Annex IV

DEMONSTRATION PROJECT TO DEVELOP WINDOW AND PACKAGED AIR-CONDITIONERS USING LOWER-GWP REFRIGERANT IN SAUDI ARABIA

FINAL REPORT

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Executive Summary

This demonstration project was conducted in response to decision 76/26 of the Executive Committee of the Multilateral Fund (May 2016 meeting), asking for the development of window and packaged air-conditioners in Saudi Arabia using alternative refrigerants with lower global warming potential (GWP). The Multilateral Fund allocated US $796,400 to two companies: Saudi Factory for Electrical Appliances Co. Ltd. would develop window AC prototypes while PETRA Engineering Industries (KSA) Co., Ltd would develop packaged air-conditioners. The window AC component was later withdrawn from the project after approval.

The project was carried out at PETRA Engineering Industries Company Saudi Arabia and consisted of designing, manufacturing and testing commercial air-cooled chillers using low GWP refrigerants R-32 and R-290. A total of six units were built (3 for R-290 and 3 for R-32) with cooling capacities of 40 kW, 70 kW and 100 kW. The design of the products was in accordance with the safety requirements of ISO-5149 and IEC-60335-2-40, given that both R-32 and R-290 are flammable refrigerants.

The air-cooled chillers were tested at a standard ambient condition of 35ºC as well as at high ambient temperatures of 46ºC and 52ºC. Results were compared to the baseline refrigerant R-410A, which for this project was tested as a drop-in to R-32. In all cases, both R-32 and R-290 units showed similar or better performance (efficiency and cooling capacity) than R-410A. However, design changes necessary to mitigate the risk of using R-290 (highly flammable refrigerant) resulted in a significant increase in the cost of the chillers. The cost increase was minimal in the case of the mildly flammable refrigerant R-32.

The project demonstrated that commercial air-cooled chillers can be successfully designed and operated with low GWP alternative refrigerants such as R-32 and R-290 for a variety of cooling capacities and operating conditions (including high ambient temperatures). Requirements of current international safety standards did not limit the amount of flammable refrigerants used for this particular project because of the specific application and location of the chillers. However, it should be noted that in most commercial applications, the use of highly flammable refrigerants such as R-290 is severely restricted by current safety standards, which is not the case for mildly flammable refrigerants like R-32.

It is believed that findings from this project will help developing countries with high ambient temperature conditions accelerate their adoption and implementation of the Kigali Amendment.

I. Introduction

In 2007, the Parties to the Montreal Protocol agreed to accelerate the phase-out schedule for hydrocholorofluorocarbons (HCFCs) in developing countries. More specifically, the Parties agreed to a freeze consumption in 2013 (based on average consumption of 2009-2010) followed by reductions of the baseline by 10%, 35%, 67.5% and 97.5% for years 2015, 2020, 2025 and 2030 respectively allowing 2.5% to continue during the period 2030 - 2040 as a service tail and a complete phase out by 2040.

The Article 5 parties, especially those in high-ambient conditions, face serious challenges in finding out suitable lower-GWP alternatives to replace HCFC-22 in air-conditioning applications while maintaining minimum energy performance standards. Although the Executive Committee has funded demonstration project to promote low-GWP alternatives for the A/C industry in high-ambient countries, there are gaps in testing lower-GWP refrigerants: R-32 and R-290 in window and packaged air-conditioners.

To address this gap, the Executive Committee of the Multilateral Fund (MLF)[1] at its 76th meeting in May 2016 approved a demonstration project in Saudi Arabia to develop window and packaged air-conditioners using low GWP alternative refrigerants. The MLF allocated US $796,400, plus agency support costs of US $55,748 for the World Bank. Funding from the Multilateral Fund has been specifically allocated to the two air-conditioning manufacturers in Saudi Arabia. Saudi Factory for Electrical Appliances Co. Ltd. would develop window AC prototypes while PETRA Engineering Industries (KSA) Co., Ltd would develop packaged air-conditioners.

After the approval of the project, Saudi Factory for Electrical Appliances Co. Ltd. did not participate in the development of window AC prototypes without providing any official explanation. The fund[2] related to the development cost of window AC prototypes has been returned to MLF at the 82nd meeting. The development of window AC using lower GWP refrigerant is expected to be covered by one of AC manufacturers as indicated by UNIDO at the 76th meeting.

PETRA Engineering Industries Company Saudi Arabia (hereinafter referred to as “PETRA”) confirmed its commitment to develop the packaged air-conditioners.

Objectives

The main objective of the demonstration project was to design, develop and test the performance of air-cooled chillers (integrated chiller and air-handling unit) using low GWP refrigerants R-32 and R-290 at 3 cooling capacities: 40 kW, 70kW, and 100 kW.

Both R-32 and R-290 are environmentally friendly refrigerants, with zero ozone depletion potential (ODP) and low GWP. Both refrigerants have excellent thermophysical properties and are considered good alternatives to R-410A (and R-22). However, both are flammable and

[1] Decision 76/26, May 24, 2016

[2] US $220,000 plus agency support costs of US $15,400

necessitate design modifications of the baseline R-410A product. Some properties of R-32, R-290 and R-410A are summarized in Table 1 below.

In order to achieve the project's objectives, PETRA conducted the following tasks:

- Review R-32 and R-290 refrigerant properties.
- Integrate the refrigerant properties in the design software simulation model.
- Use the software simulation model to design the evaporator and condenser coils including circuiting, number of rows, tube diameters and fin spacing.
- Validate the simulation results through actual tests, before producing the prototypes.
- Select the main components (evaporator, condenser, fans and compressor) to achieve similar or better performance than the baseline R-410A unit. The design took into account specific characteristics of each refrigerant such as higher operating pressures and discharge temperatures of R-32.
- Address safety measures by considering the risk associated with the flammability of both R-32 (mildly flammable) and R-290 (highly flammable). The design of the units was consistent with the requirements of ISO-5149 for refrigerant quantities and IEC-60335-2-40 for electrical components and markings.

Table 1: Properties of R-32, R-290 and R-410A

Parameters	**R-32**	**R-290**	**R-410A**
Chemical name	Difluoromethane	Propane	-
Chemical formula or mass composition	CH_2F_2	$CH_3CH_2CH_3$	R-32/R-125 (50%/50%)
Safety group (ASHRAE 34)	A2L	A3	A1
Lower Flammability Limit (Kg/m^3)	0.307	0.038	-
Boiling point (^oC)	-51.65	-42.11	-51.44
Critical Temperature (^oC)	78.11	96.74	71.36
ODP	0	0	0
GWP $_{(AR4)}$	675	3	2,088

In total, six prototype units were manufactured: three with R-32 (at cooling capacities of 40 kW, 70 kW and 100 kW), and three with R-290. The units were tested at a standard ambient condition of 35^{o}C as well as at high ambient temperatures of 46^{o}C and 52^{o}C. The results were compared to the baseline R-410A which was tested as a drop-in refrigerant to R-32.

II. Project Implementation

The project consisted of three phases: (1) software development; (2) design and fabrication of the prototypes; and (3) testing.

1. Software Development

New software was developed to simulate the performance of the R-32 and R-290 units. PETRA developed the software in 6 different stages as described below:

a. **Data acquisition** – This stage consisted of acquiring scientific information by reviewing the latest scientific research papers, case studies, etc.
b. **Design** – This is the most critical stage where the evaporator and condenser heat exchanger models are developed. The system's coefficient of performance can be evaluated as a function of the heat exchanger design and various two-phase flow heat transfer and pressure drop for both R-32 and R-290 are investigated.
c. **Implementation** – After the completion of the design phase, the algorithms are developed and translated into programming code language.
d. **Testing** – This is a critical stage in the software development stage. The software is tested to assess if it meets its intended purpose and does what it is supposed to do. Errors are identified and corrected until the software is ready for operational use.
e. **Deployment** – After completing the testing phase, the software is deployed to the technical/application team where it is used by engineers to design products. Any problem when operating the software is recorded and passed on to the support and maintenance team for appropriate action.
f. **Support and Maintenance** – This is the last stage in the life cycle process where modifications are made to the software to correct faults, improve performance or adapt the software to a modified environment.

Finally, the software makes use of a user-friendly interface as shown in Figure 1.

2. Design and Manufacturing of Prototypes

The design of the prototype units presented unique challenges as both R-32 and R-290 are flammable refrigerants. According to ASHRAE 34 [1] or ISO 817 [2], the group safety classification for R-32 is A2L, where "A" stands for lower toxicity and "2L" for lower flammability (i.e. refrigerants with a burning velocity less or equal than 10 cm/s). On the other hand, R-290 has a safety classification A3, where "3" stands for higher flammability.

Several safety features had to be taken into consideration to limit the risk of using flammable refrigerants as described below.

ISO 5149

First, the refrigerant quantities used in the chillers had to be consistent with the requirements of ISO 5149 [3]. This refrigerant charge limit depends on the type of occupancy where the chillers will be installed (i.e. general, supervised or authorized occupancy), the safety classification of the refrigerant, the air conditioning system classification (direct, indirect etc.) and where the refrigerant containing components (i.e. compressors, heat exchangers etc.) are located (outdoor, mechanical room etc.).

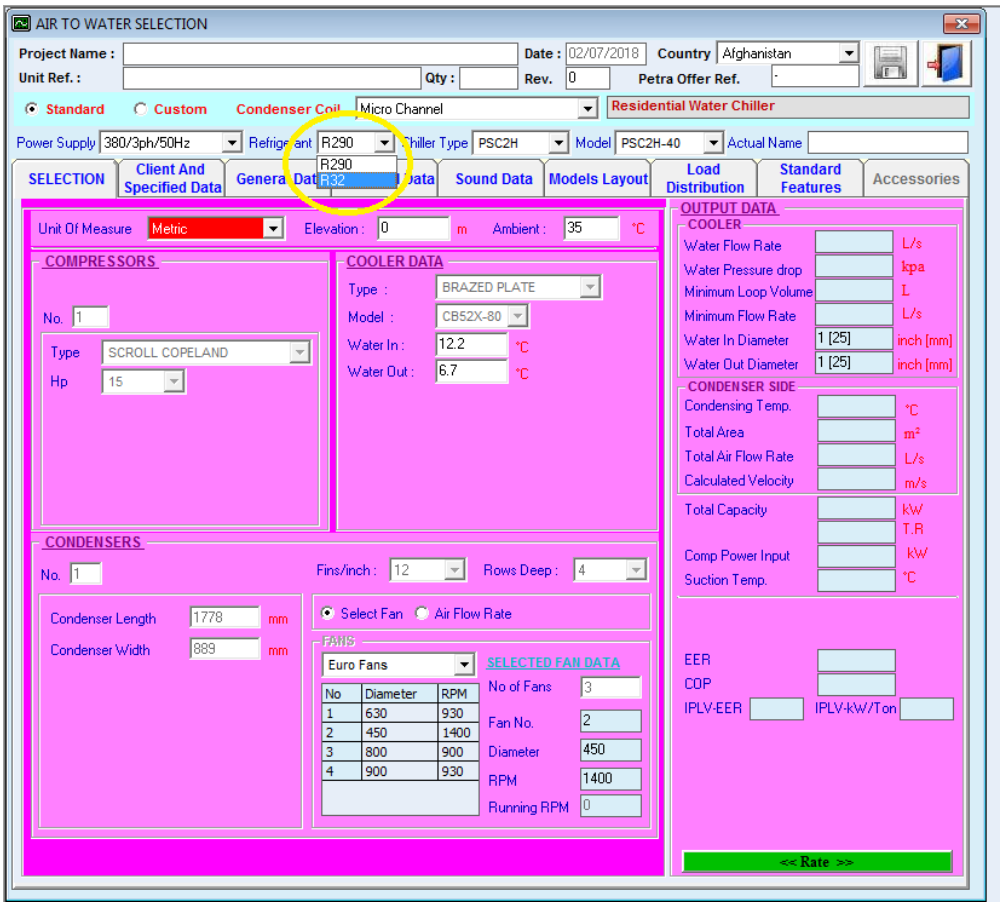

Figure 1: Software User Interface

During product development and testing, the air-cooled chillers were located in PETRA's manufacturing facility (i.e. authorized occupancy). Consequently, according to ISO 5149 there were no refrigerant charge restrictions for both R-32 and R-290. However, had the intended use of the chillers be for general occupancies (such as hospitals, schools etc.), or supervised occupancies (such as office buildings etc.), the amount of flammable refrigerant would have been severely restricted for R-290 because of its highly flammable classification (i.e. "3"), to a point where the chillers would not be able to operate properly.

