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Oak Ridge National Laboratory Evaluation of High-Performance Rooftop HVAC Unit Naval Air Station Key West, Florida

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February 2018

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Energy and Transportation Science Division

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Naval Air Station Key West, Florida

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EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) and the U.S. Navy Facilities Engineering Command (NAVFAC) collaborated on a project to measure the performance of two high performance rooftop HVAC units (RTUs) that were installed at the Navy Exchange at Naval Air Station (NAS) Key West, FL. These RTUs were manufactured by the Daikin Corporation and the Carrier Corporation as part of the Advanced RTU Campaign (http://www.advancedrtu.org) sponsored by DOE's Commercial Building Energy Alliance.

The goal of this campaign was to encourage development of a next-generation RTU that had an integrated energy efficiency rating (IEER) of 18.0 or greater. This threshold had heretofore not been achieved.

Daikin and Carrier are the two manufacturers who responded to the challenge, and they both produced units that met this performance level in a test stand environment. The purpose of this project was to test the units in a field environment to see how their energy performance compared to that which was found in the lab.

Oak Ridge National Laboratory (ORNL) was retained to analyze data that came from the two units, and to assemble a final report capturing the results. The RTUs operated from June 2016 to March 2017. When analyzing the data, ORNL realized that significant data from the Carrier unit was not captured. ORNL is continuing to work with the data acquisition system (DAS) vendor to find an acceptable solution. However, as of this report's issue in January 2018, it only contains performance data for the Daikin unit.

During the test period, the Daikin RTU installed at the site performed at an average EER of 15.7 BTU/Whr. This compares favorably to the IEER value of 18.0 that was measured by the manufacturer in a test stand.

This single biggest factor that would account for this difference in performance is the outside air temperatures that are specified by AHRI when measuring IEER, compared to the actual outside air temperatures found at NAS Key West during the evaluation period. AHRI Standard 340/360-2015, which governs measurements of IEER, specify that the outside air temperature be 68°F or below for more than 60% of the test. However, at NAS Key West, temperatures were in this range less than 3% of the time. Higher outside air temperatures cause to heat to be transferred less effectively in the condenser coils, thereby reducing the EER measured in the field environment.

1. INTRODUCTION

Rooftop HVAC Units (RTUs) are one of the most common types of heating and air conditioning units found in commercial retail and office facilities. These packaged units currently provide heating and cooling for approximately 60%[1] of commercial floor space in the United States. The ubiquity of RTUs is due to several factors. They tend to have a small footprint for the provided cooling capacity. These units are easy to install, often requiring little or no ductwork in "big box" retail locations. They require no floor space, leaving that valuable area for desks, work spaces, or display racks.

Illustration 1: A typical "big box" retail store with 120,000sf of floor area served by 23 RTUs.[2]

Given the ever-present nature of RTUs, it is not surprising that they account for a large quantity of energy consumed. By one estimate, the current fleet of RTUs in service "consume about 4.3 Quads of energy annually – about a fifth of total commercial building energy use."[3]

Because of the large amount of energy consumed by RTUs, they received special focus from the U.S. Department of Energy's (DOE's) Commercial Building Energy Alliance (CBEA) in the form of the Advanced RTU Campaign (http://www.advancedrtu.org). The CBEA is a consortium featuring many of the largest names in retail and commercial property management. Its members "control more than 8 billion sf and represent approximately 20% of the total U.S. floor space in their respective sectors."[4]

The CBEA sought to encourage RTU manufacturers to produce an RTU with energy efficiency that had never been achieved to date. In 2011, they issued what they called the "RTU Challenge" to manufacturers, using their large collective buying power as incentive. Among the many performance facets specified by the CBEA, one of the most important was the cooling performance criteria. For an

[1] "What's on your Roof? Rooftop Unit (RTU) Efficiency Advice and Guidance from the Advanced RTU Campaign". By Monica Kanojia. Published by the U.S. Department of Energy. November 10, 2015. https://energy.gov/eere/buildings/articles/what-s-your-roof-rooftop-unit-rtu-efficiency-advice-and-guidance-advanced

[2] Photo taken from Google Maps screen capture.

