-447B)	11.113			
	ARM-71a	11.113			
	R-32	9.979			
	R-410A rerun	12.247			

APPENDIX F. DATA REDUCTION METHODOLOGY

APPENDIX F. DATA REDUCTION METHODOLOGY

The measured data obtained using the instrumentation listed in APPENDIX C were recorded using a National Instrument Data Acquisition system. Data were recorded continually at 5-second intervals. LabView® code was developed to allow for real-time data visualization and performance monitoring, as shown in Figure F.1 and Figure F.2. REFPROP property calculations were included in the code, as shown in Figure F.3, in order to facilitate the real-time evaluation of the refrigerant side properties, e.g., saturation properties and capacity. The airflow, air-side capacity, refrigerant-side capacity, and refrigerant subcooling and superheat calculations are presented in the following sections. Table F.1 shows the symbols, and Table F.2 shows the subscripts used in the calculations.

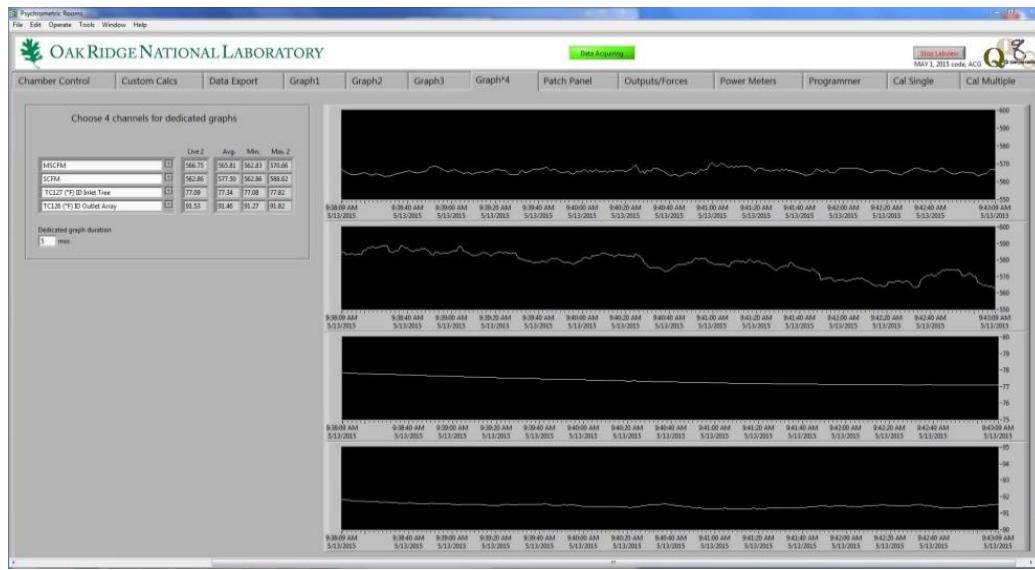


Figure F.1. LabView® display of room temperature and fan flow rate.