Based on ISO 5149 and refrigerant charges ranging from 4 – 5.5 kg per circuit (Table 4), the R-290 air-cooled chiller could be used for applications other than human comfort in supervised or authorized occupancies and when the equipment is located in an above ground machinery room. If the charge could be reduced to less than 5 kg per refrigeration circuit, they could be also used in all occupancy categories if the equipment is located in open air such as on the roof top.

On the other hand, the charge limit restriction would have been less constraining for R-32 because of its mildly flammable classification (i.e. "2L"). The following tables show possible applications for each occupancy category and location classification.

Table 2: Possible Applications of R-290 Prototypes

Occupancy category			**Location classification**			
			I[3]	**II**[4]	**III**[5]	**IV**[6]
General occupancy "a": hotels, schools, restaurant	Human comfort		No (charge > 1 kg)		No[7]	Yes[8] (charge < 5 kg)
	Other applications	Below ground	No (charge > 1 kg)		No (charge > 1 kg)	
		Above ground	No (charge > 1.5 kg)		Yes[8] (charge < 5 kg)	
Supervised occupancy "b": Offices	Human comfort		No (charge > 1 kg)		No[9]	
	Other applications	Below ground	No (charge > 1.5 kg)		No (charge > 1 kg)	
		Above ground	No (charge > 2.5 kg)		Yes (charge < 10 kg)	
Authorized occupancy "c": manufacturing facilities	Human comfort		No (charge > 1 kg)		Yes[10]	
	Other applications	Below ground	No (charge > 1.5 kg)		No (charge > 1 kg)	
		Above ground	Yes[11] (charge < 10 kg)	Yes[11] (charge < 25 kg)	Yes (no charge restriction)	

Table 3: Possible Applications of R-32 Prototypes

Occupancy category		**Location classification**			
		I	**II**	**III**	**IV**
General occupancy "a": hotels, schools, restaurant	Human comfort	Yes[12] (charge < 12 kg)		Yes (no charge restriction)	Yes (charge < 60 kg)
	Other applications	Yes[13] (charge < 12 kg)			
Supervised occupancy "b": Offices	Human comfort	Yes[12] (charge < 12 kg)			
	Other applications	Yes[13] (charge < 12 kg)	Yes[13] (charge < 25 kg)		
Authorized occupancy "c": manufacturing facilities	Human comfort	Yes[12] (charge < 12 kg)			
	Other applications	Yes[13] (charge < 12 kg)	Yes[13] (charge < 25 kg)		

[3] The refrigerating system or refrigerant-containing parts are located in the occupied space
[4] All compressors and pressure vessels are either located in a machinery room or in the open air; coil-type heat exchangers and pipework, including valves, can be located in an occupied space
[5] All refrigerant-containing parts are located in a machinery room or open air
[6] All refrigerant-containing parts are located in the ventilated enclosures
[7] In accordance with occupancy "a" other applications
[8] Only for 40 kW and 70 kW unit with charge not more than 5 kg
[9] In accordance with occupancy "b" other applications
[10] In accordance with occupancy "c" other applications
[11] Room volume larger than 526 m^3 for 70 kW unit, 658 m^3 for 40 kW unit, and 724 m^3 for 100 kW unit
[12] Floor area larger than 19 m^2 for 70 kW unit, 29 m^2 for 40 kW unit, and 34m^2 for 100 kW unit and height of supply vent at 1.8m
[13] Room volume larger than 73 m^3 for 70 kW unit, 90 m^3 for 40 kW unit, and 97 m^3 for 100 kW unit

Occupancy category		Location classification			
		I	II	III	IV
	< 1 person per 10 m²	Yes[13] (charge < 50 kg)	Yes (no charge restriction)		

Tables 2 and 3 show possible applications of R-290 and R-32 that are germane to the chillers designed for this project. As such, the tables should not be viewed as universally applicable. Designers should always refer to ISO 5149 to ensure compliance with safety requirements.

IEC 60335-2-40

The prototype units were also designed to comply with the marking requirements of IEC 60335-2-40 [4]. These requirements are necessary to warn about the flammability hazard of both R-32 and R-290.

It should be noted that IEC 60335-2-40-2018 has also requirements on refrigerant charge limits, which in some instances may be different than the requirements of ISO 5149. However, given that the IEC standard was published in the first quarter of 2018 when the preliminary design of the units was well underway and almost complete, it was decided to stick with the refrigerant charge limit requirements of ISO 5149 instead.

Prototype Unit Design

A schematic of the 100 kW air-cooled chiller is shown in Figures 2 (general view) and 3 (top and side views). Both R-32 and R-290 units are the same except that scroll compressors were used for R-32 while semi-hermetic compressors were used for R-290 as scroll compressors were not yet available for this refrigerant. All components selected (expansion valves, solenoid valves etc.) were compatible with both R-32 and R-290.

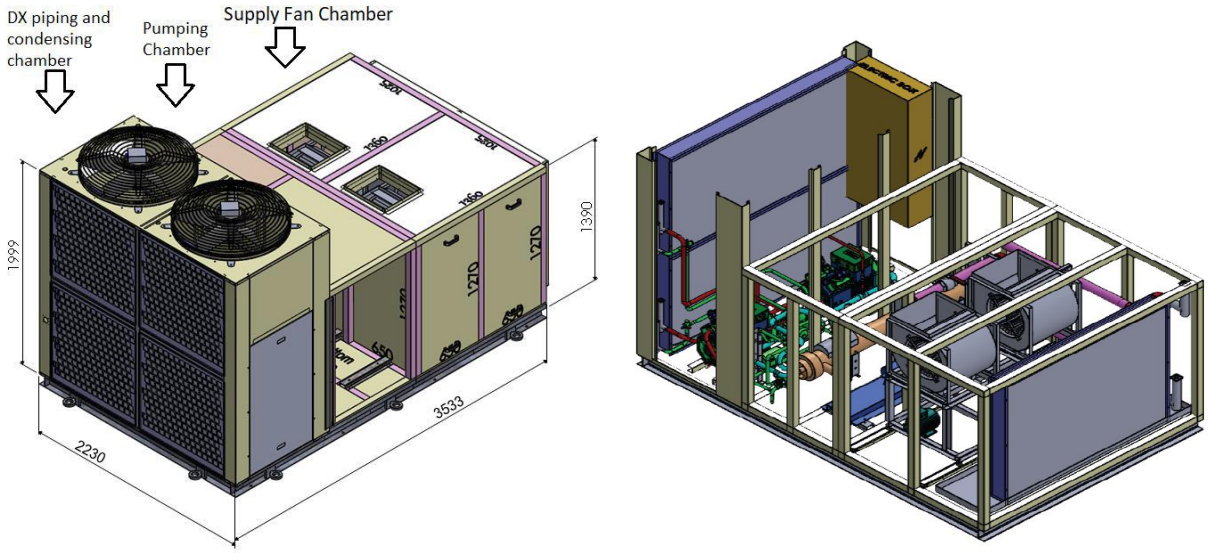

Figure 2: Schematic of 100 kW Prototype Air-Cooled Chiller

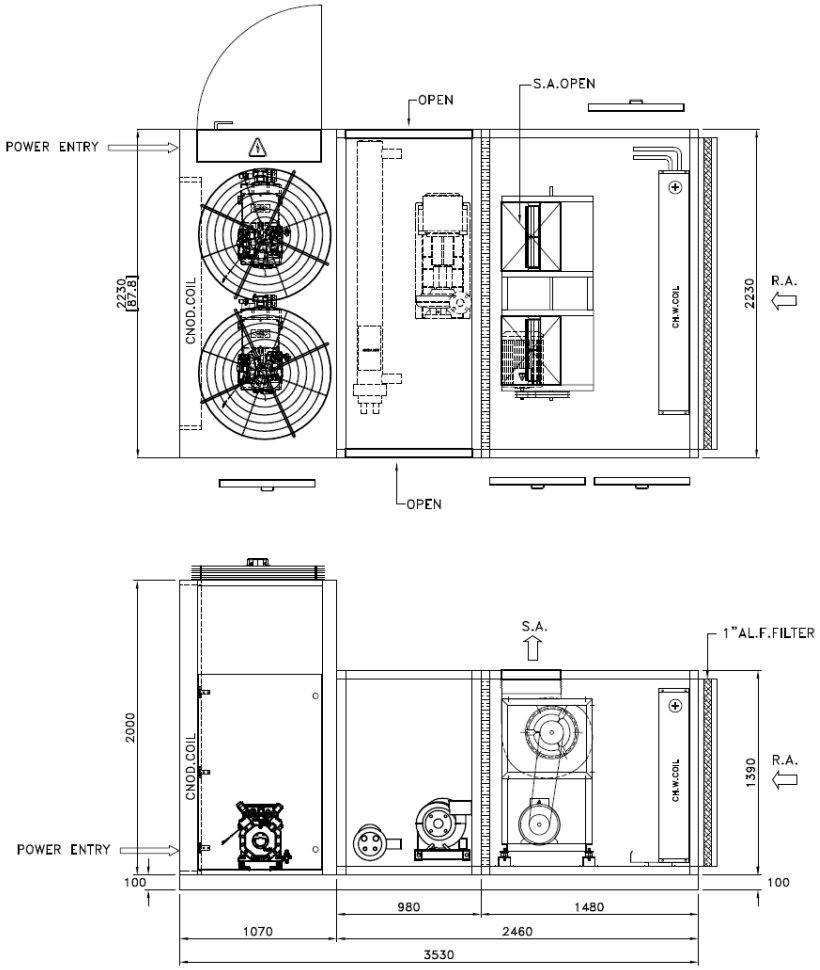

Figure 3: Top and Side Views of 100 kW Prototype Air-Cooled Chiller

As can be seen in the figures, the prototype units are of a hybrid design where the air-cooled chiller is connected with the air handlers in the same cabinet. By using an air-cooled chiller to generate chilled water and circulate it to the air handling unit via a water pump, any refrigerant leakage will be contained in the shell and tube heat exchanger and/or the finned tube cooling coil in the air handling unit so the main supply air stream will be safe from any flammable refrigerant leakage. Furthermore, PETRA separated the compressor and condenser in one chamber and shell and tube heat exchanger in another chamber to further minimize gas leakage to the air handling unit.

A schematic of the 70 kW air-cooled chiller is shown in Figures 4 (general view) and 5 (top and side views). The 40 kW units have the same dimensions but are equipped with only one compressor.

