RM12-2703 Advanced Rooftop Unit Control Retrofit Kit Field Demonstration

Hawaii and Guam Energy Improvement Technology Demonstration Project

I. Doebber, J. Dean, J. Dominick, and G. Holland

Produced under direction of Naval Facilities Engineering Command (NAVFAC) by the National Renewable Energy Laboratory (NREL) under Interagency Agreement 11-01829

NREL is a national laboratory of the U.S. Department of Energy
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NREL/TP-5500-61072
March 2014

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NATIONAL RENEWABLE ENERGY LABORATORY

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List of Abbreviations and Acronyms

AHJ	authority having jurisdiction
ARC	advanced rooftop control
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BLCC	Building Life Cycle Cost program
BMS	building management system
BPA	Bonneville Power Administration
CAV	constant air volume
CNIC	Commander Navy Installations Command
CO_2	carbon dioxide
COLS	Common Output Level Standards
DCV	demand controlled ventilation
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DX	direct expansion
ESM	energy savings mode (ARC operation)
FDD	fault detection and diagnostic
HECO	Hawaiian Electric Companies
HNL	Honolulu International Airport
HR	humidity ratio
HVAC	heating, ventilation, and air conditioning
IPT	Integrated Product Team
JBPHH	Joint Base Pearl Harbor-Hickam
MA	mixed air
NAVFAC	Naval Facilities Engineering Command

NEPA	National Environmental Policy Act
NEBB	National Environmental Balancing Bureau
NEMA	National Electrical Manufacturers Association
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
non-ESM	non energy savings mode (baseline RTU operation)
PLC	programmable logic controller
PPD	people percentage dissatisfied
SEER	seasonal energy efficiency ratio
SIR	savings to investment ratio
SZVAV	single-zone variable air volume
OA	outdoor air
OAT	outdoor air temperature
O&M	operation and maintenance
OM&R	operation, maintenance, and repair
PNNL	Pacific Northwest National Laboratory
RA	return air
ROI	return on investment
RTD	Resistance Temperature Detector
RTU	packaged air conditioning rooftop unit
SA	supply air
TAB	HVAC testing, adjusting, and balancing
TTF	thermal test facility (NREL operated)
TRL	technology readiness level
TMY3	Typical Meteorological Year 3

TWT	Transformative Wave Technologies; manufacturers of the CATALYST ARC technology and eIQ BMS
UFC	Unified Facilities Criteria
UFGS	Unified Facilities Guide Specifications
VFD	variable-speed drive

Executive Summary

As part of its overall strategy to meet its energy goals, the Naval Facilities Engineering Command (NAVFAC) partnered with U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to rapidly demonstrate and deploy cost-effective renewable energy and energy efficiency technologies. This was one of several demonstrations of new and underutilized commercial energy efficiency technologies. The common goals were to demonstrate and measure the performance and economic benefit of the system and to monitor any ancillary impacts related to standards of service and operation and maintenance (O&M) practices. In short, these demonstrations simultaneously evaluated the benefits and compatibility of the technologies with the U.S. Department of Defense (DOD) mission, and with NAVFAC's design, construction, and O&M practices.

A wide variety of DOD buildings such as offices, warehouses, gymnasiums, commissaries, exchange stores, and hangers are ventilated, cooled, and heated with packaged rooftop air conditioning units (RTUs). The term *RTU* refers to a pre-engineered unitary system that houses all the components of a heating, ventilation, and air conditioning (HVAC) system in a single package. Most RTUs are located on the roof but can also be located on concrete pads next to the buildings they serve. In Hawaii, RTUs provide only space cooling and outdoor air (OA) for ventilation, as no heating is needed. RTUs are popular for commercial buildings for three reasons: (1) minimal engineering design and specification; (2) low first costs compared to built-up systems (e.g., chillers with air handling units); and (3) quick installation. Unfortunately, RTUs have historically been one of the lowest efficiency HVAC systems on the market. Consequently, the RTU retrofit market has significant opportunities for energy savings. Within the past 5 years, advanced rooftop control (ARC) retrofit kits have become commercially available to reduce RTU energy consumption and improve thermal comfort. ARC retrofit kits boost the performance of RTU equipment by controlling its components with greater dexterity.

Demonstration Description

This report summarizes the field demonstration of ARCs installed on nine RTUs serving a 70,000-ft^2 exchange store (large retail) and two RTUs, each serving small office buildings located on Joint Base Pearl Harbor-Hickam (JBPHH). Of the commercially available ARC systems, NREL chose the CATALYST, developed by Transformative Wave Technologies (TWT), because it: (1) has been successfully involved with other DOE- and utility-sponsored field demonstrations; (2) incorporates all the advanced control features NREL had specified to demonstrate for NAVFAC; and (3) can be packaged with TWT's Web-based building management system (BMS) called the "eIQ" for remote monitoring. After overseeing their installation, NREL monitored the ARC systems' performance to quantify their energy savings potential, return on investment (ROI), thermal comfort benefits, and other performance impacts for NAVFAC.

Commercially available ARC technologies incorporate various advanced control features; however, all use a variable frequency drive (VFD) to convert the constant-speed fan to a variable-speed fan. Most ARC products supersede the RTU's original controller with a new controller. Other advanced control features include demand controlled ventilation (DCV), enhanced economizing, and demand response. Some of the more sophisticated ARC retrofit systems can also be packaged with a Web-based BMS that provides remote control, monitoring,

and automated fault detection and diagnostics (FDD). All these features were implemented with the CATALYST ARC system and eIQ BMS and closely monitored for this demonstration. The one feature that was available and not implemented was humidistat control. Although the Hawaii humidity is high, the RTUs were able to be controlled based on space temperature to maintain space RH < 65%.