[3] "Retrofitting of Commercial Rooftop Units Results in Savings of $5.6 Million". By Monica Kanojia. Published by the U.S. Department of Energy. April 21, 2017.

[4] https://www1.eere.energy.gov/buildings/alliances/m/index.html

RTU to meet the standard, it would have to have an integrated energy efficiency ratio (IEER)[5] greater than 18.0.

Two HVAC manufacturers, Carrier and Daikin-McQuay, responded to the challenge and produced RTUs that met this standard when tested in a laboratory under AHRI conditions.

The purpose of this report is to capture findings from a project where an RTU from each manufacturer was installed on a retail facility at Naval Air Station (NAS) Key West, Florida. The units were installed in Spring 2016, and performance data was gathered from June 2016 to March 2017. The major goal of this project was to measure the energy efficiency ratio (EER) of each unit when it operated under the conditions found at NAS Key West.

1.1 What Was Studied?

The project's goal was to evaluate the performance of the two RTUs installed at the site. These units were purchased from the two manufacturers who designed units to meet the RTU Challenge performance standard of IEER equal to or greater than 18.0.

- Carrier. Model: 50LC0007A2A6-1E0A0. Total cooling capacity: 56,300btu/hr.
- Daikin. Model: DPS010A. Total cooling capacity: 103,600btu/hr.

The units' cooling capacities were selected based upon needs of the particular areas which they were serving.

The specific metric used in this evaluation was the EER. This metric is based upon how much cooling output is provided by the RTU, divided by the electrical energy consumed by the device to provide that cooling. The units for this metric are British Thermal Units (BTUs) of cooling output per Watt-hour (Whr) of electrical input required. The shorthand notation for this unit is written as "BTU/Whr".

As an example, a hypothetical 5-ton RTU might be providing 60,000 BTUs per hour of cooling to a building, and consuming 6,000 Watt-hours of electricity during that same time period. The following equations show how the EER would be calculated for this example:

$$EER = 60{,}000BTUs \div 6{,}000Whr$$
$$EER = 10^{BTU}/Whr$$

For this example, the EER rating of this RTU would be 10 BTU/Whr. It is also common practice to not include the units when discussing the EER and simply say that the EER rating is "10". This is because the EER rating is always given in units of BTU/Whr.

The EER rating differs slightly from the IEER rating specified by the RTU challenge, in that the IEER rating must be measured under very tightly controlled conditions. IEER is designed to show how a given packaged HVAC unit would perform under a "standardized" season of operation. Within AHRI standard 340/360-2015, definitions are spelled out for how much time the RTU must operate at certain part load conditions, and at which outside air temperatures, supply air temperatures, and return air temperatures it must operate. To maintain all these parameters, the IEER must be measured in a laboratory.

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[5] Details of how to calculate IEER can be found in AHRI Standard 340/360-2015 at http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_340-360_2015.pdf .

The IEER is important in that it allows potential customers to compare the performance of different RTUs from a variety of manufacturers, knowing that each unit was tested under identical conditions.

For the evaluation in Key West, the EER metric was chosen because the RTUs were installed in a field location on the roof of a retail outlet. There is no way that conditions could be controlled tightly enough to meet the standards that would produce an IEER rating.

1.2 Why We Studied It?

This project was conducted to see how well these units would perform under field conditions, and compare them to their rated performance that was measured under laboratory conditions. Information like this is valuable to people considering specifying or purchasing one of these RTUs, because it is not uncommon for a unit's performance in the field to be less than its performance in the lab.

This performance shift is not a result of any dishonesty on the part of manufacturers. Rather, it's based on the simple fact that there are challenges present in a field environment that do not exist in a test laboratory.

Bench testing results used in advertising literature, which is used to establish performance within AHRI and other standards, is performed under tightly controlled steady-state conditions. These conditions allow a mechanical device and its control sequence to reach a state of optimal equilibrium, and therefore maximize performance. In a field environment, conditions are constantly changing. Outside air temperature and humidity, internal loads, sun moving behind clouds. All of these cause an RTU to operate in a constant state of flux, and it never reaches an optimal state of equilibrium. This leads to field performance being less than that found in lab tests.