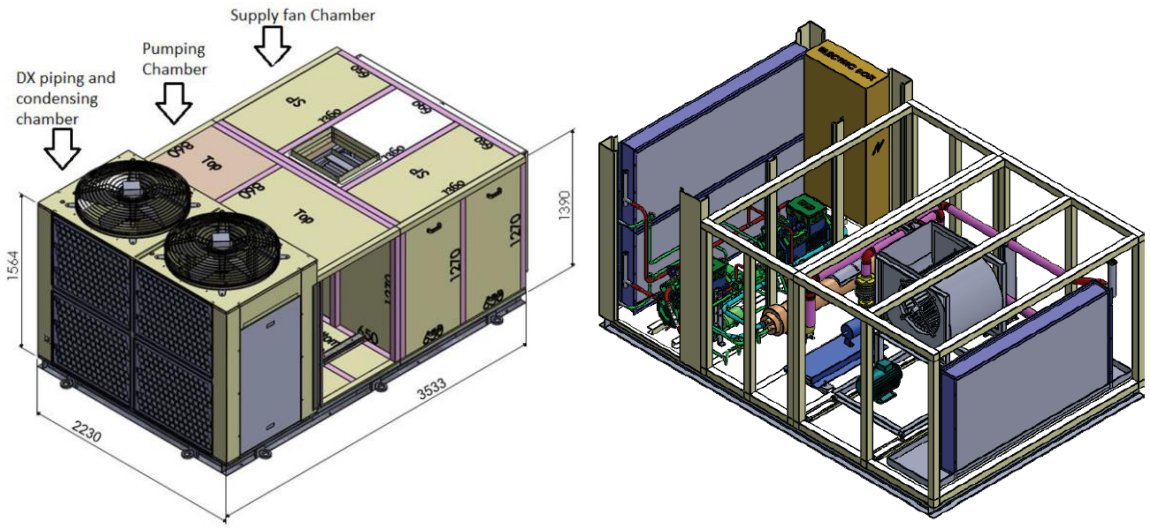

Figure 4: Schematic of 70 kW Prototype Air-Cooled Chiller

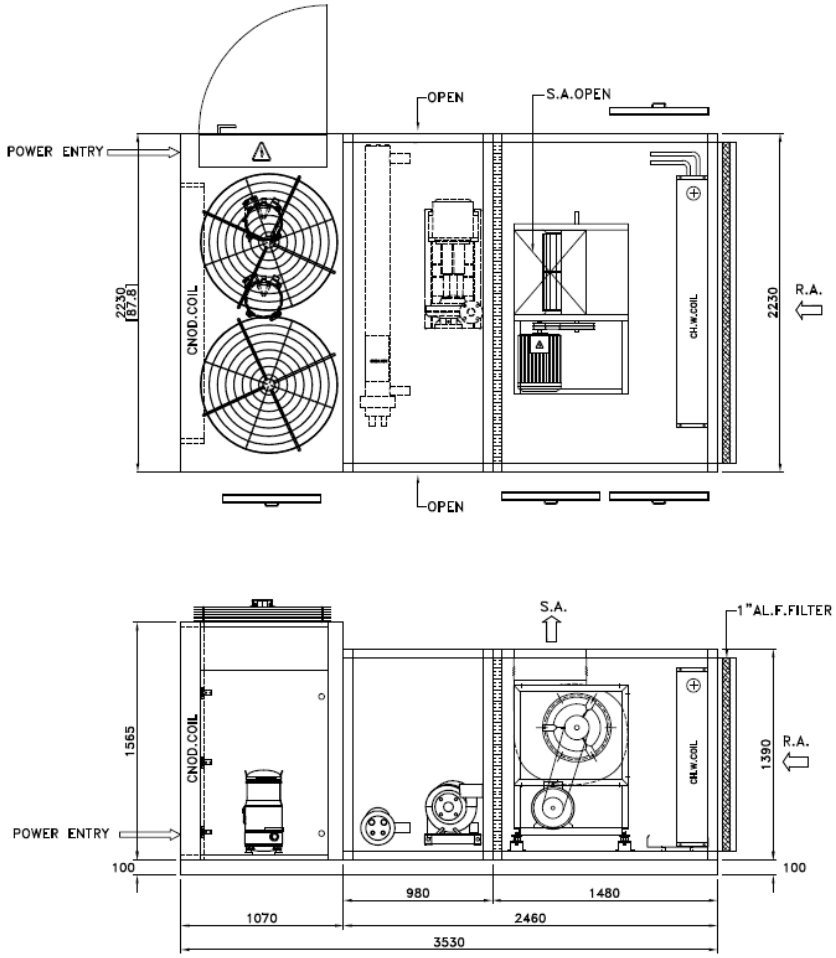

Figure 5: Top and Side Views of 70 kW Prototype Air-Cooled Chiller

Specific Design Features for Flammable Refrigerants

DX piping and condensing chamber

- Reduce number of junction boxes inside the chamber to reduce ignition source.
- Reduce number of welding joints as much as possible to prevent leakage.
- Use of automatic shut-off valves (liquid solenoid valves) to isolate parts of the refrigeration circuit when a leak occurs.
- Use of more than one independent refrigerant circuit on high capacity units to reduce refrigerant losses in case of a major leak.
- For R-290 units, installation of leak detector sensors to detect, in the event of a leak, the concentration of flammable refrigerants and immediately shut off the unit while operating the axial fans only to move the refrigerant out of the unit.

Electrical enclosure

- The electrical enclosure is located on the opposite end of the welding joints of the condenser
- NEMA 4X electrical enclosure is used to provide a degree of protection to unauthorized access and a degree of protection of the equipment inside the enclosure against ingress of solid foreign objects.
- Installation of air flow switches insider the electrical panel to ensure that the panel always has a positive pressure.
- Emergency push button switch on the electrical panel door to immediate disconnect the power.
- Electrical conduits sealed with silicone to prevent flammable refrigerant to enter the enclosure in case of leakage.
- For the location classification and requirement according ATEX such as Class 1, Division 1, Group A, B, C, or D as defined in NFPA 70, the prototype can be fitted with NEMA 7 enclosure.

Other Design Features

- Electrical safety capsule on both discharge and suctions side of the compressor to protect the compressor and refrigeration system from unsafe high and low pressure conditions. A pressure relief valve is installed as mechanical protection to control high excessive pressure as additional protection to electrical mechanical capsule. This is particularly important for high ambient temperature countries like Saudi Arabia.

Finally, all prototype units were designed to meet the minimum energy efficiency standards currently in place in Saudi Arabia [5].

Prototype Units

Petra manufactured 6 prototype units, 3 units using R-32 at cooling capacities of 40 kW, 70 kW and 100 kW, and 3 other units using R-290 (same cooling capacities), some are shown in the following figures.

Figure 6: Prototypes

Figure 7: R-32 Prototype with Markings

Figure 8: R-32 Unit with Scroll Compressor

Figure 9: R-290 Unit with Semi-Hermetic Compressor

Figure 10: R-290 Leak Sensor

Figure 11: NEMA 7 Electrical Panel Upgrade

Refrigerant Charge Amounts

Each prototype unit was charged with the amount of refrigerant needed to achieve suitable superheat and sub-cooling temperatures. Table 4 shows the refrigerant charge amounts for each unit including the baseline R-410A.

Table 4: Total Refrigerant Charge Amounts (kg) per Unit

Capacity	No. of refrigeration circuit	R-410A	R-32	R-290
100 kW	2	16	12	11
70 kW	2	12	9	8
40 kW	1	6.5	5.5	5

3. Testing

After completing the production of the six prototype units, they were installed and tested one by one in PETRA's testing facility. PETRA's testing facility has a total area of more than 840 m^2 and is fully equipped to accurately test the units according to AHRI and ASHRAE industry standards. The facility has a thermal room capable of testing air-cooled chillers at various water flow rates and ambient temperatures. The facility has also a sound room equipped with instruments capable of measuring sound pressure levels.

Test Procedure

The test setup was prepared according to AHRI 550/590 [6] as shown in Figure 12, with air flow measurement station to measure air flow rate and air sampler tree to measure ambient, return and supply air dry and wet bulb temperatures.

Figure 12: Unit Test Setup

The tests involved measurements of net capacity (kW or Btu/h) and efficiency (COP in W/W or EER in Btu/W.h) when operating under specified design conditions according to AHRI 550/590, and were carried out under steady state conditions within the tolerances specified in the procedure.

All tests were conducted in the calorimeter laboratory to enable ambient and return air temperatures at conditions shown in Table 5 below.

Table 5: Testing Temperature Conditions (^{o}C)

Rating conditions	Indoor section		Outdoor section	
	Dry Bulb	Wet Bulb	Dry Bulb	Wet Bulb
T_1	27.0	19.0	35.0	24.0
T_3	29.0	19.0	46.0	24.0
T_3^+	29.0	19.0	52.0	24.0

Laboratory Modifications for Flammable Refrigerants

PETRA made minor modifications to its laboratory to safely handle and test flammable refrigerants. More specifically, PETRA added an alarm panel to detect R-290 (Figure 13) and control the exhaust fan in case the concentration of the refrigerant in the laboratory suddenly increases.

Figure 13: Control Alarm Panel and R-290 Sensors

III. Performance Results

Figure 14 to Figure 16 show variations in Energy Efficiency Ratio (EER) and cooling capacity for the 40 kW, 70 kW and 100 kW prototypes for refrigerants R-290, R-32 and R-410A at three ambient temperatures of 35°C, 46°C and 52°C.

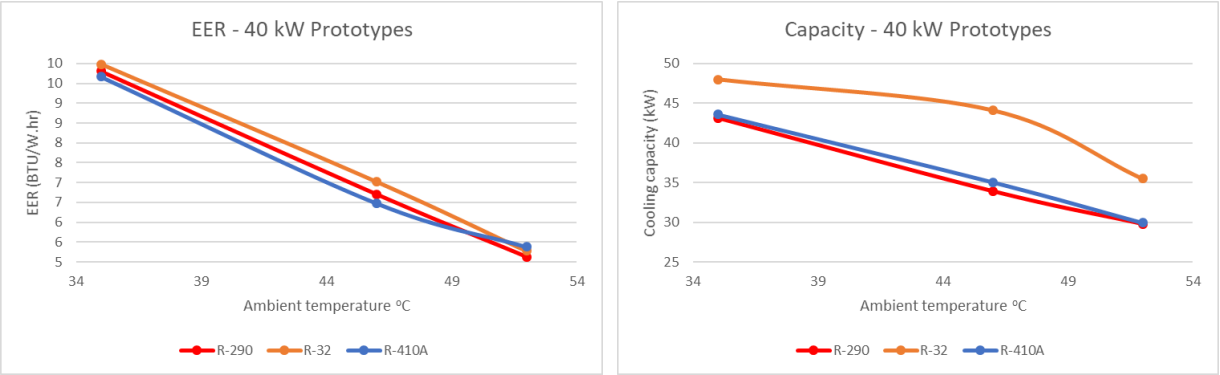

Figure 14: EER and Cooling Capacity at Various Ambient Temperatures – 40 kW Prototypes

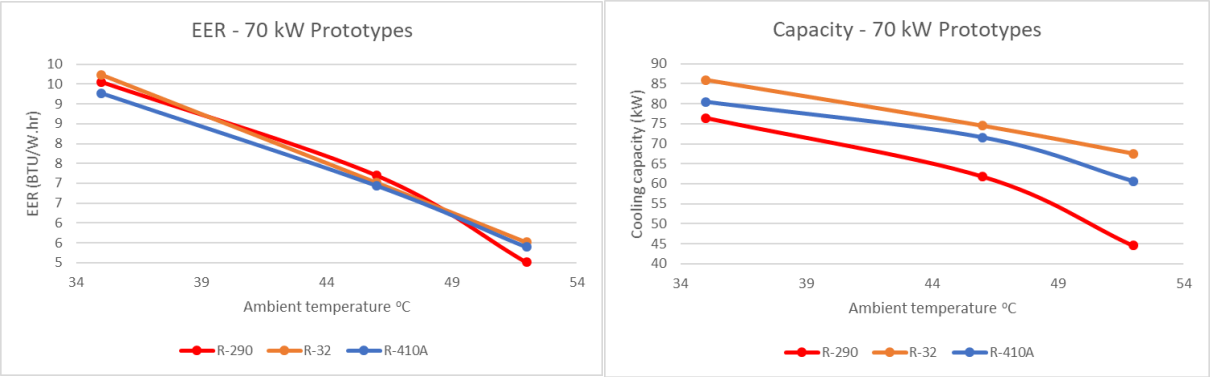

Figure 15: EER and Cooling Capacity at Various Ambient Temperatures – 70 kW Prototypes

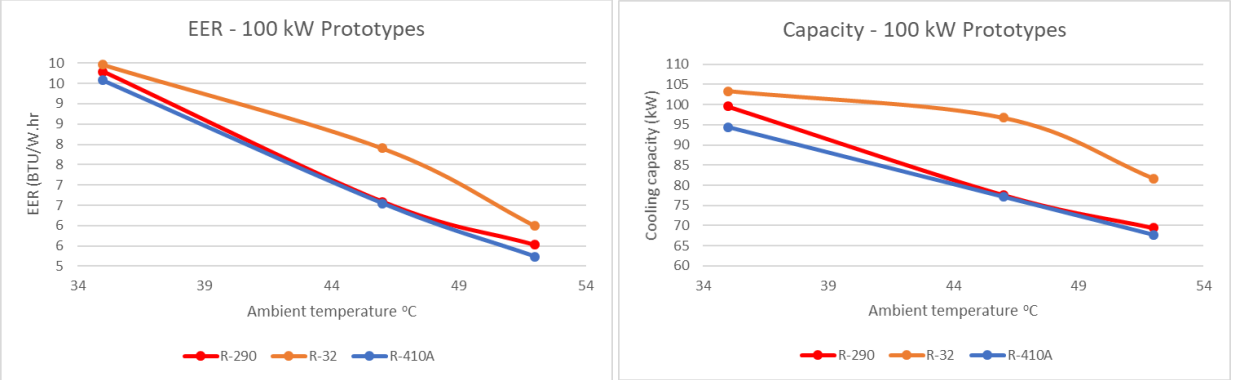

Figure 16: EER and Cooling Capacity at Various Ambient Temperatures – 100 kW Prototypes

As expected, all refrigerants experienced degradation in Energy Efficiency Ratio (EER) and cooling capacity when the ambient temperature increases. When comparing EER, both R-32 and R-290 had slightly better performance than the baseline R-410A at T1 and T3 condition but R-32 EER is lower than R-290 and R-410A at 52°C condition. The only exception is the 100 kW prototype where R-32 has better EER than both R-290 and R-410A at all testing conditions. In terms of cooling capacity, all R-32 prototypes have higher capacity than both R-290 and R-410A at each testing conditions. Comparing cooling capacity of R-410A and R-290 prototypes, the 40 kW and 100 kW have similar cooling capacity while the 70 kW R-410A has higher capacity than R-290 prototype. It should be noted that the performance of R-290 could be attributed to the semi-hermetic compressors which, in general, are less efficient than the scroll compressors used with R-32 and R-410A.