NREL incorporated field-applied coil coatings into the demonstration to determine if this is another critical feature to include in ARC installations for maritime climates. The corrosive environment of Hawaii—and even more so that of Guam—reduces RTU life expectancy. The coil coating applied to new RTUs eventually wears down such that the condenser coil corrodes. This degrades performance and increases maintenance. During the ARC installation, NREL had the evaporator and condenser coils cleaned and then coated with HVACArmor DX on five of the 11 RTUs. NREL chose the HVACArmor DX product because it can be field applied and it meets UFGS 23 82 02 00 10 requirement with a minimum of 1,000 hours exposure to the ASTM B117 salt spray test.

For a baseline, each RTU's operation was alternated weekly between non-energy savings mode (non-ESM) or baseline operation and energy savings mode (ESM). During ESM operational weeks, all the advanced control features of the ARC system were enabled. Instead of measuring the baseline operation before installing the ARC systems, alternating weekly exposed both operational modes to similar ambient conditions and building operations. The RTU baseline was a constant-speed supply fan, fixed OA damper (no economizing or DCV), and no demand response capability.

Energy Savings and Return on Investment

NREL calculated the annual energy savings at the building level rather than evaluating each RTU individually for two reasons. First the nine RTUs on the exchange store influenced each other's operation and worked as a "team" to condition the large space that they mutually served. Second, evaluation and deployment of this technology should be kept at the building level such that all RTUs serving a single space should be retrofitted together. Although the demonstration periods were short (3 to 6 months depending on the building), NREL used the monitored data to develop a linear regression model. Each building's daily total RTU energy usage was correlated against ambient conditions (NOAA's Honolulu International Airport weather station). NREL then applied the model to Honolulu International Airport Typical Meteorological Year 3 (TMY3) normalized weather data to determine the annual energy savings.

Table ES-1 shows the aggregated energy savings and ROI indices based on the Neptune eROI calculator and NIST Building Life-Cycle Cost (BLCC) program. The "Demo Actuals" ROI metrics are based on the actual demonstration ARC installation costs and calculated energy savings across the 11 RTUs. Still based on a set of 11 RTUs, the "Projected Follow-On Deployment" analysis assumes that future ARC installations abide by the demonstration's lessons learned as discussed in this report:

- Choosing facilities with multiple RTUs and significant building operating hours of at least 50 hours per week

- Choosing ARC systems with variable-speed supply fan, DCV (authority having jurisdiction (AHJ) approved per UFC 3-410-01), and Web-based BMS capabilities (permission confirmed through local NAVFAC CIO that meets IT security requirements)
- Choosing RTUs of at least 7 tons capacity and at most 10 years of age
- Leveraging proper procurement methods with the testing, adjusting, and balancing (TAB) activity limited to balancing the SA and OA flow rates at each RTU (no air distribution balancing).

Table ES-1. Economic Analysis Results

	Demo Actuals	Projected Follow-On Deployment
Annual Energy Savings	100 MWh	120 MWh
eROI Value	5.2	6.9
Net Savings	$170,000	$270,000
Savings to Investment Ratio (SIR)	1.9	2.8
Simple Payback	in 5th year	in 3rd year
Adjusted Internal Rate of Return	10%	14%

Table ES-2 shows the energy savings and the SIR for each building based on the actual demonstration costs. By choosing ARC systems with features that showed valuable energy savings in the Hawaii climate and limiting the TAB activity, the ROI can be improved; 2.8 SIR in Table ES-1 compared to a 0.3–2.3 SIR in Table ES-2.

Table ES-2. Demonstration Results by Building

	Building Description	Annual Building HVAC Energy Savings[a]	Annual Energy Savings per RTU	Annual Cost Savings per RTU[b]	SIR[c]
1235H BXtra	• Big box retail • 70,000 ft^2 • 9 RTUs @ 175 tons • 5,840 h/yr	• 15% reduction • 96,498 kWh • normalized 94 kWh/ton/1,000 h operation	10,722 kWh/yr	$4,557	2.3
Building C27	• Small office • 2,706 ft^2 • 1 RTU @ 12.5 tons • 2,210 h/yr	• 7% reduction • 1,526 kWh • normalized 55 kWh/ton/1,000 h operation	1,526 kWh/yr	$649	0.2
Building A13	• Small office • 7,834 ft^2 • 1 RTU @ 20 tons • 2,340 h/yr	• 5% reduction • 1,803 kWh • normalized 39 kWh/ton/1,000 h operation	1,803 kWh/yr	$766	0.3

[a] Normalized energy savings metric based on nominal cooling tons and annual building operating hours.
[b] Electricity pricing reflect the average price of FY 2013 and FY 2014 rates at JBPHH.
[c] SIR based on actual ARC installation costs.

Additional Advanced Rooftop Control Performance Benefits

Beyond energy savings, the ARC technology provided the following performance benefits:

- ARC operation achieved a lower relative humidity (RH) compared to the baseline operation for all three buildings because fan speeds were slower during cooling operation, the OA damper was shut during unoccupied times, and DCV reduced ventilation rates. The difference in the space temperature during occupied hours was negligible. The 1235H BXtra building showed the most dramatic improvement with a 5% reduction in average RH during occupied hours.
- NAVFAC can realize additional energy savings by leveraging ARC systems with Web-based BMS capabilities. Local NAVFAC CIO needs to approve the web-based BMS to determine if it meet IT security requirements. If approved, the BMS can provide NAVFAC energy managers remote temperature set point and scheduling capability. NAVFAC can consistently implement and enforce the latest NAVFAC Hawaii and Common Output Level Standards (COLS) requirements. The lower space RH levels maintained by ARC systems provide improved thermal comfort under warmer temperature set points. The combination of ARC systems and COLS level 3 or 4 control will push the energy savings beyond that shown in this demonstration report.
- The demand response sequence initiated on the 1235H BXtra showed a 12% (0.27 W/ft^2) to 27% (0.60 W/ft^2) peak power reduction across the predefined demand response window (1:00 p.m. to 3:00 p.m.). The greatest demand response was realized during August (the hottest month). This demand response sequence would only be implemented if the local utility was providing additional rebates to NAVFAC for permanent load reduction or DR capabilities.
- The automated FDD built into the Web-based BMS worked as expected; however, the actions taken by the local HVAC service technicians and NAVFAC's service technicians based on the FDD alarms were mixed. The BXtra experienced two maintenance alarms during the demonstration. The first, a failing fan belt, was identified and replaced before it failed. The second lost communication to one of the nine RTUs. Whether the unit continued to run based on its own controller is unknown; neither TWT nor NREL were contacted about comfort issues. It took almost a full month until action was taken to reestablish communication. Similarly, the maintenance issues with C27 and A13 were properly identified by FDD alarms but the response by HVAC technicians did not improve compared to typical O&M activities. To leverage automated FDD in preventing future comfort calls and catastrophic failures, NAVFAC HVAC technicians and contracted HVAC service providers will need to adopt a more formalized procedure to respond to web-based alarming.

Recommended Next Steps

The immediate next step will be for NREL to monitor ESM versus non-ESM performance through January 2014 and provide an addenda report to NAVFAC reflecting updated annual savings estimates. ARC retrofit technologies are TRL 9 and commercially available. Based on the results in this report, NAVFAC should adopt ARC retrofits on facilities in this climate zone that meet the building and RTU attributes summarized in the bullets above. Although the large BXtra building for this demonstration was a big box retail facility, the energy savings implications would be applicable to medium and large buildings with extended operational hours (50 or more hours per week). These include recreation centers (bowling alleys, gymnasiums), conditioned hangers or warehouses, cafeterias, and commissaries. When evaluating potential ARC projects, NAVFAC should evaluate whether the variable ventilation rates will impact building or space pressurization requirements especially with independent exhaust systems such as kitchen hoods.

For buildings smaller than 10,000 ft^2 where one RTU serves a single space, NAVFAC should conduct additional monitoring on ARC systems. Although NREL provides ARC energy savings information on A13 and C27 in this report, both buildings had issues during the demonstration period that mitigated ARC energy savings. The RTU serving building A13 experienced multiple maintenance issues unrelated to the ARC system, which minimized the valid dataset comparing ESM to non-ESM operation. The RTU serving building C27 experienced uncharacteristically long periods of second-stage cooling. After verifying that the first stage compressor was operating properly, NREL determined that the reason was because the temperature sensor was adjacent to an exit door and was significantly influenced by infiltration. Consequently, the ARC energy savings were lower than anticipated. Fortunately, the Integrated Product Team procured and had installed additional ARC systems at JBPHH. Similar to this demonstration, NAVFAC could monitor these installations to provide a larger sample size of ARC energy savings for small facilities across a broader range of building functions. With proper operation, ARC energy savings for NAVFAC's prevalent small buildings like A13 and C27 may show greater energy savings than those presented here.

NREL could discern no consistent performance difference between the RTUs with and without the coil coating. As a recommended follow-on activity, NAVFAC should keep track of the five RTUs with the HVACArmor DX coil coating to determine if their lifetimes are extended. If the RTU lifetime is extended and, depending on how many additional years can be expected, NAVFAC should consider including coil coatings in the standard ARC installation.

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1 Introduction

As part of its overall strategy to meet its energy goals, the Naval Facilities Engineering Command (NAVFAC) partnered with U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) to rapidly demonstrate and deploy cost-effective renewable energy and energy efficiency technologies. This is one of several demonstrations of new or underutilized energy technologies. The common goals are to demonstrate and measure the energy savings and return on investment (ROI) of a system and to monitor any ancillary impacts related to standards of service and operations and maintenance (O&M) practices. The standards of service may include acceptable temperature and humidity ranges, power quality, allowable setbacks, noise criteria, air quality parameters, light levels, and other related factors. In short, demonstrations at DOD facilities simultaneously evaluate the benefits and compatibility of the technologies with the DOD mission, and with its design, construction, and O&M practices.

The consistent year-round demand for air conditioning and dehumidification in Hawaii provides an advantageous demonstration location for advanced rooftop control (ARC) retrofit kits to packaged rooftop units (RTUs). The term *packaged RTU* refers to a pre-engineered unitary system that houses all the components of a heating, ventilation, and air conditioning (HVAC) system. Over the last few years, a number of innovative and cost-effective ARC retrofit kits have entered the marketplace. All convert a constant air volume (CAV) RTU into a single-zone variable air volume (SZVAV) RTU by controlling the supply fan with a variable frequency drive (VFD). The ARC retrofit supersedes the original controller, thereby improving energy usage compared with the simpler control logic typical of RTUs. Then depending on the ARC retrofit kit, other energy-saving features are included such as demand controlled ventilation (DCV) and enhanced economizing. Most commercially available ARC retrofit kits can be integrated into simple, Web-based building management systems (BMSs) to enable remote control and some automated fault detection and diagnostics (FDD). The ARC-BMS retrofit package provides a turnkey solution that can be purchased from a single manufacturer and then installed by a single contractor.