Field conditions also introduce challenges that are just not present in a lab environment. Condenser coils can get dusty or oxidize in the salt air, which impedes their ability to reject heat to atmosphere. Filters, even if changed regularly, gather material and impede airflow, whereas in the lab the units are always tested with clean filters. Actual ambient air temperatures might exceed those specified by AHRI, which hurts the unit's ability to reject heat and drives down the EER.

By measuring these unit's performance in the field, engineers, site managers, and operations staff members will be better informed and able to choose what units are right for their site.

2. EVALUATION PLAN

2.1 Evaluation Design

The evaluation was implemented at NAS Key West, FL at a facility called the "Navy Exchange". It is a single-story retail facility that serves personnel and dependents stationed at the base. HVAC needs at the building are provided by a number of RTUs. Two of these units were at end of life and selected for replacement by the Carrier and Daikin units that were to be evaluated.

Transformative Wave Technology, a controls company based in Kent, Washington, designed a system of sensors and a data acquisition system (DAS) that collected performance parameters from various points around the RTU, as well as directly from each RTU's internal control system. The data collected was supposed to replicate the informational points gathered from other high performance RTUs that have been measured as part of the RTU Challenge. A schematic of the data-gathering system used on other units is shown below.

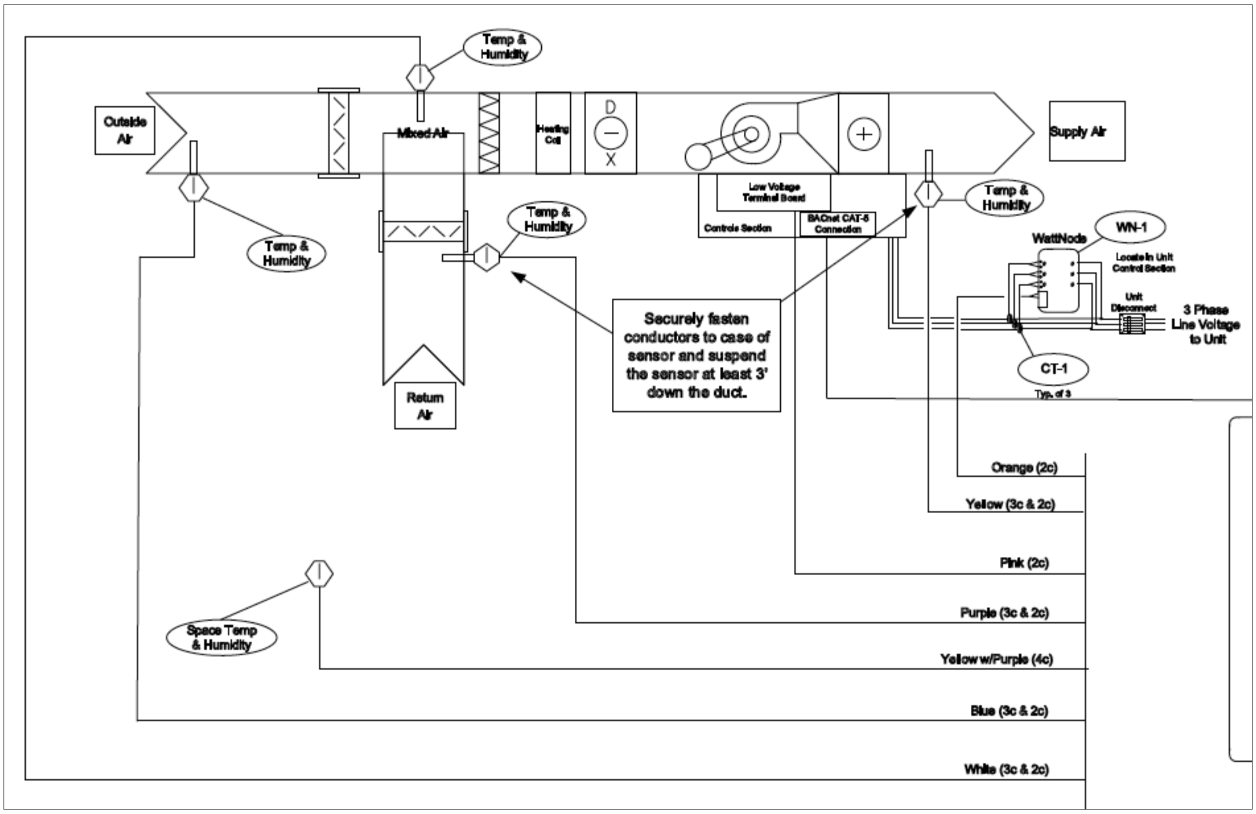

Illustration 2: Detail of Drawing MI-102, Controls Installation, for RTU Challenge projects.

Data was gathered and averaged in hourly increments from June 2016 to March 2017.

Transformative Wave plan was to install four humidity/temperature sensors per unit plus a power sensor[6], with the remaining data points being gathered from the respective units control system.

2.2 Test Bed Site

As discussed before, the units were installed on the Navy Exchange facility at NAS Key West, FL. This site is located near the southern tip of the Florida Keys. It is located in DOE Climate Zone #1, which also includes Hawaii, Guam, Puerto Rico, and the Virgin Islands. It is a warm climate. During the data-gathering period there were only 5 heating degree days, but almost 4500 cooling degree days. The average daily maximum temperature was 84°F, and the minimum was 75°F.[7]

Below is an aerial view of the southern Florida Keys with the Navy Exchange building highlighted.

[6] Proposal from Transformative Wave sent to ORNL on 9/30/2015.
[7] Data from Weather Underground, found at the following link:
https://www.wunderground.com/history/airport/KEYW/2016/6/1/CustomHistory.html?dayend=31&monthend=3&yearend=2017&req_city=&req_state=&req_statename=&reqdb.zip=&reqdb.magic=&reqdb.wmo=

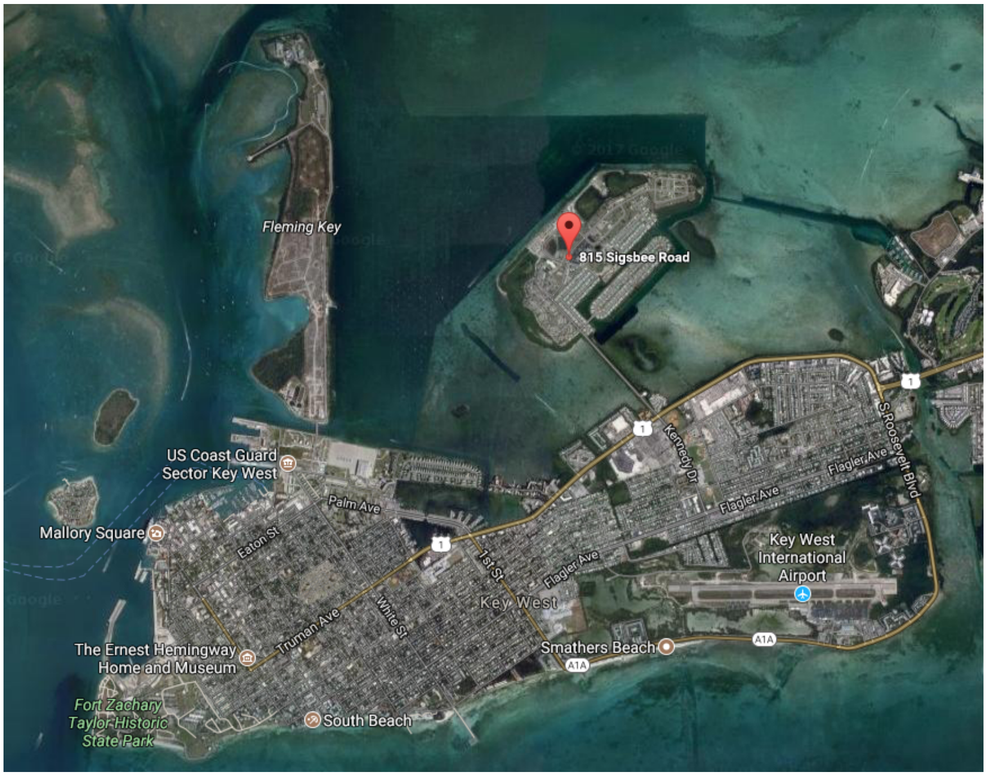

Illustration 3: Areas adjacent to test site.