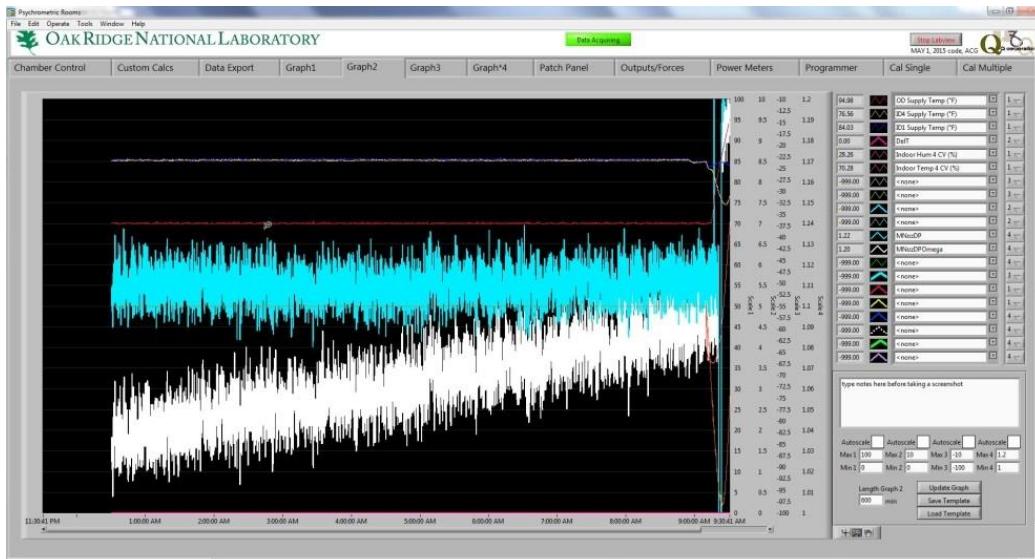


Figure F.2. LabView® display of various monitored parameters.

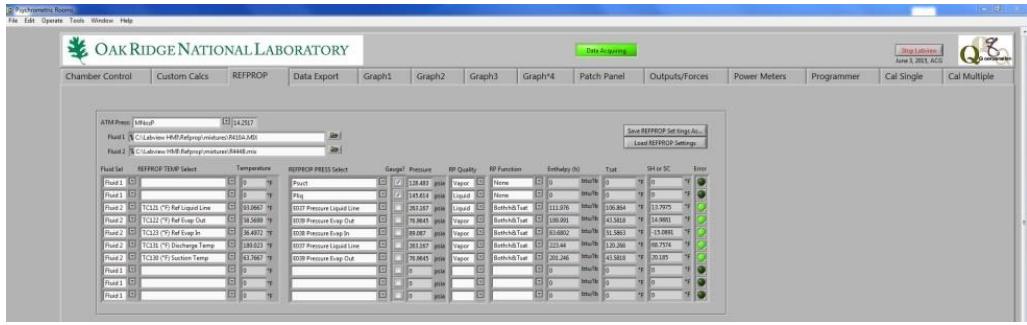


Figure F.3. LabView® display of built-in REFPROP calculation.

Table F.1. Data reduction methodology symbols

Symbol	Description	Unit
A_{nozzle}	Area of cross section at the nozzle throat	ft ²
C_{nozzle}	Nozzle discharge coefficient	-
C_p	Specific heat	Btu/lbm·°F
D	Diameter	In
h	Enthalpy	Btu/lbm
L	Side	in
\dot{m}	Flow rate	lbm/h
P	Absolute pressure	inH ₂ O
q	Heat capacity	Btu/h
Q	Airflow rate	cfm
Q_s	Standard airflow rate	scfm
Re	Reynolds number	-
T	Dry bulb temperature	°F
Y	Expansion Factor	-
W	Electric Power	Watt
α	Ratio of the absolute pressure at exit from the nozzle to the absolute pressure entering the nozzle	-
β	Ratio of nozzle throat diameter to duct diameter	-
Δ	Differential	inH ₂ O, °F
μ	Moist air humidity ratio	lb H ₂ O/lb air
ρ	Moist air density	lbm/ft ³

Table F.2. Data reduction methodology subscripts

Subscript	Description
<i>air</i>	Air side
<i>compressor</i>	Compressor
<i>condensate</i>	Condensate collected from the evaporator
<i>condenser fan</i>	Condenser fan
<i>duct</i>	Related to the duct
<i>evaporator fan</i>	Evaporator fan
<i>evap, in</i>	Evaporator inlet conditions
<i>evap, out</i>	Evaporator outlet conditions
<i>exit</i>	Exiting the nozzle
<i>latent</i>	Latent capacity
<i>nozzle</i>	Nozzle condition
<i>ref</i>	Refrigerant side
<i>coil</i>	At the coil
<i>return</i>	Return air to the indoor unit
<i>sat</i>	Saturated conditions at the equilibrium
<i>subcooling</i>	Degrees of subcooling
<i>superheat</i>	Degrees of superheat
<i>sensible</i>	Sensible capacity
<i>supply</i>	Supply air exiting the indoor unit
<i>total</i>	Total capacity
<i>tree</i>	From sampling tree
<i>upstream</i>	Entering the nozzle