A wide variety of Navy buildings such as offices, warehouses, gymnasiums, commissaries, exchange stores, and hangers are air conditioned and dehumidified with RTUs. NAVFAC's current method of saving HVAC energy has been to mandate allowable operational hours and warmer thermostat set points. Yet these mandates are not uniformly applied and maintained across NAVFAC's large portfolio of buildings. NAVFAC can leverage the ARC-BMS retrofit package to realize energy savings through the ARC standalone features as well as the capability to strictly enforce operational hours and thermostat set points through a centralized BMS. The following demonstration quantifies the energy savings and ROI of the ARC-BMS package for hot-humid climates.

2 Demonstration Objective

Innovative RTU retrofit kits can significantly reduce the energy usage of packaged RTUs, which are pervasive throughout the small- to medium-sized commercial buildings sector. Previous DOE studies have coined the term *advanced rooftop control* (ARC) retrofits for this product category. This demonstration focused on ARC retrofit impacts on (1) annual energy savings and ROI; (2) thermal comfort; and (3) demand response. Independent modeling studies (Studer 2012; Wang 2011) and other DOE and utility field demonstrations (Wang 2013; BPA 2013; Snohomish 2013; Appendix C) have shown significant energy savings potential and aggressive paybacks for ARC retrofits. Yet none of the demonstrations were in a hot-humid climate (ASHRAE climate zone 1A), and to date no studies have analyzed the impacts on interior thermal comfort and demand response. Therefore, a field demonstration was the next logical next step in demonstrating performance benefits specific to the Navy's Pacific Island facilities.

2.1 Technology Description

Typical RTUs in Hawaii and Guam use simple wall-mounted thermostat controls, constant-speed supply fans, fixed position outdoor air (OA) dampers, and single speed compressors. Most RTUs are located on the roof but can also be located on concrete pads next to the building.

Figure 1 shows the basic components of a standard RTU. An RTU uses a supply fan to draw in return air (RA) from the space along with a controlled amount of OA for ventilation. The mixed air (MA) is then cooled as it passes through an air conditioning evaporator coil filled with cold refrigerant. If the MA has a high enough humidity (all year for Hawaii and Guam), moisture condenses on the cold air conditioning evaporator coil surface and then drains from the unit. The cooled, dehumidified air is then supplied to the space.

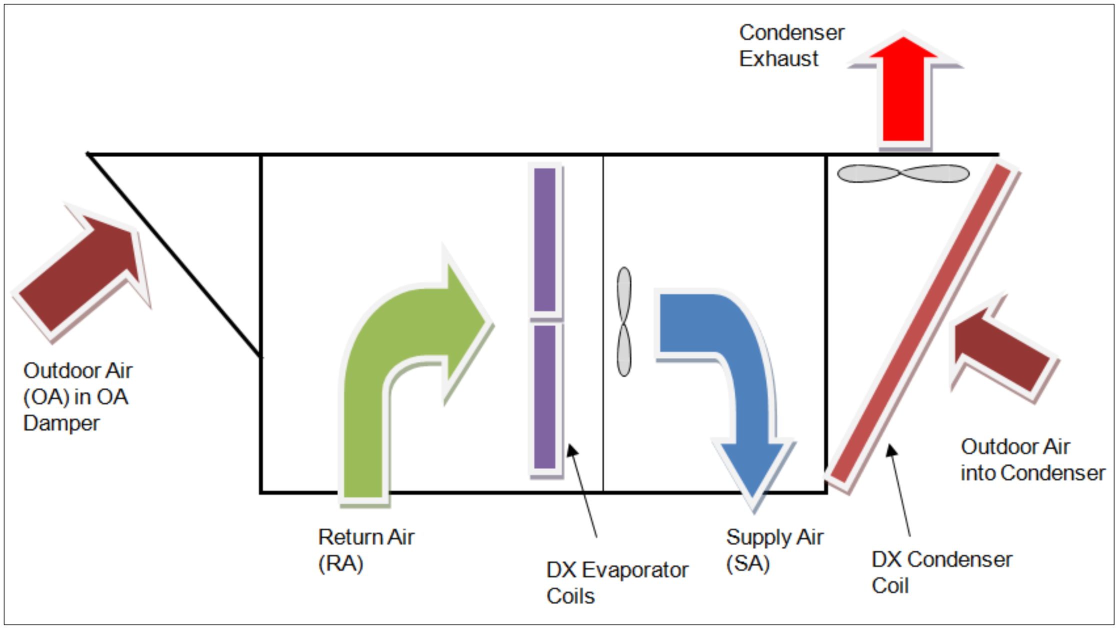

Figure 1. Generic RTU schematic

Through the use of a standard refrigeration air conditioning cycle, also called a direct expansion (DX) cycle, the heat absorbed by the refrigerant in the evaporator coil is pumped by the compressor to the condenser coil. The DX cycle rejects its heat outside the conditioned space by blowing OA across the condenser coil. Most RTUs with 10 tons of cooling capacity operate with two compressors, referred to as having two "stages." Some RTUs are large enough to have four stages of cooling with four compressors.

ARC retrofit technology is designed to integrate into existing RTUs (see Figure 2), regardless of make or model. Fortunately, there are only minor variations between manufacturers' RTUs. The ARC controller supersedes the RTU's existing controller and controls the individual components (compressors, fans, OA damper) based on a signal from the BMS or thermostat/humidistat. While the retrofit is taking place, the RTU is retro-commissioned to ensure that all components are properly tuned.