Figures 17, 18 and 19 illustrate the low GWP refrigerants' relative performance to the baseline R-410A for the 100 kW prototypes at the ambient temperatures of 35°C, 46ºC and 52ºC respectively. These figures give a better visualization of the performance of R-32 and R-290 relative to the baseline R-410A. Results in the upper right quadrant of the chart indicate a better efficiency and a better cooling capacity than R-410A. As can be seen from the figures, R-32 experienced a higher capacity and efficiency than R-410A for all three ambient temperatures. On the other hand, the R-290 prototype's performance was very similar to R-410A. As mentioned before, with better compressors, R-290 would have performed better. It should be stressed again that R-410A was tested as a drop in to R-32 and that the unit was not optimized for that refrigerant. Detailed test reports are included in Appendix A.

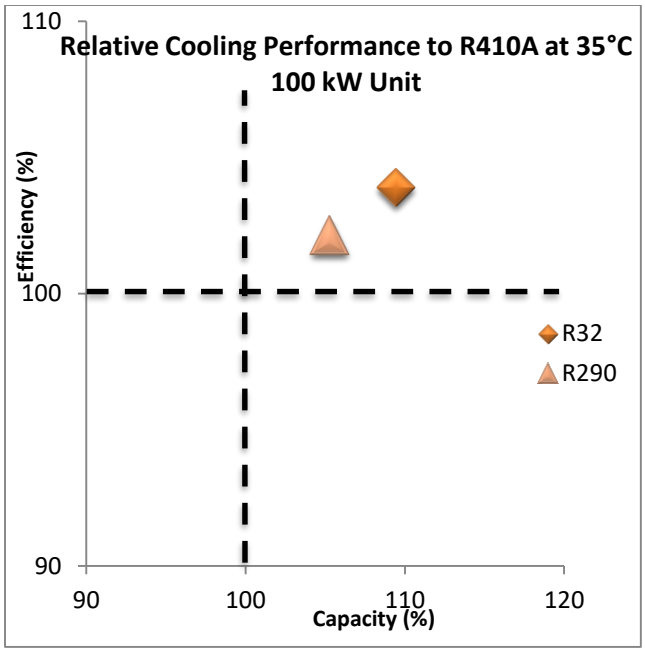

Figure 17: Low GWP refrigerants relative performance to R-410A at 35°C – 100 kW Prototypes

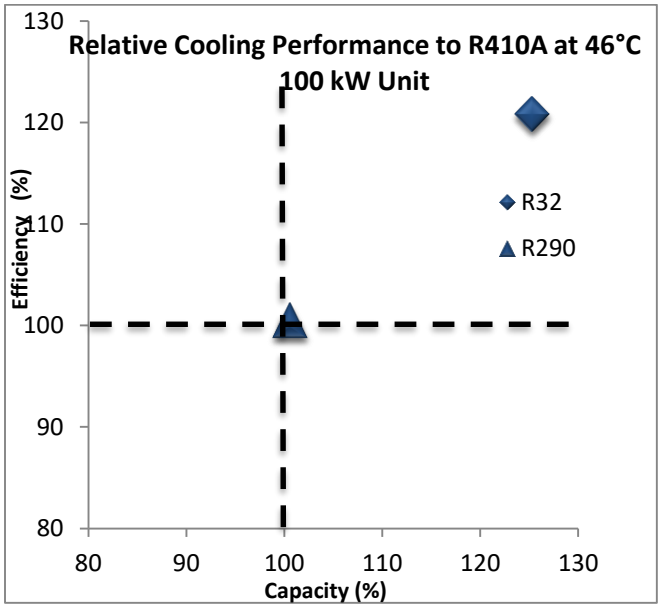

Figure 18: Low GWP refrigerants relative performance to R-410A at 46°C – 100 kW Prototypes

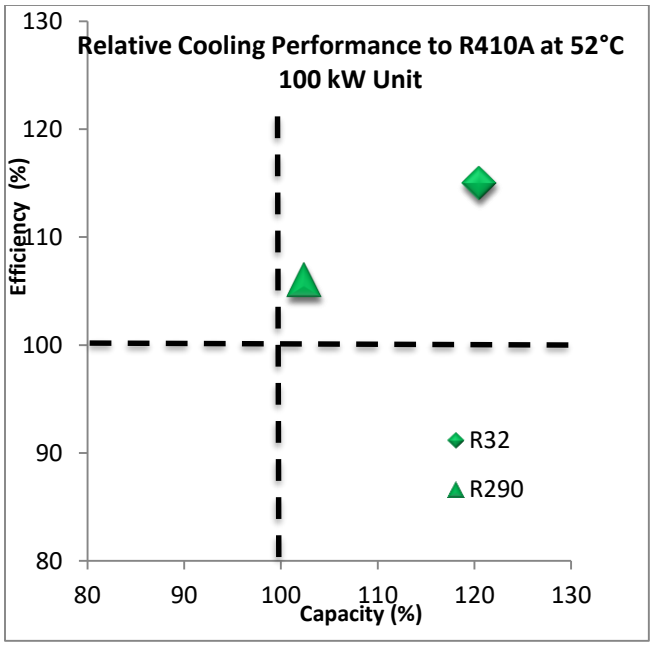

Figure 19: Low GWP refrigerants relative performance to R-410A at 52°C – 100 kW Prototypes

IV. Cost Analysis

An analysis was conducted to compare the cost of the low GWP alternative refrigerants and the major components of the chillers to the baseline R-410A. Tables 6, 7 and 8 indicate that the cost of charging the units with R-290 is 25 to 44% higher than R-410A. On the other hand, the cost of charging R-32 is about 50 to 57% less. The higher cost of R-290 is attributed to a weak demand for this refrigerant in the GCC countries and in particular Saudi Arabia.

Table 6: Cost Comparison of Refrigerant – 100 kW Unit

	R-410A	**R-32**	**R-290**
Refrigerant charge (kg)	16	12	11
Charge ratio to R-410A (%)		75%	68.8%
Unit cost ($/kg)	6.55	4.44	12.25
Cost of Refrigerant ($)	104.8	53.33	134.75
Cost ratio to R-410A (%)		50.88%	128.58%

Table 7: Cost Comparison of Refrigerant – 70 kW Unit

	R-410A	**R-32**	**R-290**
Refrigerant charge (kg)	12	9	8
Charge ratio to R-410A (%)		75%	66.7%
Unit cost ($/kg)	6.55	4.44	12.25
Cost of Refrigerant ($)	78.6	40.0	98.0
Cost ratio to R-410A (%)		50.89%	124.68%

Table 8: Cost Comparison of Refrigerant – 40 kW Unit

	R-410A	R-32	R-290
Refrigerant charge (kg)	6.5	5.5	5
Charge ratio to R-410A (%)		84.6%	76.9%
Unit cost ($/kg)	6.55	4.44	12.25
Cost of Refrigerant ($)	42.58	24.42	61.25
Cost ratio to R-410A (%)		57.35%	143.85%

Table 9 compares the cost of major components of the 100 kW chiller using R-32 and R-290 to the baseline R-410A. The last column in the table reflects the cost of the components designed to meet the European Directive 2014/34/EU also known as "ATEX Equipment Directive" [7]. The ATEX Directive covers equipment and protective systems intended for use in potentially explosive atmospheres. It specifies safety requirements and conformity assessment procedures that are to be applied before products are sold on the EU market.

Table 9: Cost Comparison of Major Components - 100 kW Unit (US $)

Major Components – 100 kW Unit	R-410A Unit (baseline)	R-32 Unit	R-290 Unit	R-290 Unit with ATEX Components
Compressor (2)	1,821	1,821	6,286	10,686
Condenser coil	2,560	2,560	2,560	2,560
Evaporator heat exchanger	1,829	1,829	1,829	1,829
Water Pump, water coil and supply fan	6,691	6,691	6,691	10,036
Expansion valve (2)	123	123	196	196
Electrical panel and cables	2,054	4,414	4,414	13,242
Piping (2)	693	640	693	693
Pressure relief valve (2)	275	275	246	246
Filter drier (2)	275	275	275	275
Solenoid valve (2)	156	156	156	467
Leak detector R-290 (2)	0	0	544	1,632
TOTAL (US $)	16,477	18,784	23,890	41,862
Percentage increase to R-410A unit	0%	14%	45%	154%

Results from Table 9 show that the exception of the electrical panel, the cost of R-32 components is very similar to R-410A. Overall, the cost is 14% higher than R-410A, mainly due to upgrade electrical panel. On the other hand, R-290 components are more expensive resulting in an overall cost increase of 45% over R-410A. This increase is mainly due to the high cost of the R-290 semi-hermetic compressor. The ATEX requirements increase significantly the cost of R-290 components; more than 150% over the cost of R-410A. However, while the cost of R-290 components is relatively high today, this cost could decrease if production increases in the future.

Cost comparisons for the 70 and 40 kW chillers can be found in Tables 10 and 11 respectively.

Table 10: Cost Comparison of Major Components - 70 kW Unit (US $)

Major Components – 70 kW Unit	R-410A Unit (baseline)	R-32 Unit	R-290 Unit	R-290 Unit with ATEX Components
Compressor (2)	1,493	1,493	5,155	8,763
Condenser coil	2,099	2,099	2,099	2,099
Evaporator heat exchanger	1,500	1,500	1,500	1,500
Water Pump, water coil and supply fan	6,259	6,259	6,259	9,389
Expansion valve (2)	101	101	161	161
Electrical panel and cables	1,684	3,619	3,619	10,858
Piping (2)	568	525	568	568
Pressure relief valve (2)	275	275	246	246
Filter drier (2)	275	275	275	275
Solenoid valve (2)	156	156	156	467
Leak detector R-290 (2)	0	0	544	1,632
TOTAL (US $)	14,411	16,302	20,582	32,828
Percentage increase to R-410A unit	0%	13%	43%	128%

Table 11: Cost Comparison of Major Components - 40 kW Unit (US $)

Major Components – 40 kW Unit	R-410A Unit (baseline)	R-32 Unit	R-290 Unit	R-290 Unit with ATEX Components
Compressor	911	911	3,143	5,343
Condenser coil	1,280	1,280	1,280	1,280
Evaporator heat exchanger	915	915	915	915
Water Pump, water coil and supply fan	5,896	5,896	5,896	8,844
Expansion valve (2)	62	62	98	98
Electrical panel and cables	1,027	2,207	2,207	6,621
Piping (2)	347	320	347	347
Pressure relief valve (2)	138	138	123	123
Filter drier (2)	138	138	138	138
Solenoid valve (2)	78	78	78	234
Leak detector R-290 (2)	0	0	544	1,632
TOTAL (US $)	10,789	11,943	14,768	25,573
Percentage increase to R-410A unit	0%	11%	37%	137%

V. Conclusions

This project successfully demonstrated that commercial air-cooled chillers can be designed and operated with flammable low GWP alternative refrigerants for a variety of cooling capacities and operating conditions, including high ambient temperatures. A total of six units were built with cooling capacities of 40 kW, 70 kW and 100 kW. The design of the products was in accordance with the safety requirements of ISO-5149 and IEC-60335-2-40.

The air-cooled chillers were tested at a standard ambient condition of 35°C as well as at high ambient temperatures of 46°C and 52°C. In all cases, both R-32 and R-290 units showed similar or better performance (efficiency and cooling capacity) than the baseline R-410A chiller. The design changes necessary to mitigate the risk of using R-32 resulted in a marginal increase in the cost of the chillers. However, the cost increase was significantly higher in the case of the highly flammable refrigerant R-290. It is expected that both the cost of the R-32 and R-290 chillers will decrease in the future as production increases.

Requirements of current international safety standards did not limit the amount of flammable refrigerants used for this particular project because of the specific application and location of the chillers. However, it should be noted that in most commercial applications, the use of highly flammable refrigerants such as R-290 is severely restricted by current safety standards, which is not the case for mildly flammable refrigerants like R-32.