Airflow Rate Calculation:

The airflow rate calculations were performed according to ASHRAE Standard 41.2-87 (RA92). The airflow rate is calculated as shown in equation (1). Equations (2) and (5) are used to calculate the expansion factor, Y , and the nozzle discharge coefficient, C_{nozzle} , respectively; both of them are inputs to Equation (1). The expansion factor is in turn a function of two parameters: α , the ratio of absolute pressures at the exit and the inlet of the nozzle, and β , the ratio of nozzle throat diameter to duct diameter. α and β are calculated as shown in Equations (3) and (4), respectively. The nozzle discharge coefficient, C_{nozzle} , is calculated based on Re , which can be approximately calculated using Equation (6) since the airflow velocity is not known. Finally, in order to evaluate the standard airflow rate, we use Equation (7) to normalize using the standard dry air density at 70°F and 14.696 psia of 0.075 lbm/ft³.

$$Q = 1096 \times Y \times \sqrt{\Delta P_{nozzle}/\rho_{nozzle}} \times C_{nozzle} \times A_{nozzle} \quad (1)$$

$$Y = 1 - (0.548 + 0.71 \times \beta^4)(1 - \alpha) \quad (2)$$

$$\alpha = \frac{P_{nozzle, exit}}{P_{nozzle, upstream}} \quad (3)$$

$$\beta = \frac{D_{nozzle}}{D_{duct}} = \left(\frac{D_{nozzle}}{\sqrt{\frac{4}{\pi} \times L_{duct}^2}} \right) = \left(\frac{5}{\sqrt{\frac{4}{\pi} \times 20^2}} \right) = 0.22155673 \quad (4)$$

$$C_{nozzle} = 0.9986 - \left(\frac{7.006}{\sqrt{Re}} \right) + \left(\frac{134.6}{Re} \right) \quad (5)$$

$$Re = 1,363,000 \times D_{nozzle} \times \sqrt{\frac{\Delta P \times \rho_{nozzle}}{1 - \beta^4}} \quad (6)$$

$$Q_s = \frac{Q \times \rho_{nozzle}}{(1 + \mu_{nozzle})} / 0.075 \quad (7)$$

In the above calculations, ρ_{nozzle} is calculated based on barometric pressure, temperature, and dew-point measurement upstream of the nozzle using equations from the *ASHRAE Handbook of Fundamentals*, 2009, Chapter 1 (Equations 23 and 28). The $P_{nozzle, upstream}$ is measured using a barometric pressure sensor and the $P_{nozzle, exit}$ is calculated using the $P_{nozzle, upstream}$ and the differential pressure drop across the nozzle, which is measured using a differential pressure sensor and can be calculated as shown in Equation (8) below.

$$P_{nozzle, exit} = P_{nozzle, upstream} - \Delta P_{nozzle} \quad (8)$$

Air-Side Capacity Calculations:

Air-side capacity is calculated according to ANSI/ASHRAE Standard 37-2009 Air Enthalpy Method. The total air-side capacity can be calculated as shown in Equation (9); the supply and return enthalpies used in Equation (9) are calculated using Equations (10) and (11). The factor of 60 is used to convert the airflow rate from cfm to ft³/h.

$$q_{total} = Q_s \times 0.075 \times 60 \times (h_{return} - h_{supply}) \quad (9)$$

$$h_{return} = 0.24 \times T_{return, tree} + \mu_{return, tree} \times (1061 + 0.444 \times T_{return, tree}) \quad (10)$$

$$h_{supply} = 0.24 \times T_{supply, tree} + \mu_{supply, tree} \times (1061 + 0.444 \times T_{supply, tree}) \quad (11)$$

The air-side sensible and latent capacities can be calculated as shown in Equations (12) and (15). Also, when the dew-point temperature difference is low, it would be more accurate to use the condensate measurement for latent capacity measurement, as shown in Equation (16).