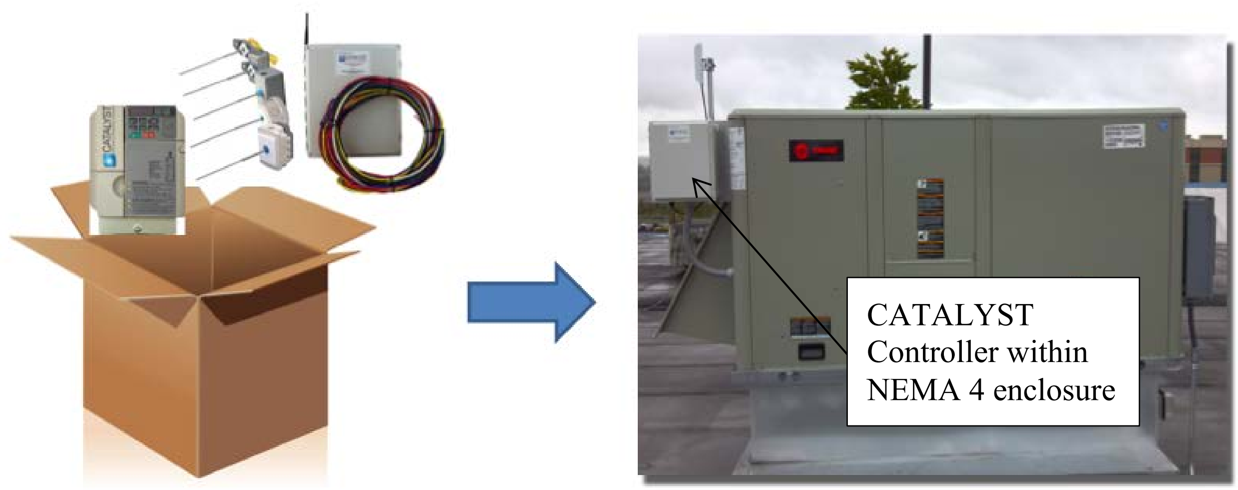

Figure 2. CATALYST retrofit kit

Of the commercially available ARC retrofit kits summarized in Section 7.1, NREL selected the CATALYST system for this demonstration. The CATALYST ARC retrofit consists of the following components:

- Programmable logic controller (PLC) with multiple analog and digital input/outputs
- Supply fan variable frequency drive (VFD) (Yaskawa V1000)
- Additional sensors providing input to the controller include:
    - Supply air (SA) temperature sensor
    - RA temperature and relative humidity (RH) sensor
    - RA carbon dioxide (CO_2) sensor,
    - Outside air temperature (OAT) and RH sensor
    - Total RTU power meter
    - Fan power meter (embedded within the VFD)

- Communication equipment via wireless modem or direct landline connection.

Typical of ARC retrofit systems, the CATALYST is installed inside the RTU cabinet if sufficient room is available; otherwise, it can be installed in a National Electrical Manufacturers Association (NEMA) 4 rated enclosure outside the RTU cabinet (Figure 2).

The CATALYST ARC uses five primary features to reduce energy use, improve thermal comfort, and shift peak demand.

2.1.1 Variable-Speed Supply Fan Operation

An RTU's airflow rate is sized to meet the most demanding heating or cooling day of the year. RTUs are typically configured with a constant-speed supply fan that moves more air than is necessary during part load operation (which constitutes most of the year). The ARC retrofit VFD modulates the supply fan speed based on the mode of operation, moving only the amount of air necessary to meet the space demands.

2.1.2 Demand Controlled Ventilation

Based on Unified Facilities Guide Specifications (UFGS) 23 81 00 00 20, NAVFAC facilities are to be ventilated according to the ASHRAE 62.1-2010 standard. The 62.1 standard's "ventilation rate procedure" stipulates that the OA flow rate must meet a summation of two minimum requirements: (1) ventilation to offset material off-gassing (OA flow rate per conditioned square footage); and (2) ventilation to offset human odors and meet breathing needs (OA flow rate per occupant). These requirements depend on building type (e.g., office, retail). The OA damper must provide sufficient ventilation that equals or exceeds the sum of both ventilation requirements.

By enabling DCV, ARC retrofits can control the OA damper to maintain a lower ventilation rate to offset the material off-gassing minimum requirements. Most commercially available ARC technologies, including the CATALYST, implement DCV by actuating the OA damper based on a CO_2 sensor in the RA duct. When the CO_2 concentration exceeds a defined threshold, typically 1,000 ppm, the OA damper opens. The ventilation rate is increased until the CO_2 concentration drops below the threshold minus a defined deadband, typically 250 ppm.

DCV saves energy throughout the year regardless of climate because it reduces the heating or cooling needed to condition the ventilation air. Other ARC studies, particularly Wang et al. 2011, showed that the most significant DCV savings were in heating-dominated climates. Heating of ventilation air requires significantly more energy than does cooling or dehumidification. Yet the energy savings can be appreciable in humid climates such as Hawaii and especially Guam.

The CATALYST ARC retrofit uses electronically actuated OA. Depending on the condition of the OA damper and actuator, they may need to be replaced to ensure proper operation.

UFC 3-410-01 section 401.1 states that "*Use of CO2 sensors for ventilation control is prohibited unless approved by AHJ*". AHJ stands for authority having jurisdiction. Based on correspondence with NAVFAC, the reason for this stipulation is regarding the concern that CO_2

sensors are inaccurate and will drift overtime. There are a wide range in CO_2 sensor quality and different methods by which these sensors auto-calibrate overtime.[1] If the AHJ decides that CO_2 sensors will not provide sufficient accuracy over time then the DCV feature of the ARC technology will need to be eliminated. Although another method of measuring real-time occupancy may be acceptable. According to ASHRAE Standard 62.1, other methods include: population counters, timers, occupancy schedules, or occupancy sensors. Yet NREL has not found ARC technologies that use these other methods of measuring occupancy.