Here is a detail of the Navy Exchange, with the RTUs highlighted.

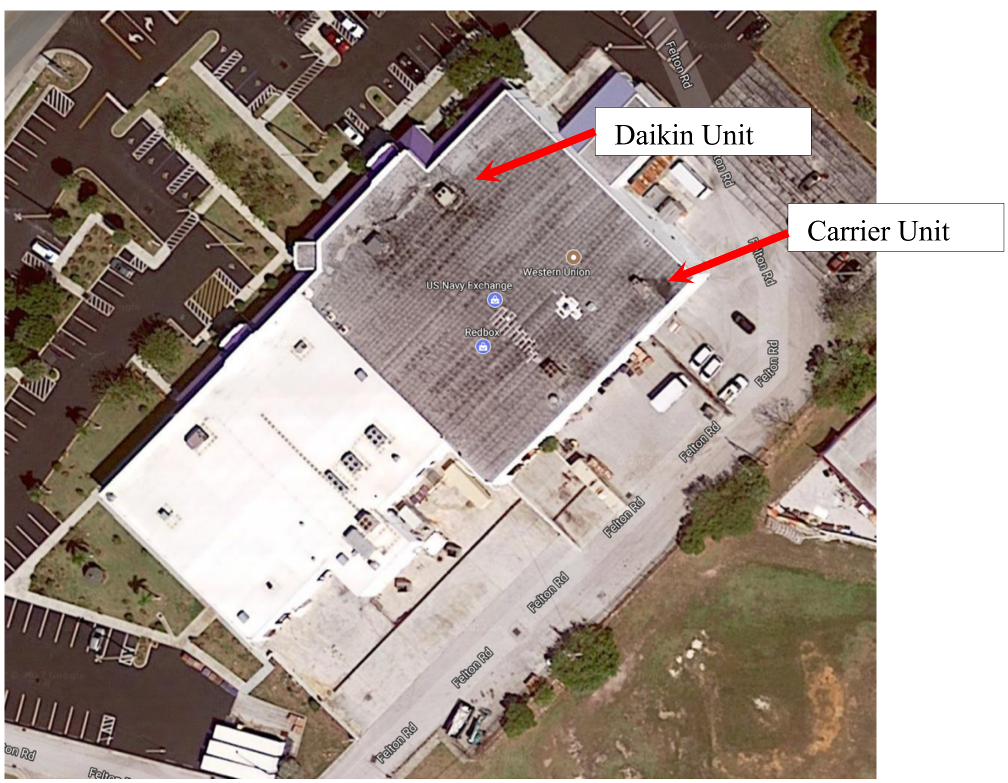

Illustration 4: Roof of Navy Exchange

This building made an ideal test site due to its near constant cooling load when the facility was in operation. Also, there had not been another performance evaluation of these units in a warm ocean-front climate like that found at Key West.

2.3 Methodology

The methodology for calculating the Daikin unit's EER was very straight forward. For each hour that the unit was operating, the total cooling capacity was converted to BTUs, and the average electrical energy consumption was converted to Whr. Dividing the former by the latter gave the unit's average EER for that given hour. It should be noted that there were 5,450 hours during the test period in which the Daikin unit was actually operating.

With each hour's EER calculated, it was a simple matter to average all 5,450 data points to determine the unit's average EER during this test period.

3. DEMONSTRATION RESULTS

3.1 Quantitative Results

The Daikin unit's EER was measured every hour. The outside air temperature was also measured over the same time spans. The graph below shows how the EER varied as the outside air temperature changed.