$$q_{sensible} = Q_s \times 0.075 \times 60 \times ((CpT)_{return} - (CpT)_{supply}) \quad (12)$$

$$(CpT)_{return} = 0.24 \times T_{return, tree} + \mu_{return, tree} \times 0.444 \times T_{return, tree} \quad (13)$$

$$(CpT)_{supply} = 0.24 \times T_{supply, tree} + \mu_{supply, tree} \times 0.444 \times T_{supply, tree} \quad (14)$$

$$q_{latent} = Q_s \times 0.075 \times 60 \times 1061 \times (\mu_{return, tree} - \mu_{supply, tree}) \quad (15)$$

$$q_{latent, condensate} = \dot{m}_{condensate} \times 1061 \quad (16)$$

Refrigerant-Side Capacity Calculations:

The refrigerant-side capacity is calculated according to ANSI/ASHRAE Standard 37-2009 Refrigerant Enthalpy Method with refrigerant mass flow measurement. It can be calculated as shown in Equation (17) below.

$$q_{ref, coil} = \dot{m}_{ref} \times (h_{evap, out} - h_{evap, in}) \quad (17)$$

In this equation, the refrigerant flow rate, \dot{m}_{ref} , was measured using a Coriolis mass flow meter, and the refrigerant enthalpies were calculated using NIST REFPROP based on pressure and temperature measurements at the evaporator outlet and the condenser liquid line for $h_{evap, out}$ and $h_{evap, in}$, respectively. To compare both the air-side and the refrigerant-side capacities, the fan power dissipated into the airstream has to be considered: $W_{evaporator\ fan}$.

Efficiency Calculations:

The EER can be calculated based on the air-side or the refrigerant-side measurements by using Equations (18) or (19), respectively. The COP can be obtained from the EER through a unit conversion, as shown in Equations (20) and (21) for the air side and the refrigerant side, respectively.

$$EER_{air} = \frac{q_{total}}{W_{compressor} + W_{condenser\ fan} + W_{evaporator\ fan}} \quad (18)$$

$$EER_{ref} = \frac{q_{ref, coil} - W_{evaporator\ fan}}{W_{compressor} + W_{condenser\ fan} + W_{evaporator\ fan}} \quad (19)$$

$$COP_{air} = \frac{EER_{air}}{3.4121} \quad (20)$$

$$COP_{ref} = \frac{EER_{ref}}{3.4121} \quad (21)$$

Subcooling:

The liquid line subcooling was calculated based on the equation below, in which the saturation temperature, T_{sat} , was calculated using NIST REFPROP based on pressure measurements at the liquid line. The temperature, T , was directly measured using an in-stream thermocouple or RTD.

$$\Delta T_{subcooling} = T_{sat} - T \quad (22)$$

Superheat:

The evaporator outlet and compressor inlet superheat were calculated based on the equation below, in which the saturation temperature, T_{sat} , was calculated using NIST REFPROP based on the pressure at the evaporator outlet. The temperature, T , was directly measured at both locations using in-stream thermocouples or RTDs.

$$\Delta T_{superheat} = T - T_{sat} \quad (23)$$

APPENDIX G. DISCLOSURES OF INTEREST

APPENDIX G. DISCLOSURES OF INTEREST

The disclosures of interest of the panel members are included in this appendix.

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Radhey S. Agarwal
Sector Phase-out Plan Unit, Ozone Cell
India

I, Radhey S. Agarwal, residing in New-Delhi, India, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include: I work as a Technical Consultant for implementation of ODS phase-out projects. I am the former Professor of Mechanical Engineering and Dean Industrial Research and Development, Indian Institute of Technology Delhi. I was teaching and guiding Ph. D. research students in the field of refrigeration and Air-Conditioning. As an expert of Refrigeration and Air-Conditioning, I provide advise on implementation ODS phase-out projects to various entities. These include organizations dealing with refrigeration and air conditioning issues, and organizations dealing with Montreal Protocol and UNFCCC related climate issues. Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - a. Proprietary interests related to ODS, HFCs, or their alternatives: [None]
 - b. Financial interests related to ODS, HFCs, or their alternatives: [None]
 - c. Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: [Technacal Consultant, for implementation of ODS phase-out projects]
 - d. Government advice and other policy development related to ODS, HFCs, or their alternatives: [Technical and policy advise on ODS phase-out to Ozone Cell, India]
 - e. Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: [None]
 - f. Other interests related to ODS, HFCs, or their alternatives: [None]
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Radhey S. Agarwal