2.1.3 Enhanced Economizing

During the swing season (spring and summer in most U.S. climates), OA flow rates beyond the minimum ventilation rates can be used to provide cooling. This "free cooling" leverages OA to reduce compressor runtime and save energy. Building engineers and HVAC technicians primarily apply a dry-bulb temperature based control sequence in dry climates because it is simple and does not require a humidity sensor. The CATALYST applies a differential dry bulb with dew point lockout sequence. The CATALYST disables economizer operation when the OA dew point exceeds 60°F. Unfortunately, Hawaii's and Guam's climate is so humid that the OA dew point exceeds the 60°F lockout during most of the year. For this demonstration, NREL enabled the OA economizer control sequence to evaluate its effectiveness in this climate zone to determine if this feature should be included in future Hawaii ARC retrofit installations.

2.1.4 Peak Demand Reduction

Because utilities reach their peak generation capacity on extremely hot days, peak demand charges for commercial buildings have been increasing much faster than energy rates in densely populated parts of the country. ARC retrofit systems have sufficient intelligence to be set up to cycle compressors and increase space temperature set points as needed during a demand event. The demand event can be triggered based on a signal from a BMS, a building operator, or a "load-shed" signal from the utility company. This is not a standard feature of the CATALYST system; however, NREL had this feature added to evaluate the peak demand reduction capabilities of ARC technologies. The peak demand capability demonstrated was a proof of concept. It would only be implemented if the local utility agreed to provide specific rebates for the ARC system based on its permanent load reduction and DR capabilities. Currently the only applicable rebate for the CATALYST system on JBPHH was approximately $15 per motor hp for adding a VFD. The capability for end-uses like RTUs to shed load when the utility needs too will be valued and incentivized in the near future.

2.1.5 Building Management System Functionality

RTUs are typically controlled through standalone, wall-mounted thermostats. These simplified controls are not typically tied into a centralized BMS and are primarily used to set an operational schedule and space set point temperature. Typically the OA damper operation is tied to the thermostat set point. Some ARC manufacturers integrate Web-based BMSs that were developed

[1] The Iowa Energy Center conducted a study evaluating the accuracy of 15 wall mounted CO_2 sensors from 13 manufacturers. All of the sensors were found to have an accuracy range of +/-100 to 200 ppm over a CO_2 concentration range of 400 to 1,800 ppm. These accuracies were for new sensors and do not include the error induced by drift over time. For more information, see www.iowaenergycenter.org/wp-content/uploads/2012/05/PTR_CO2.pdf.

for their own retrofit kits. Specifically for this demonstration, the CATALYST was packaged with the "eIQ Energy Intelligence Platform" that serves as a standalone Web-based BMS or can tie into an existing BMS. A screenshot of the eIQ user interface for a single RTU is provided in Figure 3. NAVFAC can access the eIQ website at www.eiqonline.com.

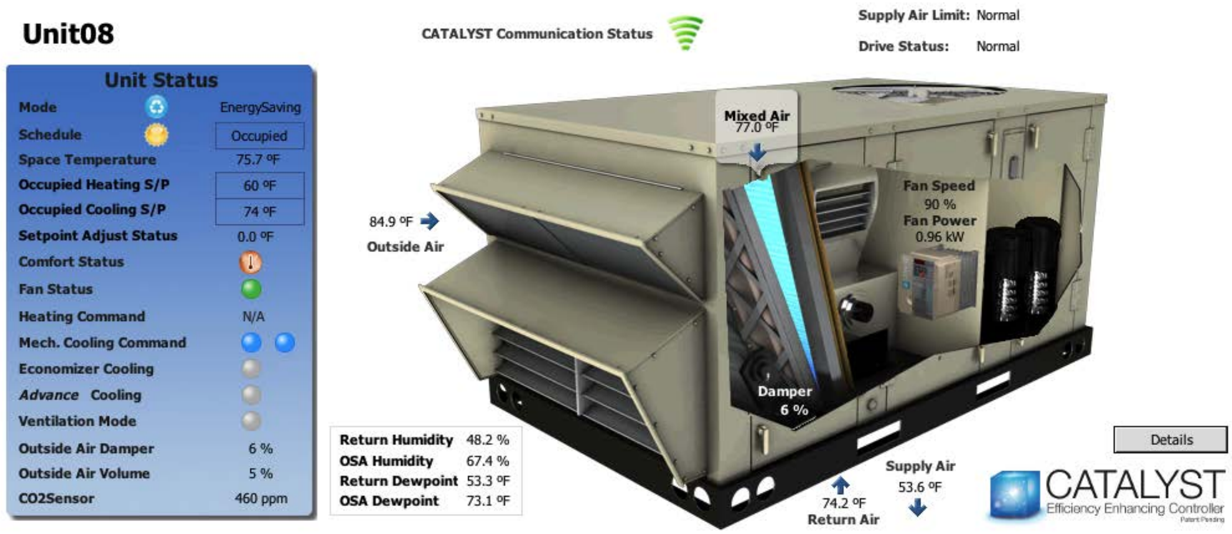

Figure 3. eIQ RTU dashboard showing status and basic automated FDD

Beyond remote control of thermostat set points and occupancy schedules, these ARC-BMS packages can provide energy management and various levels of automated FDD.

The CATALYST ARC retrofit has a number of proprietary automated FDD control sequences such as detecting fan belt slippage and breaks, determining filter replacements, ensuring adequate airflow, and ensuring appropriate discharge air temperatures. To understand the O&M impact of automated FDD, NREL monitored the notifications throughout the demonstration and documented whether these improved or hindered typical NAVFAC O&M procedures. Figure 4 provides another snapshot of the eIQ Web interface providing high-level RTU status information. If a maintenance issue with the RTU were alerted by an automated FDD algorithm, the "health" icon would indicate a problem and have an associated notification to provide some insight into the cause.