Finally, it is believed that findings from this project will help developing countries with high ambient temperature conditions accelerate their adoption and implementation of the Kigali Amendment.

VI. References

1- ANSI/ASHRAE 34, 2016, *Designation and Safety Classification of Refrigerants*, ASHRAE, Atlanta, Georgia, USA.
2- ISO 817, 2014, *Refrigerants -- Designation and safety classification*, International Organization for Standardization, Geneva, Switzerland.
3- ISO 5149, 2014, *Refrigerating systems and heat pumps — Safety and environmental requirements —Part 1: Definitions, classification and selection criteria*, International Organization for Standardization, Geneva, Switzerland.
4- IEC 60335-2-40, 2018, *Household and similar electrical appliances - Safety - Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers*, International Electrotechnical Commission, Geneva, Switzerland.
5- SASO 2874, 2016, *Air-Conditioners – Minimum Energy Performance Requirements and Testing Requirements*, Saudi Standards, Metrology and Quality Organization, Riyadh, Saudi Arabia.
6- AHRI 550/590, 2018, *Performance Rating of Water-chilling and Heat Pump Water-heating Packages Using the Vapor Compression Cycle*, Air-Conditioning, Heating, and Refrigeration Institute, Arlington, Virginia, USA.
7- Directive 2014/34/EU, 2014, *Harmonization of the laws of the Member States Relating to Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres*, European Union, Brussels, Belgium.

VII. Appendix A

Test reports for all prototypes and low GWP alternatives as well as the baseline R-410A are shown in the following tables.

Test Results: 100 kW Prototype (R-32) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.51
		S-T	Volts	453.95
		R-T	Volts	456.45
	Current	R	Amps	58.83
		S	Amps	61.75
		T	Amps	59.39
	Watts	R	KW	13.27
		S	KW	13.77
		T	KW	12.97
		Total KW	KW	40.00
	Power Factor		---	0.85
	Total Power Exclude pump & fan		KW	35.40
	Frequency		Hz	60.49
COOLER	Water In		°C	10.42
	Water Out		°C	4.99
	Temperature Drop 1		°C	5.43
	Flow Rate		GPM	72.90
Air condition	Return Air Dry Bulb		°C	26.80
	Return Air Wet Bulb		°C	19.28
	Supply Air Dry Bulb		°C	15.04
	Supply Wet Bulb		°C	13.17
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	35.33
Compressor Data 1	Discharge Temp.		°C	92.90
	Liquid Temp.		°C	45.34
	Suction Temp.		°C	7.08
	Discharge Pressure		[psi]	407.70
	Liquid Pressure		[psi]	402.87
	Suction Pressure		[psi]	104.67
Compressor Data 2	Discharge Temp.		°C	91.04
	Liquid Temp.		°C	47.06
	Suction Temp.		°C	7.77
	Discharge Pressure		[psi]	423.66
	Liquid Pressure		[psi]	413.93
	Suction Pressure		[psi]	105.54

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	7.71
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.436
	water Flow Rate	ft^3/hr	584.86
Air Side	Enthalpy in	KJ/KG	54.87
	Enthalpy out	KJ/KG	37.110
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	359767
		KW	105.4
		TR	30.0
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	352556
		KW	103.3
		TR	29.4
Unit Eff.	UNIT EER	Btu/W.hr	9.96
	COP	W/W	2.92
Energy Balance	Heat Balance	Energy Balance Different Percentage	2%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-32) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	452.12
		S-T	Volts	452.52
		R-T	Volts	454.64
	Current	R	Amps	66.85
		S	Amps	70.64
		T	Amps	67.33
	Watts	R	KW	15.38
		S	KW	16.03
		T	KW	14.95
		Total KW	KW	46.35
	Power Factor		---	0.87
	Total Power Exclude pump & fan		KW	41.75
	Frequency		Hz	60.46
COOLER	Water In		°C	12.03
	Water Out		°C	6.88
	Temperature Drop 1		°C	5.15
	Flow Rate		GPM	72.70
Air condition	Return Air Dry Bulb		°C	29.15
	Return Air Wet Bulb		°C	19.00
	Supply Air Dry Bulb		°C	16.21
	Supply Wet Bulb		°C	13.23
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	45.92
Compressor Data 1	Discharge Temp.		°C	109.84
	Liquid Temp.		°C	55.17
	Suction Temp.		°C	9.48
	Discharge Pressure		[psi]	501.27
	Liquid Pressure		[psi]	501.17
	Suction Pressure		[psi]	111.34
Compressor Data 2	Discharge Temp.		°C	107.70
	Liquid Temp.		°C	56.78
	Suction Temp.		°C	10.20
	Discharge Pressure		[psi]	520.35
	Liquid Pressure		[psi]	511.27
	Suction Pressure		[psi]	111.05

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	9.45
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.428
	water Flow Rate	ft^3/hr	583.26
Air Side	Enthalpy in	KJ/KG	53.87
	Enthalpy out	KJ/KG	37.250
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	340037
		KW	99.7
		TR	28.3
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	329926
		KW	96.7
		TR	27.5
Unit Eff.	UNIT EER	Btu/W.hr	7.90
	COP	W/W	2.32
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-32) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	452.31
		S-T	Volts	452.72
		R-T	Volts	454.74
	Current	R	Amps	72.89
		S	Amps	77.31
		T	Amps	73.49
	Watts	R	KW	16.92
		S	KW	17.71
		T	KW	16.46
		Total KW	KW	51.09
	Power Factor		---	0.87
	Total Power Exclude pump & fan		KW	46.49
	Frequency		Hz	60.51
COOLER	Water In		°C	13.59
	Water Out		°C	9.22
	Temperature Drop 1		°C	4.37
	Flow Rate		GPM	72.80
Air condition	Return Air Dry Bulb		°C	29.23
	Return Air Wet Bulb		°C	18.82
	Supply Air Dry Bulb		°C	17.91
	Supply Wet Bulb		°C	13.99
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	51.80
Compressor Data 1	Discharge Temp.		°C	117.99
	Liquid Temp.		°C	60.76
	Suction Temp.		°C	11.94
	Discharge Pressure		[psi]	561.23
	Liquid Pressure		[psi]	562.55
	Suction Pressure		[psi]	119.86
Compressor Data 2	Discharge Temp.		°C	117.60
	Liquid Temp.		°C	62.68
	Suction Temp.		°C	12.77
	Discharge Pressure		[psi]	588.42
	Liquid Pressure		[psi]	578.44
	Suction Pressure		[psi]	119.05

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	11.41
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.417
	water Flow Rate	ft^3/hr	584.06
Air Side	Enthalpy in	KJ/KG	53.28
	Enthalpy out	KJ/KG	39.240
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	289310
		KW	84.8
		TR	24.1
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	278710
		KW	81.7
		TR	23.2
Unit Eff.	UNIT EER	Btu/W.hr	6.00
	COP	W/W	1.76
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-410A) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.89
		S-T	Volts	454.27
		R-T	Volts	456.57
	Current	R	Amps	56.74
		S	Amps	59.45
		T	Amps	57.05
	Watts	R	KW	12.73
		S	KW	13.15
		T	KW	12.37
		Total KW	KW	38.25
	Power Factor		---	0.84
	Total Power Exclude pump & fan		KW	33.65
	Frequency		Hz	60.50
COOLER	Water In		°C	10.71
	Water Out		°C	5.66
	Temperature Drop 1		°C	5.05
	Flow Rate		GPM	72.70
Air condition	Return Air Dry Bulb		°C	26.85
	Return Air Wet Bulb		°C	19.51
	Supply Air Dry Bulb		°C	15.59
	Supply Wet Bulb		°C	14.02
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	35.16
Compressor Data 1	Discharge Temp.		°C	72.55
	Liquid Temp.		°C	43.96
	Suction Temp.		°C	7.77
	Discharge Pressure		[psi]	388.76
	Liquid Pressure		[psi]	382.02
	Suction Pressure		[psi]	102.71
Compressor Data 2	Discharge Temp.		°C	70.08
	Liquid Temp.		°C	44.37
	Suction Temp.		°C	7.17
	Discharge Pressure		[psi]	417.69
	Liquid Pressure		[psi]	406.09
	Suction Pressure		[psi]	104.40

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	8.19
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.434
	water Flow Rate	ft^3/hr	583.26
Air Side	Enthalpy in	KJ/KG	55.61
	Enthalpy out	KJ/KG	39.380
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	333695
		KW	97.8
		TR	27.8
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	322184
		KW	94.4
		TR	26.8
Unit Eff.	UNIT EER	Btu/W.hr	9.57
	COP	W/W	2.81
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-410A) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	452.58
		S-T	Volts	452.98
		R-T	Volts	455.35
	Current	R	Amps	65.44
		S	Amps	67.84
		T	Amps	63.36
	Watts	R	KW	14.88
		S	KW	15.44
		T	KW	14.49
		Total KW	KW	44.81
	Power Factor		---	0.87
	Total Power Exclude pump & fan		KW	40.21
	Frequency		Hz	60.48
COOLER	Water In		°C	13.19
	Water Out		°C	9.06
	Temperature Drop 1		°C	4.13
	Flow Rate		GPM	72.60
Air condition	Return Air Dry Bulb		°C	26.26
	Return Air Wet Bulb		°C	19.20
	Supply Air Dry Bulb		°C	17.69
	Supply Wet Bulb		°C	14.76
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	45.92
Compressor Data 1	Discharge Temp.		°C	86.68
	Liquid Temp.		°C	54.65
	Suction Temp.		°C	11.33
	Discharge Pressure		[psi]	488.66
	Liquid Pressure		[psi]	486.04
	Suction Pressure		[psi]	114.86
Compressor Data 2	Discharge Temp.		°C	83.82
	Liquid Temp.		°C	55.91
	Suction Temp.		°C	10.03
	Discharge Pressure		[psi]	529.55
	Liquid Pressure		[psi]	517.50
	Suction Pressure		[psi]	113.26

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	11.13
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.418
	water Flow Rate	ft^3/hr	582.46
Air Side	Enthalpy in	KJ/KG	54.62
	Enthalpy out	KJ/KG	41.360
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	272656
		KW	79.9
		TR	22.7
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	263226
		KW	77.1
		TR	21.9
Unit Eff.	UNIT EER	Btu/W.hr	6.55
	COP	W/W	1.92
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-410A) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	452.48
		S-T	Volts	452.77
		R-T	Volts	455.18
	Current	R	Amps	70.34
		S	Amps	73.13
		T	Amps	68.09
	Watts	R	KW	16.17
		S	KW	16.82
		T	KW	15.75
		Total KW	KW	48.74
	Power Factor		---	0.88
	Total Power Exclude pump & fan		KW	44.14
	Frequency		Hz	60.50
COOLER	Water In		°C	14.47
	Water Out		°C	10.85
	Temperature Drop 1		°C	3.62
	Flow Rate		GPM	72.80
Air condition	Return Air Dry Bulb		°C	29.15
	Return Air Wet Bulb		°C	18.90
	Supply Air Dry Bulb		°C	18.74
	Supply Wet Bulb		°C	14.96
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	51.50
Compressor Data 1	Discharge Temp.		°C	95.85
	Liquid Temp.		°C	60.43
	Suction Temp.		°C	13.03
	Discharge Pressure		[psi]	552.17
	Liquid Pressure		[psi]	550.15
	Suction Pressure		[psi]	117.73
Compressor Data 2	Discharge Temp.		°C	91.89
	Liquid Temp.		°C	60.72
	Suction Temp.		°C	11.14
	Discharge Pressure		[psi]	584.35
	Liquid Pressure		[psi]	572.26
	Suction Pressure		[psi]	114.22