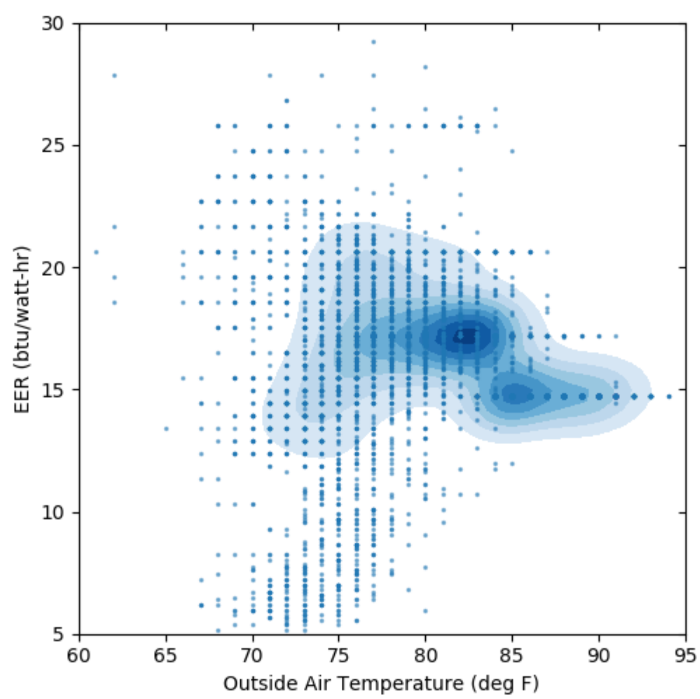

Illustration 5a: EER vs Outside Air Temperature

The Daikin unit's average EER over the test period was 15.7BTU/Whr. Given that this value was measured under field conditions, it compares favorably with the RTU Challenge threshold IEER of 18.0BTU/Whr.

Note that in this graph, individual data points are shown as dots. However, due to the large amount of data gathered, there are parts of the graph where individual points are too dense to be seen clearly. In these areas, "contour lines" and coloration have been applied to communicate areas of greatest density. In this graph, the darkest colors with the smallest areas indicate the ranges which have the greatest densities of data points. As the encompassed areas become larger and the colors become lighter, the density of data points becomes less until individual points become visible.

Also note that the graph shows individual moments when the EER was as low as 5 or as high as 30, with most of these moments reporting lower EERs. These points are excursions that occur when the unit is undergoing rapid changes in its operating conditions. Typically, these are during startup and shutdown of the unit.

For example, during startup, an RTU typically is drawing a large quantity of electrical power, but it takes time for the refrigerant circuit to reach a state of equilibrium and provide the cooling that is called for. During these times, the EER will be dramatically less than what it would be once it reaches an optimal state. It is important to note the lower excursions are what cause the field-measured average EER to be lower than the lab-measured IEER.

Another major contributor to the difference between the field-measured EER and the lab-measured IEER is the outside air conditions under which the unit is operated when measuring performance. When measuring IEER in the laboratory, the "standard" operating profile specified by AHRI dictates that the unit spends over 60% of its time with an outside air temperature of 68.0°F or less[8]. This value represents what which might be found in a "typical" operating environment in many parts of the country. However, at NAS Key West, the ambient temperature was in this range only 2.3% of the time due to its warmer climate. The charts below show the actual distribution of average hourly outside air temperatures when the RTUs were in operation.

This issue can be clearly seen in Illustration 5a. Looking at the dark areas of the graph, where the data points are most dense, there is a clear trend that shows the EER going down as the outside air temperature going up. Extrapolating this trend, it is reasonable to expect that the EER would go up as the outside air temperature becomes cooler. As the average air temperature goes below 68°F, the field-measured EER would approach the lab-measured IEER of 18.0.

[8] Details of how to calculate IEER can be found in AHRI Standard 340/360-2015 at http://www.ahrinet.org/App_Content/ahri/files/STANDARDS/AHRI/AHRI_Standard_340-360_2015.pdf .