Signature: Signature on File

**Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program**

Fotouh Al-Raqom
Kuwait Institute for Scientific Research
Kuwait

I, Fotouh Al-Raqom, residing in Surra, Kuwait, as a member of the International Expert Panel for the High-Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Manager, Energy Efficiency Technologies Program, where I conduct research in areas of energy efficiency, hydrogen production and air conditioning.
 - Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - Research in areas of energy efficiency, hydrogen production and air conditioning: none for my children
 - Proprietary interests related to ODS, HFCs, or their alternatives: None
 - Financial interests related to ODS, HFCs, or their alternatives: None
 - Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: None
 - Government advice and other policy development related to ODS, HFCs, or their alternatives: Currently none, but I previously served as a member of Kuwait National Ozone Unit 1998 – 2006.
 - Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: Currently leading a project on Effect of R-410A on the performance of air conditioning units in high ambient temperatures
 - Other interests related to ODS, HFCs, or their alternatives: None currently
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than 1 year after I have signed it.

Printed Name: Fotouh Al-Raqom
Date: August 26, 2016

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Karim Amrane
Air-Conditioning, Heating, and Refrigeration Institute
USA

I, Karim Amrane, residing in Bethesda, Maryland, USA, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Managing the industry cooperative research program, where I oversee research activities on HVAC technologies including alternative refrigerants to HFCs.
 - Developing and implementing AHRI's regulatory and international policy on issues affecting refrigerants including HFCs and their alternatives.
 - Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - a. Proprietary interests related to ODS, HFCs, or their alternatives: None
 - b. Financial interests related to ODS, HFCs, or their alternatives: None
 - c. Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: See above
 - d. Government advice and other policy development related to ODS, HFCs, or their alternatives: None
 - e. Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: None
 - f. Other interests related to ODS, HFCs, or their alternatives: None
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Karim Amrane
Date: September 6, 2015

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

ENIO PEDONE BANDARRA FILHO
FEDERAL UNIVERSITY OF UBERLANDIA
BRAZIL

I, Enio Pedone Bandarra Filho, residing in Uberlandia - Brazil, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include: I work as an associate Professor of Mechanical Engineering, teaching courses and doing research in the fields of thermal sciences and refrigeration and air conditioning, at Federal University of Uberlandia, in Uberlandia, Minas Gerais, Brazil. As an expert of my institution, I consult for various entities. These include organizations dealing with refrigeration and air conditioning issues, and organizations dealing with Montreal Protocol and UNFCCC related climate issues. All consultancies are conducted on a short-term assignment basis. Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include are related to research in the academy, mainly associated to developments in refrigeration and air conditioning areas with PhD and Masters students.
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: ENIO PEDONE BANDARRA FILHO

Signature: Signature on File

Date : MAY, 20th, 2015

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Jitendra M. Bhambure
Blue Star Limited
2nd Pokhran Road, Majiwada
Thane, Maharashtra, INDIA

I, Jitendra M. Bhambure, residing in Thane, Maharashtra, INDIA, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Understanding of various refrigerants and developing refrigeration and air-conditioning products, as Head of R&D, for Blue Star Limited, INDIA.
 - Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - Research and teaching in the areas of heat transfer and sustainable energy: None
 - Proprietary interests related to ODS, HFCs, or their alternatives: None
 - Financial interests related to ODS, HFCs, or their alternatives: None
 - Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: None, except for holding shares of Blue Star Limited, India
 - Government advice and other policy development related to ODS, HFCs, or their alternatives: Participate in workshops and as ODS Sub-Committee Head of Refrigeration and Air-Conditioning Manufacturers Association of India (RAMA)
 - Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: None
 - Other interests related to ODS, HFCs, or their alternatives: None
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Jitendra M. Bhambure