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	12.66
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.408
	water Flow Rate	ft^3/hr	584.06
Air Side	Enthalpy in	KJ/KG	53.54
	Enthalpy out	KJ/KG	41.900
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	239717
		KW	70.3
		TR	20.0
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	231067
		KW	67.7
		TR	19.3
Unit Eff.	UNIT EER	Btu/W.hr	5.23
	COP	W/W	1.53
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-290) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.27
		S-T	Volts	453.94
		R-T	Volts	455.94
	Current	R	Amps	60.79
		S	Amps	62.70
		T	Amps	61.80
	Watts	R	KW	12.97
		S	KW	13.38
		T	KW	12.94
		Total KW	KW	39.29
	Power Factor		---	0.81
	Total Power Exclude pump & fan		KW	34.69
	Frequency		Hz	60.52
COOLER	Water In		°C	10.35
	Water Out		°C	5.06
	Temperature Drop 1		°C	5.29
	Flow Rate		GPM	72.90
Air condition	Return Air Dry Bulb		°C	27.00
	Return Air Wet Bulb		°C	19.40
	Supply Air Dry Bulb		°C	14.90
	Supply Wet Bulb		°C	13.56
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	35.46
Compressor Data 1	Discharge Temp.		°C	69.99
	Liquid Temp.		°C	39.41
	Suction Temp.		°C	8.57
	Discharge Pressure		[psi]	248.14
	Liquid Pressure		[psi]	241.92
	Suction Pressure		[psi]	56.25
Compressor Data 2	Discharge Temp.		°C	67.94
	Liquid Temp.		°C	39.52
	Suction Temp.		°C	6.73
	Discharge Pressure		[psi]	243.09
	Liquid Pressure		[psi]	237.48
	Suction Pressure		[psi]	59.74

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	7.71
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.436
	water Flow Rate	ft^3/hr	584.86
Air Side	Enthalpy in	KJ/KG	55.27
	Enthalpy out	KJ/KG	38.160
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	350492
		KW	102.7
		TR	29.2
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	339653
		KW	99.5
		TR	28.3
Unit Eff.	UNIT EER	Btu/W.hr	9.79
	COP	W/W	2.87
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-290) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	452.73
		S-T	Volts	453.36
		R-T	Volts	455.51
	Current	R	Amps	67.29
		S	Amps	69.78
		T	Amps	68.94
	Watts	R	KW	14.70
		S	KW	15.30
		T	KW	14.78
		Total KW	KW	44.78
	Power Factor		---	0.83
	Total Power Exclude pump & fan		KW	40.18
	Frequency		Hz	60.48
COOLER	Water In		°C	12.27
	Water Out		°C	8.15
	Temperature Drop 1		°C	4.12
	Flow Rate		GPM	72.60
Air condition	Return Air Dry Bulb		°C	28.89
	Return Air Wet Bulb		°C	19.30
	Supply Air Dry Bulb		°C	16.74
	Supply Wet Bulb		°C	14.81
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	45.50
Compressor Data 1	Discharge Temp.		°C	74.11
	Liquid Temp.		°C	48.42
	Suction Temp.		°C	8.18
	Discharge Pressure		[psi]	297.17
	Liquid Pressure		[psi]	290.70
	Suction Pressure		[psi]	62.75
Compressor Data 2	Discharge Temp.		°C	74.74
	Liquid Temp.		°C	47.59
	Suction Temp.		°C	10.98
	Discharge Pressure		[psi]	334.14
	Liquid Pressure		[psi]	330.71
	Suction Pressure		[psi]	62.28

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	10.21
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.424
	water Flow Rate	ft^3/hr	582.46
Air Side	Enthalpy in	KJ/KG	54.87
	Enthalpy out	KJ/KG	41.530
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	271953
		KW	79.7
		TR	22.7
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	264814
		KW	77.6
		TR	22.1
Unit Eff.	UNIT EER	Btu/W.hr	6.59
	COP	W/W	1.93
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 100 kW Prototype (R-290) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	452.93
		S-T	Volts	453.33
		R-T	Volts	455.33
	Current	R	Amps	70.63
		S	Amps	73.46
		T	Amps	72.33
	Watts	R	KW	15.58
		S	KW	16.25
		T	KW	15.62
		Total KW	KW	47.45
	Power Factor		---	0.84
	Total Power Exclude pump & fan		KW	42.85
	Frequency		Hz	60.45
COOLER	Water In		°C	13.69
	Water Out		°C	9.98
	Temperature Drop 1		°C	3.71
	Flow Rate		GPM	72.90
Air condition	Return Air Dry Bulb		°C	29.42
	Return Air Wet Bulb		°C	19.52
	Supply Air Dry Bulb		°C	17.87
	Supply Wet Bulb		°C	15.57
	Air Flow rate		CFM	10256
Condenser	Ambient		°C	52.01
Compressor Data 1	Discharge Temp.		°C	81.24
	Liquid Temp.		°C	54.74
	Suction Temp.		°C	10.61
	Discharge Pressure		[psi]	341.76
	Liquid Pressure		[psi]	335.48
	Suction Pressure		[psi]	67.78
Compressor Data 2	Discharge Temp.		°C	80.26
	Liquid Temp.		°C	53.74
	Suction Temp.		°C	13.19
	Discharge Pressure		[psi]	367.74
	Liquid Pressure		[psi]	366.24
	Suction Pressure		[psi]	69.00

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	11.84
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.414
	water Flow Rate	ft^3/hr	584.86
Air Side	Enthalpy in	KJ/KG	55.59
	Enthalpy out	KJ/KG	43.660
	Air Flow Rate	ft^3/min	10256
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	245973
		KW	72.1
		TR	20.5
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	236824
		KW	69.4
		TR	19.7
Unit Eff.	UNIT EER	Btu/W.hr	5.53
	COP	W/W	1.62
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-32) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.51
		S-T	Volts	454.20
		R-T	Volts	455.71
	Current	R	Amps	50.46
		S	Amps	48.12
		T	Amps	49.84
	Watts	R	KW	11.04
		S	KW	10.62
		T	KW	11.24
		Total KW	KW	32.90
	Power Factor		---	0.84
	Total Power Exclude pump & fan		KW	30.10
	Frequency		Hz	60.49
COOLER	Water In		°C	9.87
	Water Out		°C	4.62
	Temperature Drop 1		°C	5.26
	Flow Rate		GPM	62.90
Air condition	Return Air Dry Bulb		°C	26.49
	Return Air Wet Bulb		°C	19.60
	Supply Air Dry Bulb		°C	14.25
	Supply Wet Bulb		°C	13.06
	Air Flow rate		CFM	8068
Condenser	Ambient		°C	35.22
Compressor Data 1	Discharge Temp.		°C	99.27
	Liquid Temp.		°C	45.23
	Suction Temp.		°C	11.48
	Discharge Pressure		[psi]	427.41
	Liquid Pressure		[psi]	421.68
	Suction Pressure		[psi]	104.60
Compressor Data 2	Discharge Temp.		°C	100.02
	Liquid Temp.		°C	44.11
	Suction Temp.		°C	12.73
	Discharge Pressure		[psi]	440.95
	Liquid Pressure		[psi]	434.95
	Suction Pressure		[psi]	100.67

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	7.24
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.438
	water Flow Rate	ft^3/hr	504.63
Air Side	Enthalpy in	KJ/KG	55.62
	Enthalpy out	KJ/KG	36.850
	Air Flow Rate	ft^3/min	8068
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	300394
		KW	88.0
		TR	25.0
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	293114
		KW	85.9
		TR	24.4
Unit Eff.	UNIT EER	Btu/W.hr	9.74
	COP	W/W	2.85
Energy Balance	Heat Balance	Energy Balance Different Percentage	2%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-32) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	452.34
		S-T	Volts	453.20
		R-T	Volts	454.63
	Current	R	Amps	58.69
		S	Amps	55.72
		T	Amps	58.08
	Watts	R	KW	13.07
		S	KW	12.55
		T	KW	13.35
		Total KW	KW	38.97
	Power Factor		---	0.86
	Total Power Exclude pump & fan		KW	36.17
	Frequency		Hz	60.48
COOLER	Water In		°C	10.92
	Water Out		°C	6.32
	Temperature Drop 1		°C	4.60
	Flow Rate		GPM	62.80
Air condition	Return Air Dry Bulb		°C	28.61
	Return Air Wet Bulb		°C	19.13
	Supply Air Dry Bulb		°C	15.17
	Supply Wet Bulb		°C	13.52
	Air Flow rate		CFM	8068
Condenser	Ambient		°C	45.87
Compressor Data 1	Discharge Temp.		°C	120.56
	Liquid Temp.		°C	56.10
	Suction Temp.		°C	12.32
	Discharge Pressure		[psi]	551.61
	Liquid Pressure		[psi]	546.27
	Suction Pressure		[psi]	111.01
Compressor Data 2	Discharge Temp.		°C	119.90
	Liquid Temp.		°C	54.58
	Suction Temp.		°C	15.30
	Discharge Pressure		[psi]	557.59
	Liquid Pressure		[psi]	551.59
	Suction Pressure		[psi]	107.53

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	8.62
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.432
	water Flow Rate	ft^3/hr	503.83
Air Side	Enthalpy in	KJ/KG	54.31
	Enthalpy out	KJ/KG	38.040
	Air Flow Rate	ft^3/min	8068
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	262584
		KW	77.0
		TR	21.9
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	254074
		KW	74.5
		TR	21.2
Unit Eff.	UNIT EER	Btu/W.hr	7.02
	COP	W/W	2.06
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-32) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	450.93
		S-T	Volts	452.00
		R-T	Volts	453.08
	Current	R	Amps	65.67
		S	Amps	63.94
		T	Amps	66.46
	Watts	R	KW	14.88
		S	KW	14.52
		T	KW	15.12
		Total KW	KW	44.52
	Power Factor		---	0.86
	Total Power Exclude pump & fan		KW	41.72
	Frequency		Hz	60.50
COOLER	Water In		°C	11.64
	Water Out		°C	7.44
	Temperature Drop 1		°C	4.20
	Flow Rate		GPM	62.60
Air condition	Return Air Dry Bulb		°C	29.19
	Return Air Wet Bulb		°C	19.42
	Supply Air Dry Bulb		°C	16.51
	Supply Wet Bulb		°C	14.45
	Air Flow rate		CFM	8068
Condenser	Ambient		°C	51.80
Compressor Data 1	Discharge Temp.		°C	126.40
	Liquid Temp.		°C	59.38
	Suction Temp.		°C	14.60
	Discharge Pressure		[psi]	595.49
	Liquid Pressure		[psi]	590.33
	Suction Pressure		[psi]	114.02
Compressor Data 2	Discharge Temp.		°C	125.17
	Liquid Temp.		°C	58.14
	Suction Temp.		°C	16.77
	Discharge Pressure		[psi]	602.08
	Liquid Pressure		[psi]	596.08
	Suction Pressure		[psi]	111.98

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	9.54
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.428
	water Flow Rate	ft^3/hr	502.23
Air Side	Enthalpy in	KJ/KG	55.25
	Enthalpy out	KJ/KG	40.500
	Air Flow Rate	ft^3/min	8068
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	239021
		KW	70.1
		TR	19.9
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	230338
		KW	67.5
		TR	19.2
Unit Eff.	UNIT EER	Btu/W.hr	5.52
	COP	W/W	1.62
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-410A) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.48
		S-T	Volts	454.27
		R-T	Volts	456.10
	Current	R	Amps	49.79
		S	Amps	47.44
		T	Amps	49.37
	Watts	R	KW	10.85
		S	KW	10.46
		T	KW	11.11
		Total KW	KW	32.41
	Power Factor		---	0.84
	Total Power Exclude pump & fan		KW	29.61
	Frequency		Hz	60.43
COOLER	Water In		°C	10.41
	Water Out		°C	5.50
	Temperature Drop 1		°C	4.91
	Flow Rate		GPM	63.20
Air condition	Return Air Dry Bulb		°C	26.68
	Return Air Wet Bulb		°C	19.50
	Supply Air Dry Bulb		°C	14.78
	Supply Wet Bulb		°C	13.51
	Air Flow rate		CFM	8068
Condenser	Ambient		°C	35.53
Compressor Data 1	Discharge Temp.		°C	82.12
	Liquid Temp.		°C	41.82
	Suction Temp.		°C	10.19
	Discharge Pressure		[psi]	433.96
	Liquid Pressure		[psi]	425.77
	Suction Pressure		[psi]	106.13
Compressor Data 2	Discharge Temp.		°C	80.68
	Liquid Temp.		°C	43.33
	Suction Temp.		°C	11.73
	Discharge Pressure		[psi]	437.66
	Liquid Pressure		[psi]	431.56
	Suction Pressure		[psi]	103.46