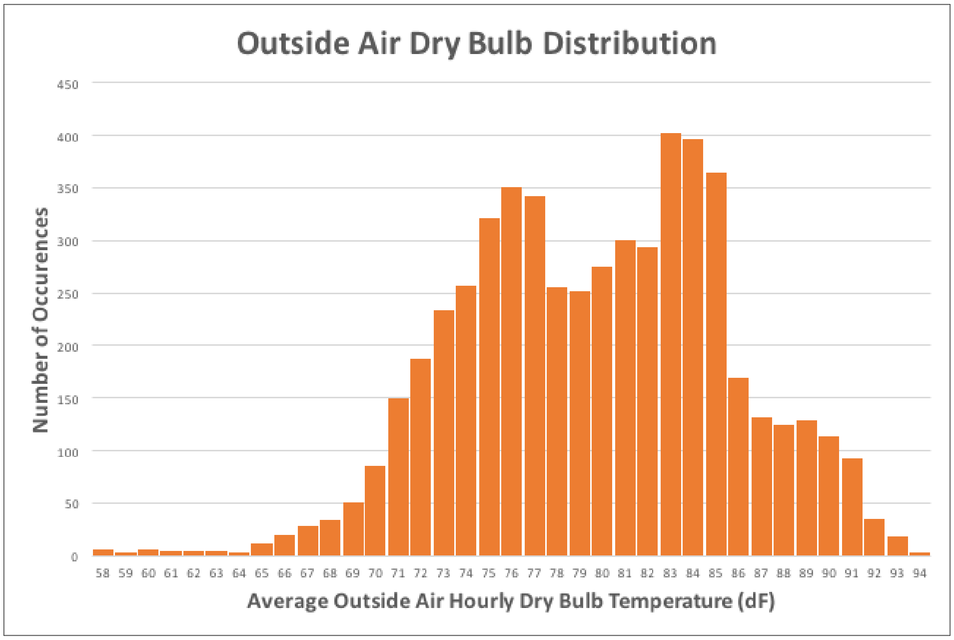

Illustration 5b: Average Outside Air Temperature Distribution

According to the laws of thermodynamics, it is harder for the RTU's condenser section to reject heat to the ambient air when its temperature is warmer. That difficulty results in the compressor motor operating harder to pump more refrigerant, and the condenser fans operating more frequently to circulate warmer air over the condenser coils. Extra run time on these motors results in greater consumption of electricity for the same cooling capacity delivered, thereby increasing the EER measured in the field environment.

In addition to the differences in outside air temperature, other factors can adversely affect performance in a field environment. Filters can become dirty and impede airflow. Cooling coils can be dirty, impeding airflow and heat transfer. Condenser coils can collect dust from the atmosphere. In the case of an ocean side location, it would not be unexpected to find a salt crust forming on the condenser coils as ocean spray evaporates from the warm surfaces. This coating would further impede heat transfer and degrade performance.

3.2 Qualitative Results

ORNL received no negative feedback from site personnel regarding the qualitative traits of either units' performance. They both maintained comfort conditions with their respective spaces. Neither unit's area reported any unusual hot or cold calls.

Both units operated reliably, needing nothing more than routing maintenance such as changing filters.

One negative trait of both units is that they are heavier than typical RTUs of similar cooling capacity. This is presumably due to larger cooling and condenser coils that increase heat transfer rates and contribute to the units' greater efficiency. The added weight must be accounted for when designing structural elements for their use. In the case of a retrofit application, it is possible that roof members would have to be upgraded to support the weight.

One negative qualitative trait occurred with the Carrier unit. As discussed in Section 2.1 Evaluation Design, Transformative Wave's plan was to install humidity and power sensors on the unit, and gather remaining data from the respective unit's control system. The Carrier unit's control system did not have a digital or analog output that communicated the total cooling capacity being provided at any point in time. This data point is important to some building energy managers, especially if they are implementing a more sophisticated energy control strategy. The Carrier unit controls also did not have any combination of outputs (ex: airflow and inlet/outlet temperatures) that could be used to calculate the cooling capacity.

This lack of ability to measure cooling capacity has also led to an inability to calculate the Carrier unit's EER at any point in time, which was the key metric that the report was attempting to gather. ORNL is still working with Transformative Wave to figure out a path forward to gather this information from the Carrier unit.