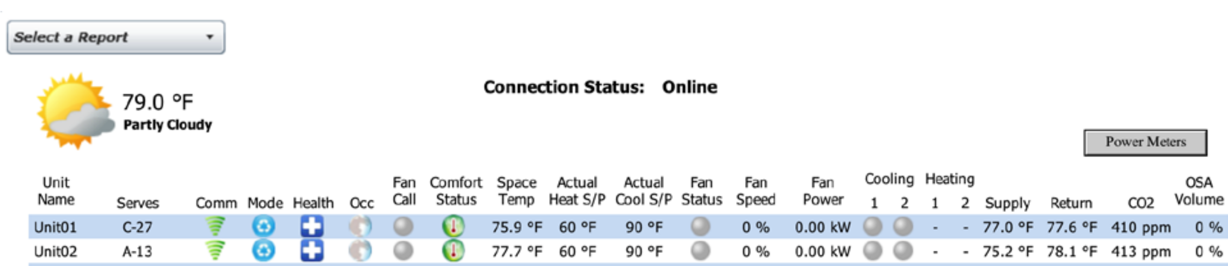

Figure 4. eIQ BMS Web interface showing important RTU status and automated FDD, which are incorporated into the CATALYST-defined "health" of the RTU

ARC systems use wireless communication from RTU to RTU and then cellular communication from the building to a central database located on a cloud server. The CATALYST used Wi-Fi standard 802.11a and broadcast at 5 GHz on its own network at each building. Each building then communicated back to an Amazon server through a Verizon Private Network. Prior to installing, the local NAVFAC CIO will need to approve the RTU-to-RTU communication at the building and then the cellular communication from the building. Additionally, the local CIO will need to approve NAVFAC HVAC technician and building energy manager access to the ARC's Web-based BMS to ensure it meets NAVFAC IT requirements.

2.2 Advanced Rooftop Control Retrofit Sequence of Operation

An RTU has several modes of operation to maintain comfortable temperature and humidity ranges and sufficient ventilation. Each is explained below, using an example of a 10-ton RTU with maximum SA flow of 4,000 cfm and a two-stage DX system operating at a cooling set point of 76°F, and a heating set point of 70°F. The operation of a "baseline RTU" with a constant-speed fan is compared to an RTU enhanced with the ARC retrofit system. The following sequence is based on the CATALYST system. Other ARC retrofit systems may have slightly different sequences.

- **Ventilation operation.** When the space temperature (75°F for example) is lower than the thermostat cooling set point plus a 1°F deadband (76°F) but higher than the thermostat heating set points minus 1°F deadband (69°F), no heating or cooling stages will be on. A baseline RTU supplies 4,000 cfm and maintains the OA damper at a fixed position. The ARC RTU dials down the supply fan speed to 40% (supplies 1,600 cfm) when its RA CO_2 sensor confirms adequate occupancy-based ventilation is being provided. Under this mode, the baseline and ARC RTU simply provide ventilation air and mix the space air. If properly balanced, the ARC RTU provides half the ventilation air as the baseline RTU.
- **First-stage cooling operation.** If the thermostat registers that the space temperature (77.3°F for example) is more than a 1°F deadband above set point (77°F) but less than a 1.5°F deadband above set point (77.5°F), a signal is sent to the RTU that a small amount of cooling is needed. The baseline and ARC initiate the first stage of cooling by turning on the lead compressor. While the baseline unit supplies 4,000 cfm, the ARC RTU supplies only 3,000 cfm by maintaining the VFD at 75% of the maximum fan speed. The ARC RTU modulates the OA damper based on the monitored CO_2 concentrations to ensure sufficient ventilation but not wasting energy by over ventilating. Typically the CO_2 concentration is below the 1,000 ppm threshold such that the ARC provides 75% of the ventilation of the baseline.
- **Second-stage cooling operation.** When the space temperature (78.4°F) is more than a 1.5°F deadband above set point (77.5°F), the thermostat signals the RTU that a large amount of cooling is needed. Both RTUs activate both stages of cooling such that all compressors operate. The baseline RTU supplies 4,000 cfm and the SZVAV RTU supplies 3,600 cfm to maintain the VFD at 90% of maximum fan speed. The baseline RTU maintains the same damper position as in first-stage cooling operation. The ARC RTU slightly closes the OA damper from its first-stage position because the supply fan has increased speed but no additional ventilation is needed. The ARC RTU continues to

monitor the CO_2 concentration and modulate the OA damper accordingly. If the system is properly balanced, the ARC will provide 50% of the ventilation of the baseline.

- **Economizer operation.** During a cooling call (either first stage or second stage), the ARC checks whether the OAT is colder than the RA temperature (differential economizing sequence) and whether the OA dew point is below the 60°F lockout. If the OA meets both conditions, the ARC will open the OA damper to leverage the OA for space cooling. Under first-stage cooling commands, only the economizer is allowed to operate. Under second-stage cooling commands, only the first-stage DX is allowed to operate along with the economizer (this is called *integrated economizer operation*). NREL initiated the CATALYST economizer sequence for the demonstration to determine if Hawaii has enough economizing hours to justify this ARC feature.

2.3 Coil Coating

The marine environment of Hawaii and Guam is corrosive. NREL evaluated NAVFAC's current requirements for coil coatings on new HVAC equipment. UFGS 23 82 02 00 10 Section 2.10.1.1 "Coil Corrosion Protection" covers the factory coating requirements for new unitary heating and cooling equipment. The main requirement is that the coating "*shall be capable of withstanding a minimum 1,000 hours exposure to the salt spray test specified in ASTM B117 using a 5 percent sodium chloride solution*." During the site surveys, NREL noted the aluminum fins to be corroded and brittle. Stickers on the RTUs indicated that the condenser coils had received a Blygold coating which NAVFAC Hawaii has applied to new RTUs by a local Oahu company. It would appear that the Blygold coating in Hawaii does not properly protect the RTU, namely condenser coils, for its entire life.