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Carvalho, Suely M. Machado

I, **Suely M. Machado Carvalho**, residing in São Paulo, SP, Brazil, as a member (co-chair) of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Senior expert UNEP Technology and Economics Assessment Panel, TEAP, in the field of policy, technology and energy efficiency, nominated by Brazil.
 - Participant expert of the Energy Efficiency Partnership programme with the Instituto de Pesquisas Energéticas e Nucleares (IPEN) and the Instituto de Energia e Ambiente, (IEE) of the University of São Paulo. As such, I liaise with organizations dealing with Montreal Protocol and UNFCCC related climate issues, manufacturers of equipment and alternatives to HFCs, NGOs and industry associations.
 - Invited author, LAC Regional Assessment of Short Lived Climate Pollutants (SLCPs), UNEP ROLAC and Climate and Clean Air Coalition to Reduce Short Lived Climate Pollutants, CCAC.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:

Research on energy efficiency improvements, chemicals and policy options to mitigate climate change. None for my spouse and children.

Proprietary interests related to ODS, HFCs, or their alternatives: *None for me nor for spouse and children*

Financial interests related to ODS, HFCs, or their alternatives: *None*

Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: *Short-term consultant for the World Bank (OORG), Institute for Governance and Sustainable Development and UNDP; Co-chair of the International Expert Panel for the High-Ambient Testing Program (pro-bono)*

Government advice and other policy development related to ODS, HFCs, or their alternatives: *eventual and upon request*.

Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: *None currently*.

Other interests related to ODS, HFCs, or their alternatives: *Providing expert advice and leadership to facilitate decision making processes that can help mitigate climate change and protect the ozone layer, and synergies among international agreements.*

- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name and signature:
Suely Maria Machado Carvalho

Date: 12 September 2016

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Ayman El-Talouny
Programme Officer
United Nations Environment Programme, UNEP
Regional Office for West Asia, ROWA
Bahrain

I, Ayman El-Talouny, residing in Manama- Bahrain, as a member of the International Expert Panel for the High Ambient Testing Program, managed by US Departgtement of Energy, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Manage HCFC phase-out programs and projects, in developing countries, within my job responsibilities as UNEP Staff Member
 - Coordinate international partnership and projects between UNEP and several international HVAC&R associations and organizations
 - Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing, trading or servicing any type of refrigerants including HFCs and their substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - My interest is within my job description, as UNEP staff member, by advising governments and supporting industry/private sectors, in developing countries, to implimente projects and manage initiatives to phase-out HCFCs and minmize the use of high-GWP alterantives.
 - Proprietary interests related to ODS, HFCs, or their alternatives: None
 - Financial interests related to ODS, HFCs, or their alternatives: None
 - Pesonally received funds or grants for relevant reserach: None
 - Neither my spouse nor my children has interests in any research, commercial or policy related topic to ODS, HFCs or alterantives.
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change and till the end of the project.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Ayman T El-Talouny
Date: September 19, 2015

Signature: Signature on File

Daniel Giguère*

*Disclosure of Interest for Mr. Daniel Giguère was unavailable at the time of publishing.

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Tingxun Li
Sun Yat Sen University
China

I, Tingxun Li, residing in GUANGZHOU, China, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include: I work as an associate Professor, teaching courses and doing research in the fields of thermal sciences and refrigeration and air conditioning, at Sun Yat Sen University, a comprehensive University in Guangzhou, Guangdong, China. As an expert of China national HPMP of RAC, I consult for various entities. These include organizations dealing with refrigeration and air conditioning issues, and organizations dealing with Montreal Protocol and UNFCCC related climate issues. All consultancies are conducted on a short-term assignment basis. Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - a. Proprietary interests related to ODS, HFCs, or their alternatives: [No]
 - b. Financial interests related to ODS, HFCs, or their alternatives: [No]
 - c. Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: [No]
 - d. Government advice and other policy development related to ODS, HFCs, or their alternatives: [No]
 - e. Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: [No]
 - f. Other interests related to ODS, HFCs, or their alternatives: [No]
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Tingxun Li

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Samuel F Yana Motta
Honeywell International Inc.
USA