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	7.96
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.435
	water Flow Rate	ft^3/hr	507.04
Air Side	Enthalpy in	KJ/KG	55.61
	Enthalpy out	KJ/KG	38.030
	Air Flow Rate	ft^3/min	8068
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	282038
		KW	82.7
		TR	23.5
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	274531
		KW	80.5
		TR	22.9
Unit Eff.	UNIT EER	Btu/W.hr	9.27
	COP	W/W	2.72
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-410A) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.11
		S-T	Volts	453.94
		R-T	Volts	455.70
	Current	R	Amps	57.22
		S	Amps	54.32
		T	Amps	56.79
	Watts	R	KW	12.71
		S	KW	12.22
		T	KW	13.04
		Total KW	KW	37.97
	Power Factor		---	0.86
	Total Power Exclude pump & fan		KW	35.17
	Frequency		Hz	60.45
COOLER	Water In		°C	11.92
	Water Out		°C	7.49
	Temperature Drop 1		°C	4.43
	Flow Rate		GPM	62.80
Air condition	Return Air Dry Bulb		°C	29.05
	Return Air Wet Bulb		°C	19.24
	Supply Air Dry Bulb		°C	15.73
	Supply Wet Bulb		°C	13.89
	Air Flow rate		CFM	8068
Condenser	Ambient		°C	46.49
Compressor Data 1	Discharge Temp.		°C	99.08
	Liquid Temp.		°C	53.25
	Suction Temp.		°C	13.02
	Discharge Pressure		[psi]	556.60
	Liquid Pressure		[psi]	549.79
	Suction Pressure		[psi]	113.13
Compressor Data 2	Discharge Temp.		°C	97.21
	Liquid Temp.		°C	53.82
	Suction Temp.		°C	15.03
	Discharge Pressure		[psi]	551.21
	Liquid Pressure		[psi]	545.21
	Suction Pressure		[psi]	109.28

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	9.70
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.427
	water Flow Rate	ft^3/hr	503.83
Air Side	Enthalpy in	KJ/KG	54.66
	Enthalpy out	KJ/KG	39.020
	Air Flow Rate	ft^3/min	8068
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	252808
		KW	74.1
		TR	21.1
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	244236
		KW	71.6
		TR	20.4
Unit Eff.	UNIT EER	Btu/W.hr	6.94
	COP	W/W	2.04
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-410A) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.72
		S-T	Volts	454.68
		R-T	Volts	456.08
	Current	R	Amps	61.51
		S	Amps	58.40
		T	Amps	61.05
	Watts	R	KW	13.78
		S	KW	13.25
		T	KW	14.12
		Total KW	KW	41.15
	Power Factor		---	0.87
	Total Power Exclude pump & fan		KW	38.35
	Frequency		Hz	60.49
COOLER	Water In		°C	14.71
	Water Out		°C	10.93
	Temperature Drop 1		°C	3.78
	Flow Rate		GPM	62.70
Air condition	Return Air Dry Bulb		°C	29.42
	Return Air Wet Bulb		°C	19.02
	Supply Air Dry Bulb		°C	18.66
	Supply Wet Bulb		°C	14.52
	Air Flow rate		CFM	8068
Condenser	Ambient		°C	51.53
Compressor Data 1	Discharge Temp.		°C	106.99
	Liquid Temp.		°C	60.66
	Suction Temp.		°C	21.52
	Discharge Pressure		[psi]	607.20
	Liquid Pressure		[psi]	599.55
	Suction Pressure		[psi]	121.60
Compressor Data 2	Discharge Temp.		°C	105.13
	Liquid Temp.		°C	60.04
	Suction Temp.		°C	19.31
	Discharge Pressure		[psi]	609.40
	Liquid Pressure		[psi]	603.40
	Suction Pressure		[psi]	118.00

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	12.82
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.406
	water Flow Rate	ft^3/hr	503.03
Air Side	Enthalpy in	KJ/KG	53.92
	Enthalpy out	KJ/KG	40.670
	Air Flow Rate	ft^3/min	8068
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	215592
		KW	63.2
		TR	18.0
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	206914
		KW	60.6
		TR	17.2
Unit Eff.	UNIT EER	Btu/W.hr	5.40
	COP	W/W	1.58
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-290) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	454.74
		S-T	Volts	455.01
		R-T	Volts	457.20
	Current	R	Amps	47.37
		S	Amps	48.60
		T	Amps	47.95
	Watts	R	KW	9.97
		S	KW	10.22
		T	KW	9.92
		Total KW	KW	30.12
	Power Factor		---	0.80
	Total Power Exclude pump & fan		KW	27.32
	Frequency		Hz	60.49
COOLER	Water In		°C	11.63
	Water Out		°C	6.86
	Temperature Drop 1		°C	4.77
	Flow Rate		GPM	62.10
Air condition	Return Air Dry Bulb		°C	27.31
	Return Air Wet Bulb		°C	19.50
	Supply Air Dry Bulb		°C	15.02
	Supply Wet Bulb		°C	13.85
	Air Flow rate		CFM	8085
Condenser	Ambient		°C	35.56
Compressor Data 1	Discharge Temp.		°C	67.71
	Liquid Temp.		°C	40.63
	Suction Temp.		°C	15.76
	Discharge Pressure		[psi]	244.23
	Liquid Pressure		[psi]	236.60
	Suction Pressure		[psi]	56.83
Compressor Data 2	Discharge Temp.		°C	65.42
	Liquid Temp.		°C	44.40
	Suction Temp.		°C	11.55
	Discharge Pressure		[psi]	222.11
	Liquid Pressure		[psi]	213.44
	Suction Pressure		[psi]	50.49

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	9.24
	Specific Heat	Btu/lbm·°F	1.008
	Density	lbm/ft^3	62.429
	water Flow Rate	ft^3/hr	498.22
Air Side	Enthalpy in	KJ/KG	55.60
	Enthalpy out	KJ/KG	38.930
	Air Flow Rate	ft^3/min	8085
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	269448
		KW	79.0
		TR	22.5
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	260869
		KW	76.5
		TR	21.7
Unit Eff.	UNIT EER	Btu/W.hr	9.55
	COP	W/W	2.80
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-290) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	454.32
		S-T	Volts	454.74
		R-T	Volts	456.76
	Current	R	Amps	49.67
		S	Amps	51.15
		T	Amps	50.32
	Watts	R	KW	10.62
		S	KW	10.92
		T	KW	10.56
		Total KW	KW	32.10
	Power Factor		---	0.81
	Total Power Exclude pump & fan		KW	29.30
	Frequency		Hz	60.47
COOLER	Water In		°C	12.85
	Water Out		°C	8.96
	Temperature Drop 1		°C	3.89
	Flow Rate		GPM	62.10
Air condition	Return Air Dry Bulb		°C	29.16
	Return Air Wet Bulb		°C	19.77
	Supply Air Dry Bulb		°C	16.13
	Supply Wet Bulb		°C	15.31
	Air Flow rate		CFM	8085
Condenser	Ambient		°C	46.04
Compressor Data 1	Discharge Temp.		°C	76.31
	Liquid Temp.		°C	48.40
	Suction Temp.		°C	18.28
	Discharge Pressure		[psi]	286.08
	Liquid Pressure		[psi]	279.37
	Suction Pressure		[psi]	60.23
Compressor Data 2	Discharge Temp.		°C	75.40
	Liquid Temp.		°C	52.47
	Suction Temp.		°C	13.60
	Discharge Pressure		[psi]	282.87
	Liquid Pressure		[psi]	275.00
	Suction Pressure		[psi]	58.84

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	10.91
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.420
	water Flow Rate	ft^3/hr	498.22
Air Side	Enthalpy in	KJ/KG	56.44
	Enthalpy out	KJ/KG	42.960
	Air Flow Rate	ft^3/min	8085
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	219661
		KW	64.4
		TR	18.3
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	210949
		KW	61.8
		TR	17.6
Unit Eff.	UNIT EER	Btu/W.hr	7.20
	COP	W/W	2.11
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 70 kW Prototype (R-290) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	453.97
		S-T	Volts	454.18
		R-T	Volts	456.43
	Current	R	Amps	50.93
		S	Amps	52.44
		T	Amps	51.57
	Watts	R	KW	10.96
		S	KW	11.26
		T	KW	10.89
		Total KW	KW	33.11
	Power Factor		---	81.00
	Total Power Exclude pump & fan		KW	30.31
	Frequency		Hz	60.49
COOLER	Water In		°C	13.01
	Water Out		°C	10.20
	Temperature Drop 1		°C	2.81
	Flow Rate		GPM	62.30
Air condition	Return Air Dry Bulb		°C	29.24
	Return Air Wet Bulb		°C	19.58
	Supply Air Dry Bulb		°C	17.06
	Supply Wet Bulb		°C	16.39
	Air Flow rate		CFM	8085
Condenser	Ambient		°C	51.68
Compressor Data 1	Discharge Temp.		°C	80.83
	Liquid Temp.		°C	53.24
	Suction Temp.		°C	19.80
	Discharge Pressure		[psi]	334.11
	Liquid Pressure		[psi]	327.98
	Suction Pressure		[psi]	62.66
Compressor Data 2	Discharge Temp.		°C	80.10
	Liquid Temp.		°C	57.17
	Suction Temp.		°C	15.06
	Discharge Pressure		[psi]	327.32
	Liquid Pressure		[psi]	319.75
	Suction Pressure		[psi]	60.31

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	11.61
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.415
	water Flow Rate	ft^3/hr	499.82
Air Side	Enthalpy in	KJ/KG	55.79
	Enthalpy out	KJ/KG	46.080
	Air Flow Rate	ft^3/min	8085
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	159207
		KW	46.7
		TR	13.3
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	151952
		KW	44.5
		TR	12.7
Unit Eff.	UNIT EER	Btu/W.hr	5.01
	COP	W/W	1.47
Energy Balance	Heat Balance	Energy Balance Different Percentage	5%
		Allowable tolerance as AHRI 550/590	5%

Test Results: 40 kW Prototype (R-32) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	454.31
		S-T	Volts	454.64
		R-T	Volts	457.21
	Current	R	Amps	26.89
		S	Amps	28.17
		T	Amps	27.29
	Watts	R	KW	6.18
		S	KW	6.43
		T	KW	6.10
		Total KW	KW	18.71
	Power Factor		---	0.86
	Total Power Exclude pump & fan		KW	16.41
	Frequency		Hz	60.48
COOLER	Water In		°C	14.71
	Water Out		°C	10.17
	Temperature Drop 1		°C	4.54
	Flow Rate		GPM	39.90
Air condition	Return Air Dry Bulb		°C	26.22
	Return Air Wet Bulb		°C	19.40
	Supply Air Dry Bulb		°C	15.90
	Supply Wet Bulb		°C	14.60
	Air Flow rate		CFM	5900
Condenser	Ambient		°C	35.24
Compressor Data	Discharge Temp.		°C	100.63
	Liquid Temp.		°C	47.48
	Suction Temp.		°C	11.29
	Discharge Pressure		[psi]	492.93
	Liquid Pressure		[psi]	489.31
	Suction Pressure		[psi]	126.38

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	12.44
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.409
	water Flow Rate	ft^3/hr	320.11
Air Side	Enthalpy in	KJ/KG	55.30
	Enthalpy out	KJ/KG	40.960
	Air Flow Rate	ft^3/min	5900
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	164766
		KW	48.3
		TR	13.7
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	163760
		KW	48.0
		TR	13.6
Unit Eff.	UNIT EER	Btu/W.hr	9.98
	COP	W/W	2.93
Energy Balance	Heat Balance	Energy Balance Different Percentage	1%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-32) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	455.49
		S-T	Volts	455.93
		R-T	Volts	458.14
	Current	R	Amps	33.25
		S	Amps	35.20
		T	Amps	33.79
	Watts	R	KW	7.82
		S	KW	8.21
		T	KW	7.70
		Total KW	KW	23.72
	Power Factor		---	0.88
	Total Power Exclude pump & fan		KW	21.42
	Frequency		Hz	60.51
COOLER	Water In		°C	16.09
	Water Out		°C	11.81
	Temperature Drop 1		°C	4.28
	Flow Rate		GPM	39.70
Air condition	Return Air Dry Bulb		°C	29.42
	Return Air Wet Bulb		°C	19.49
	Supply Air Dry Bulb		°C	17.20
	Supply Wet Bulb		°C	15.09
	Air Flow rate		CFM	5900
Condenser	Ambient		°C	45.19
Compressor Data	Discharge Temp.		°C	119.92
	Liquid Temp.		°C	57.99
	Suction Temp.		°C	15.67
	Discharge Pressure		[psi]	628.25
	Liquid Pressure		[psi]	626.47
	Suction Pressure		[psi]	134.72