3.3 COST EFFECTIVENESS

Based on the data collected it is reasonable to conclude that the Daikin unit demonstrated that savings are possible when installing this type of unit. Table 1 calculates the annual cost of operating the system based on a range of annual energy consumption values and a commercial cost of electricity of $0.08/kWh. Table 2 uses this information to calculate the potential energy cost savings between the tested Daikin unit and RTUs with EERs of 12, 10, and 8. Finally, assuming the cost of the Daikin unit is $11K and a standard unit is $7K ($4K difference) Table 3 calculates the payback time in years for annual energy spends between 100 and 1,000 MMBtu.

Table 1 –Annual cost based on EER and load

	Annual load, MMBtu									
EER	100	200	300	400	500	600	700	800	900	1,000
8	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
9	889	1778	2667	3556	4444	5333	6222	7111	8000	8889
10	800	1600	2400	3200	4000	4800	5600	6400	7200	8000
11	727	1455	2182	2909	3636	4364	5091	5818	6545	7273
12	667	1333	2000	2667	3333	4000	4667	5333	6000	6667
13	615	1231	1846	2462	3077	3692	4308	4923	5538	6154
14	571	1143	1714	2286	2857	3429	4000	4571	5143	5714
15	533	1067	1600	2133	2667	3200	3733	4267	4800	5333
15.7	510	1019	1529	2038	2548	3057	3567	4076	4586	5096
16	500	1000	1500	2000	2500	3000	3500	4000	4500	5000

Table 2 – Potential annual savings between test unit and RTUs with a different EER

	$ Savings per year									
Test unit vs EER 12	157	314	471	628	786	943	1100	1257	1414	1571
Test unit vs EER 10	290	581	871	1162	1452	1743	2033	2324	2614	2904
Test unit vs EER 8	490	981	1471	1962	2452	2943	3433	3924	4414	4904

Table 3 – Payback period in years based on annual load

	Annual load, MMBtu									
	100	200	300	400	500	600	700	800	900	1,000
Test unit vs EER 12	25.5	12.7	8.5	6.4	5.1	4.2	3.6	3.2	2.8	2.5
Test unit vs EER 10	13.8	6.9	4.6	3.4	2.8	2.3	2.0	1.7	1.5	1.4
Test unit vs EER 8	8.2	4.1	2.7	2.0	1.6	1.4	1.2	1.0	0.9	0.8

4. SUMMARY FINDINGS AND CONCLUSIONS

4.1 Overall Technology Assessment at Demonstration Facility

The Daikin unit installed at the Navy Exchange at NAS Key West, Florida performed consistently with what its lab-measured IEER rating said it should under the local climate conditions. The average measured EER at the site was 15.7. Given that outside air temperatures at the site were substantially warmer than the well-defined conditions for measuring a unit's IEER, this value can be considered consistent with the IEER.

Both units appeared to be reliable, without requiring any maintenance beyond that which might be required by a typical unit of standard efficiency.

Both units appeared to maintain comfort conditions without any abnormal complaints.

4.2 Deployment Recommendations

There is nothing to prohibit either the Daikin or Carrier unit from being deployed in any climate zone or building type where a standard efficiency RTU would be installed.

The economic viability of the High Performance RTUs needs to be carefully evaluated at each given site to determine if it would be appropriate to purchase one of these units over a standard efficiency RTU. Characteristics that would make the high-performance unit more attractive include, but are not limited to, the following:

- A low marginal cost of the High Performance RTU compared to the standard efficiency unit.
- An extended cooling season with a large number of cooling degree days.
- A facility that operates extended hours and on weekends, thereby requiring additional cooling.
- A facility with high internal heat loads, thereby requiring additional cooling.
- High unit costs of electricity, as measured in dollars per kilowatt-hour ($/kwh)

5. APPENDICES

5.1 Manufacturer Cut References

Carrier: https://www.carrier.com/commercial/en/us/products/packaged-outdoor/outdoor-packaged-units/50lc/

Daikin: http://www.daikinapplied.com/rooftop-rebel.php