I, Samuel F Yana Motta, residing in Buffalo NY, USA, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Director of Technology (refrigerants) for Honeywell International, where I direct R&D activities.
- 2) My interests related to ODS, HFCs, or their alternatives include the following:
 - Research in the areas of heat transfer and development of heat transfer for HVAC applications.
 - Proprietary interests related to ODS, HFCs, or their alternatives: None
 - Financial interests related to ODS, HFCs, or their alternatives: None
 - Other interests related to ODS, HFCs, or their alternatives: None currently
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Samuel F Yana Motta

Date: September 22, 2015

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Maher H. Mousa
Consultant, HVACR Industry and Environmental Policy
The Consultancy Office of Maher H. Mousa
Jeddah, Saudi Arabia

I, Maher H. Mousa, located in Jeddah, Saudi Arabia, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Consultancy, HVAC Product development, program management, testing laboratories, technology transfer and energy and environmental regulations, under my private consultancy office located in Jeddah, Saudi Arabia.
 - Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - Consultancy, to private and public sectors on short tasks bases.
 - Business research for my MBA degree at University of Leicester, UK.
 - Proprietary interests related to ODS, HFCs, or their alternatives: None
 - Financial interests related to ODS, HFCs, or their alternatives: None
 - Employment, directorship, or other positions related to ODS, HFCs, or their alternatives: None
 - Government advice and other policy development related to ODS, HFCs, or their alternatives: technical advisory in my capacity as a consultant, on short tasks bases
 - Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: None currently
 - Other interests related to ODS, HFCs, or their alternatives: None currently
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Maher H Mousa

Signature: Signature on File

**Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program**

Ole Reinholdt Nielsen
United Nations Industrial Development Organization, UNIDO
Austria

I, Ole Reinholdt Nielsen, residing in Vienna, Austria, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include: I work as Chief of the Montreal Protocol Unit within the Environmental Branch of UNIDO. The overall objective of the work is to assist developing countries – at their request - in meeting their obligations within the framework of the Montreal Protocol on Substances that Deplete the Ozone Layer. The assistance comprise: a) Support in drafting a country strategy to phase-out ODS as per Montreal Protocol schedule; including necessary policy requirements; institutional activities and investment components; b) Ensure funding for the before-mentioned strategy from the Multilateral Fund of the Montreal Protocol; and c) implement the before-mentioned strategy in accordance with the agreed schedule of activities. All advices given are based on Montreal Protocol eligibility and modus operandi; and are fully neutral towards specific substances, processes and equipment.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - a. Proprietary interests related to ODS, HFCs, or their alternatives: Neither I, nor my spouse or my children have proprietary interests related to ODS, HFCs or their alternatives.
 - b. Financial interests related to ODS, HFCs, or their alternatives: Neither I, nor my spouse or my children have financial interests related to ODS, HFCs or their alternatives.
 - c. Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: In addition to what has been specified under paragraph 1) above; neither I, nor my spouse or my children have employment, consultancy, directorship, or other positions related to ODS, HFCs or their alternatives.
 - d. Government advice and other policy development related to ODS, HFCs, or their alternatives: In addition to what has been specified under paragraph 1) above; neither I, nor my spouse or my children provide government advices and other policy development activities related to ODS, HFCs or their alternatives.
 - e. Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: Neither I, nor my spouse or my children have paid research activities, fellowships, or grants related to ODS, HFCs or their alternatives.
 - f. Other interests related to ODS, HFCs, or their alternatives: Neither I, nor my spouse or my children have other interests related to ODS, HFCs or their alternatives.

- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Ole Reinholdt Nielsen

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Tetsuji Okada
Japan Refrigeration and Air conditioning Industry Association
Japan

I, Tetsuji Okada, residing in Tokyo, Japan, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include: I work as the president of JRAIA, managing the development or research of the equipment or refrigerants. I have been a member of the UNEP RTOC from 2013. I have engaged in the research and development of the air conditioners and the hot water systems by CO2 (Eco cute). I am also familiar with the heat exchangers used in the air conditioners and the refrigerant circuits of the heat pump systems. Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - a. Proprietary interests related to ODS, HFCs, or their alternatives: [None]
 - b. Financial interests related to ODS, HFCs, or their alternatives: [None]
 - c. Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: [described in number 1 above]
 - d. Government advice and other policy development related to ODS, HFCs, or their alternatives: [None]
 - e. Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: [None]
 - f. Other interests related to ODS, HFCs, or their alternatives: [None]
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name:
Tetsuji Okada

Signature: Signature on File

Disclosure of Interest Declaration

International Expert Panel for the High-Ambient Testing Program

Dr M. Alaa Olama
Independent consultant
Egypt.