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	13.95
	Specific Heat	Btu/lbm·°F	1.010
	Density	lbm/ft^3	62.397
	water Flow Rate	ft^3/hr	318.51
Air Side	Enthalpy in	KJ/KG	55.48
	Enthalpy out	KJ/KG	42.300
	Air Flow Rate	ft^3/min	5900
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	154747
		KW	45.4
		TR	12.9
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	150513
		KW	44.1
		TR	12.5
Unit Eff.	UNIT EER	Btu/W.hr	7.03
	COP	W/W	2.06
Energy Balance	Heat Balance	Energy Balance Different Percentage	3%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-32) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	455.43
		S-T	Volts	455.90
		R-T	Volts	458.06
	Current	R	Amps	36.41
		S	Amps	36.77
		T	Amps	35.65
	Watts	R	KW	8.42
		S	KW	8.52
		T	KW	8.30
		Total KW	KW	25.24
	Power Factor		---	0.88
	Total Power Exclude pump & fan		KW	22.94
	Frequency		Hz	60.51
COOLER	Water In		°C	16.91
	Water Out		°C	13.42
	Temperature Drop 1		°C	3.49
	Flow Rate		GPM	39.80
Air condition	Return Air Dry Bulb		°C	29.49
	Return Air Wet Bulb		°C	19.07
	Supply Air Dry Bulb		°C	18.16
	Supply Wet Bulb		°C	15.51
	Air Flow rate		CFM	5900
Condenser	Ambient		°C	51.90
Compressor Data	Discharge Temp.		°C	126.40
	Liquid Temp.		°C	63.10
	Suction Temp.		°C	16.10
	Discharge Pressure		[psi]	635.10
	Liquid Pressure		[psi]	632.20
	Suction Pressure		[psi]	142.40

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	15.17
	Specific Heat	Btu/lbm·°F	1.010
	Density	lbm/ft^3	62.386
	water Flow Rate	ft^3/hr	319.31
Air Side	Enthalpy in	KJ/KG	54.09
	Enthalpy out	KJ/KG	43.480
	Air Flow Rate	ft^3/min	5900
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	126422
		KW	37.1
		TR	10.5
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	121164
		KW	35.5
		TR	10.1
Unit Eff.	UNIT EER	Btu/W.hr	5.28
	COP	W/W	1.55
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-410A) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	454.94
		S-T	Volts	455.19
		R-T	Volts	457.85
	Current	R	Amps	25.62
		S	Amps	26.78
		T	Amps	25.96
	Watts	R	KW	5.85
		S	KW	6.06
		T	KW	5.76
		Total KW	KW	17.67
	Power Factor		---	0.86
	Total Power Exclude pump & fan		KW	15.37
	Frequency		Hz	60.46
COOLER	Water In		°C	14.32
	Water Out		°C	10.18
	Temperature Drop 1		°C	4.14
	Flow Rate		GPM	40.10
Air condition	Return Air Dry Bulb		°C	26.44
	Return Air Wet Bulb		°C	19.47
	Supply Air Dry Bulb		°C	16.50
	Supply Wet Bulb		°C	15.10
	Air Flow rate		CFM	5900
Condenser	Ambient		°C	35.56
Compressor Data	Discharge Temp.		°C	83.36
	Liquid Temp.		°C	47.93
	Suction Temp.		°C	14.27
	Discharge Pressure		[psi]	474.30
	Liquid Pressure		[psi]	470.11
	Suction Pressure		[psi]	124.16

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	12.25
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.411
	water Flow Rate	ft^3/hr	321.71
Air Side	Enthalpy in	KJ/KG	55.52
	Enthalpy out	KJ/KG	42.500
	Air Flow Rate	ft^3/min	5900
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	150997
		KW	44.3
		TR	12.6
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	148686
		KW	43.6
		TR	12.4
Unit Eff.	UNIT EER	Btu/W.hr	9.67
	COP	W/W	2.83
Energy Balance	Heat Balance	Energy Balance Different Percentage	2%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-410A) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	454.61
		S-T	Volts	455.00
		R-T	Volts	457.51
	Current	R	Amps	29.46
		S	Amps	30.96
		T	Amps	29.91
	Watts	R	KW	6.85
		S	KW	7.15
		T	KW	6.76
		Total KW	KW	20.75
	Power Factor		---	0.87
	Total Power Exclude pump & fan		KW	18.45
	Frequency		Hz	60.48
COOLER	Water In		°C	16.96
	Water Out		°C	13.59
	Temperature Drop 1		°C	3.37
	Flow Rate		GPM	39.90
Air condition	Return Air Dry Bulb		°C	28.92
	Return Air Wet Bulb		°C	19.32
	Supply Air Dry Bulb		°C	19.28
	Supply Wet Bulb		°C	15.86
	Air Flow rate		CFM	5900
Condenser	Ambient		°C	46.16
Compressor Data	Discharge Temp.		°C	100.66
	Liquid Temp.		°C	57.25
	Suction Temp.		°C	18.50
	Discharge Pressure		[psi]	589.98
	Liquid Pressure		[psi]	586.74
	Suction Pressure		[psi]	128.13

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	15.28
	Specific Heat	Btu/lbm·°F	1.010
	Density	lbm/ft^3	62.385
	water Flow Rate	ft^3/hr	320.11
Air Side	Enthalpy in	KJ/KG	54.93
	Enthalpy out	KJ/KG	44.460
	Air Flow Rate	ft^3/min	5900
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	122386
		KW	35.9
		TR	10.2
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	119565
		KW	35.0
		TR	10.0
Unit Eff.	UNIT EER	Btu/W.hr	6.48
	COP	W/W	1.90
Energy Balance	Heat Balance	Energy Balance Different Percentage	2%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-410A) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	455.99
		S-T	Volts	456.58
		R-T	Volts	458.73
	Current	R	Amps	30.08
		S	Amps	31.72
		T	Amps	30.56
	Watts	R	KW	7.02
		S	KW	7.35
		T	KW	6.92
		Total KW	KW	21.29
	Power Factor		---	0.87
	Total Power Exclude pump & fan		KW	18.99
	Frequency		Hz	60.50
COOLER	Water In		°C	17.42
	Water Out		°C	14.48
	Temperature Drop 1		°C	2.94
	Flow Rate		GPM	39.80
Air condition	Return Air Dry Bulb		°C	29.14
	Return Air Wet Bulb		°C	19.16
	Supply Air Dry Bulb		°C	20.08
	Supply Wet Bulb		°C	16.21
	Air Flow rate		CFM	5900
Condenser	Ambient		°C	51.90
Compressor Data	Discharge Temp.		°C	103.74
	Liquid Temp.		°C	58.78
	Suction Temp.		°C	19.38
	Discharge Pressure		[psi]	606.45
	Liquid Pressure		[psi]	604.02
	Suction Pressure		[psi]	134.49

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	15.95
	Specific Heat	Btu/lbm·°F	1.011
	Density	lbm/ft^3	62.379
	water Flow Rate	ft^3/hr	319.31
Air Side	Enthalpy in	KJ/KG	54.40
	Enthalpy out	KJ/KG	45.460
	Air Flow Rate	ft^3/min	5900
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	106522
		KW	31.2
		TR	8.9
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	102093
		KW	29.9
		TR	8.5
Unit Eff.	UNIT EER	Btu/W.hr	5.38
	COP	W/W	1.58
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-290) @T1 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	454.85
		S-T	Volts	455.10
		R-T	Volts	457.35
	Current	R	Amps	26.84
		S	Amps	27.55
		T	Amps	27.18
	Watts	R	KW	5.72
		S	KW	5.87
		T	KW	5.70
		Total KW	KW	17.29
	Power Factor		---	0.81
	Total Power Exclude pump & fan		KW	14.99
	Frequency		Hz	60.48
COOLER	Water In		°C	14.64
	Water Out		°C	10.50
	Temperature Drop 1		°C	4.14
	Flow Rate		GPM	39.70
Air condition	Return Air Dry Bulb		°C	26.47
	Return Air Wet Bulb		°C	18.95
	Supply Air Dry Bulb		°C	15.66
	Supply Wet Bulb		°C	14.66
	Air Flow rate		CFM	6008
Condenser	Ambient		°C	35.44
Compressor Data	Discharge Temp.		°C	78.36
	Liquid Temp.		°C	42.21
	Suction Temp.		°C	13.90
	Discharge Pressure		[psi]	289.01
	Liquid Pressure		[psi]	286.76
	Suction Pressure		[psi]	62.87

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	12.57
	Specific Heat	Btu/lbm·°F	1.009
	Density	lbm/ft^3	62.408
	water Flow Rate	ft^3/hr	318.51
Air Side	Enthalpy in	KJ/KG	53.79
	Enthalpy out	KJ/KG	41.140
	Air Flow Rate	ft^3/min	6008
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	149645
		KW	43.9
		TR	12.5
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	147105
		KW	43.1
		TR	12.3
Unit Eff.	UNIT EER	Btu/W.hr	9.82
	COP	W/W	2.88
Energy Balance	Heat Balance	Energy Balance Different Percentage	2%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-290) @T3 Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	455.44
		S-T	Volts	455.54
		R-T	Volts	457.93
	Current	R	Amps	29.77
		S	Amps	30.48
		T	Amps	30.23
	Watts	R	KW	6.45
		S	KW	6.63
		T	KW	6.47
		Total KW	KW	19.55
	Power Factor		---	0.82
	Total Power Exclude pump & fan		KW	17.25
	Frequency		Hz	60.48
COOLER	Water In		°C	16.96
	Water Out		°C	13.64
	Temperature Drop 1		°C	3.32
	Flow Rate		GPM	39.70
Air condition	Return Air Dry Bulb		°C	29.28
	Return Air Wet Bulb		°C	18.99
	Supply Air Dry Bulb		°C	18.17
	Supply Wet Bulb		°C	15.65
	Air Flow rate		CFM	6008
Condenser	Ambient		°C	45.06
Compressor Data	Discharge Temp.		°C	89.97
	Liquid Temp.		°C	54.49
	Suction Temp.		°C	18.18
	Discharge Pressure		[psi]	364.19
	Liquid Pressure		[psi]	363.75
	Suction Pressure		[psi]	71.22

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	15.30
	Specific Heat	Btu/lbm·°F	1.010
	Density	lbm/ft^3	62.385
	water Flow Rate	ft^3/hr	318.51
Air Side	Enthalpy in	KJ/KG	53.83
	Enthalpy out	KJ/KG	43.880
	Air Flow Rate	ft^3/min	6008
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	119966
		KW	35.2
		TR	10.0
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	115707
		KW	33.9
		TR	9.6
Unit Eff.	UNIT EER	Btu/W.hr	6.71
	COP	W/W	1.97
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%

Test Results: 40 kW Prototype (R-290) @52°C Condition

TEST Results				
Parameter			Unit	Reading
Electrical Data	Voltage	R-S	Volts	455.23
		S-T	Volts	455.36
		R-T	Volts	457.73
	Current	R	Amps	33.83
		S	Amps	34.05
		T	Amps	33.43
	Watts	R	KW	7.38
		S	KW	7.43
		T	KW	7.33
		Total KW	KW	22.14
	Power Factor		---	0.83
	Total Power Exclude pump & fan		KW	19.84
	Frequency		Hz	60.49
COOLER	Water In		°C	17.68
	Water Out		°C	14.74
	Temperature Drop 1		°C	2.94
	Flow Rate		GPM	39.80
Air condition	Return Air Dry Bulb		°C	29.43
	Return Air Wet Bulb		°C	19.10
	Supply Air Dry Bulb		°C	19.23
	Supply Wet Bulb		°C	16.20
	Air Flow rate		CFM	6008
Condenser	Ambient		°C	52.10
Compressor Data	Discharge Temp.		°C	94.90
	Liquid Temp.		°C	59.21
	Suction Temp.		°C	20.37
	Discharge Pressure		[psi]	404.13
	Liquid Pressure		[psi]	401.00
	Suction Pressure		[psi]	74.77

Unit Performance Calculations			
Parameter		Unit	READING
Water Prop	Mean Temp.	°C	16.21
	Specific Heat	Btu/lbm·°F	1.011
	Density	lbm/ft^3	62.376
	water Flow Rate	ft^3/hr	319.31
Air Side	Enthalpy in	KJ/KG	54.19
	Enthalpy out	KJ/KG	45.450
	Air Flow Rate	ft^3/min	6008
Water Capacity & EER	Water Side Cooling Capacity	Btu/hr	106385
		KW	31.2
		TR	8.9
Air Capacity & EER	Air Side Cooling Capacity	Btu/hr	101636
		KW	29.8
		TR	8.5
Unit Eff.	UNIT EER	Btu/W.hr	5.12
	COP	W/W	1.50
Energy Balance	Heat Balance	Energy Balance Different Percentage	4%
		Allowable tolerance as AHRI 550/590	4%