I, Dr Olama, residing in Cairo, Egypt, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
- 2) I work as an independent Refrigeration and Air Conditioning Consultant, providing consultancy services in the fields of refrigeration and air conditioning and thermal sciences. As an expert I consult for various entities. These include organizations dealing with refrigeration and air conditioning issues, and organizations dealing with Montreal Protocol and UNFCCC related climate issues. All consultancies are conducted on a short-term assignment basis. Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 3) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
None.
- 4) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 5) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 6) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Dr M. Alaa A. Olama

Signature: Signature on File

Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program

Alessandro Giuliano Peru
Department of Environment
CUEIM (University Consortium for Industrial Economy and Management)
Rome
ITALY

I, Alessandro Giuliano Peru, residing in Rome, ITALY, as a member of the International Expert Panel for the High Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Programme manager for several publications and papers in relation to the management of chemical substances, including those who harm the climate change and deplete the ozone layer. Past President of the EU Italian Presidency of the International Ozone group and Senior Environmental Expert for the Italian Ministry of the Environment, Land and the Sea.
 - Member of the European Association for the refrigeration and air conditioning (AREA)
 - Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - Proprietary interests related to ODS, HFCs, or their alternatives: None
 - Financial interests related to ODS, HFCs, or their alternatives: None
 - Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: None
 - Government advice and other policy development related to ODS, HFCs, or their alternatives: yes
 - Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: None currently
 - Other interests related to ODS, HFCs, or their alternatives: None currently
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than one year after I have signed it.

Printed Name: Alessandro Giuliano Peru

Date: May 16, 2015

Signature: Signature on File

**Disclosure of Interest Declaration
International Expert Panel for the High-Ambient Testing Program**

Patrick E. Phelan
Arizona State University, School for Engineering of Matter, Transport & Energy
USA

I, Patrick E. Phelan, residing in Scottsdale, Arizona, USA, as a member (co-chair) of the International Expert Panel (co-chair) for the High-Ambient Testing Program, declare as follows:

- 1) That my responsibilities related to ODS, HFCs, or their alternatives include:
 - Professor of Mechanical & Aerospace Engineering, and Senior Sustainability Scientist, Arizona State University, where I conduct research and teach in areas of heat transfer and sustainable energy
 - Neither I, nor my spouse or my children own stock or have proprietary interest in companies producing HFCs or their alternatives or substitutes.
- 2) My interests and those of my spouse or children related to ODS, HFCs, or their alternatives include the following:
 - Research and teaching in the areas of heat transfer and sustainable energy; my spouse has research interests in urban heat island and its impacts on economics and public health; none for my children
 - Proprietary interests related to ODS, HFCs, or their alternatives: None
 - Financial interests related to ODS, HFCs, or their alternatives: None
 - Employment, consultancy, directorship, or other positions related to ODS, HFCs, or their alternatives: None
 - Government advice and other policy development related to ODS, HFCs, or their alternatives: Currently none, but I previously served as the Emerging Technologies Manager for the US Department of Energy, Building Technologies Office
 - Paid research activities, fellowships, or grants related to ODS, HFCs, or their alternatives: None currently
 - Other interests related to ODS, HFCs, or their alternatives: None currently
- 3) I undertake to disclose any material change to any of the above information, within 30 days of any such change.
- 4) I undertake to make further declarations of interest needed for so long as I remain a member of this Panel.
- 5) I understand that this Disclosure of Interest will expire no later than 1 year after I have signed it.

Printed Name: Patrick E. Phelan
Date: August 10, 2016

Signature: Signature on File