ARC retrofits improve the performance of existing RTUs that still have at least several years of life until they are replaced. Therefore, NREL included a field-installed coil coating as a part of the ARC retrofit's retro-commissioning process to evaluate the potential to extend the life of the RTU. Corrosion of the condenser coil is one of the main drivers behind performance degradation and factors into decisions to replace old equipment. NREL wanted to investigate whether (1) coil coatings boost or decrease RTU performance immediately; and (2) coil coating would extend the RTU's lifetime and therefore decrease the ARC retrofit life cycle cost.

NREL specified the HVACArmor DX coating product since it can be field applied. HVACArmor DX is composed of Hempel Hempathane DX 55610 polyurethane impregnated with 65% by weight of aluminum. Applied after the coil is power washed with a solvent, the HVACarmor DX forms a 1-mil coating over the fins and coils. The aluminum doping is meant to prevent the coating from inhibiting heat transfer. Section 3.5.6 provides a summary of how many RTUs received the coating and the differences between Blygold and HVACArmor DX.

3 Demonstration Design

This section provides a detailed description of the site selection process, field data acquisition, equipment calibration and testing procedures, and baseline characterization.

3.1 Site Selection

JBPHH and NAVFAC PAC were selected as the demonstration sites because the hot-humid climate poses unique challenges for ARC retrofit technologies. Other utility- and DOE-sponsored ARC field demonstrations have not included this climate. The following criteria were used to select the RTUs:

1. The supply fan motor electrical service must be three phase.
2. The RTU must be controlled to have the fan constantly on during occupied hours to meet ventilation requirements (not “auto” fan control).
3. The RTU had to be less than 15 years old for Hawaii. Any RTU that is more than 15 years old should be considered for replacement because it is nearing the end of its operational life, particularly in a marine climate. Guam typical RTU life expectancy is 7 years.
4. The larger the RTU capacity, particularly the supply fan motor size, the greater the savings and the quicker the payback. RTUs larger than 7 tons were targeted for this demonstration.

A site visit was conducted in May 2012 and 11 RTUs across three buildings were selected for demonstration. These are described in the following sections.

3.1.1 BXtra 1235H

ARC retrofit kits were installed on all nine RTUs serving the BXtra 1235H, an exchange store located on Hickam Air Force Base. The entire building has a total floor area of 118,338 ft^2 based on the Navy’s iNFADS report, and is operated 7 days per week. The RTUs have a combined capacity of 175 cooling tons and serve the 69,576-ft^2 sales floor and one small back of house storage room. The space type was chosen because it has a significant number of annual operating hours, a large cooling load, and experiences large occupancy fluctuations.

Table 1 provides detailed information about the RTUs. The fixed OA dampers on the four 30-ton Carrier units originally provided all the ventilation. A third-party vendor could not be found to provide a means to motorize these OA dampers, so they were forced closed. Instead, four of the other RTUs were fitted with OA dampers and connected to the ARC retrofit controllers. Appendix E provides in-depth information based on the TAB report conducted as a part of the ARC retrofit installation.

Figure 5 shows a picture of the two main RTU types serving the BXtra. Table 1 provides additional BXtra RTU characteristics. Figure 6 shows an aerial view of the BXtra with the RTU locations.

Table 1. BXtra RTU Specifications

Eq_Id	RTU				Supply Fan Motor			Compressor		OA Damper		HVACArmor Evap. and Cond. Coil Coating
	Tons	Brand	Model NO.	HP	Motor FLA	Motor Nominal Efficiency	Motor Power Factor	Number and Stages	RLA per Compressor	Non-ESM Operation	ESM Operation	
Unit 01	30	Carrier	50AJ-030CC	10	13.4	89.50%	78%	4 comp 2 stages	10.2	Forced Shut		Yes
Unit 02	30	Carrier	50AJ-030CC	10	13.4	89.50%	78%	4 comp 2 stages	10.2	Forced Shut		Yes
Unit 03	30	Carrier	50AJ-030CC	10	13.4	89.50%	78%	4 comp 2 stages	10.2	Forced Shut		No
Unit 04	30	Carrier	50AJ-030CC	10	13.4	89.50%	78%	4 comp 2 stages	10.2	Forced Shut		No
Unit 05	10	Trane	TCD120	3	4.3	??	75%	2 comp 2 stages	10	All Day 20% Fixed Open	6% @ 90% capacity 12.5% @ 40% capacity Open 5:00 am – 9:00 pm / 7 days a week	Yes
Unit 06	10	Trane	TCD120	3	4.6	??	75%	2 comp 2 stages	10	All Day 20% Fixed Open	6% @ 90% capacity 12.5% @ 40% capacity Open 5:00 am – 9:00 pm / 7 days a week	No
Unit 07	12.5	Trane	TCD150	3	4.6	??	75%	2 comp 2 stages	10.8	All Day 20% Fixed Open	6% @ 90% capacity 12.5% @ 40% capacity Open 5:00 am – 9:00 pm / 7 days a week	Yes
Unit 08	10	Trane	TCD120	3	4.6	??	75%	2 comp 2 stages	10	All Day 20% Fixed Open	6% @ 90% capacity 12.5% @ 40% capacity Open 5:00 am – 9:00 pm / 7 days a week	No
Unit 09	12.5	Trane	TCD150	3	4.6	??	75%	2 comp 2 stages	10.8	No OA damper		Yes
Total	175	–	–	55	–	–	–	–	–	–	–	–

Figure 5. (a) One of the four 30-ton Carrier RTUs (left) and (b) one of the five Trane RTUs (right)

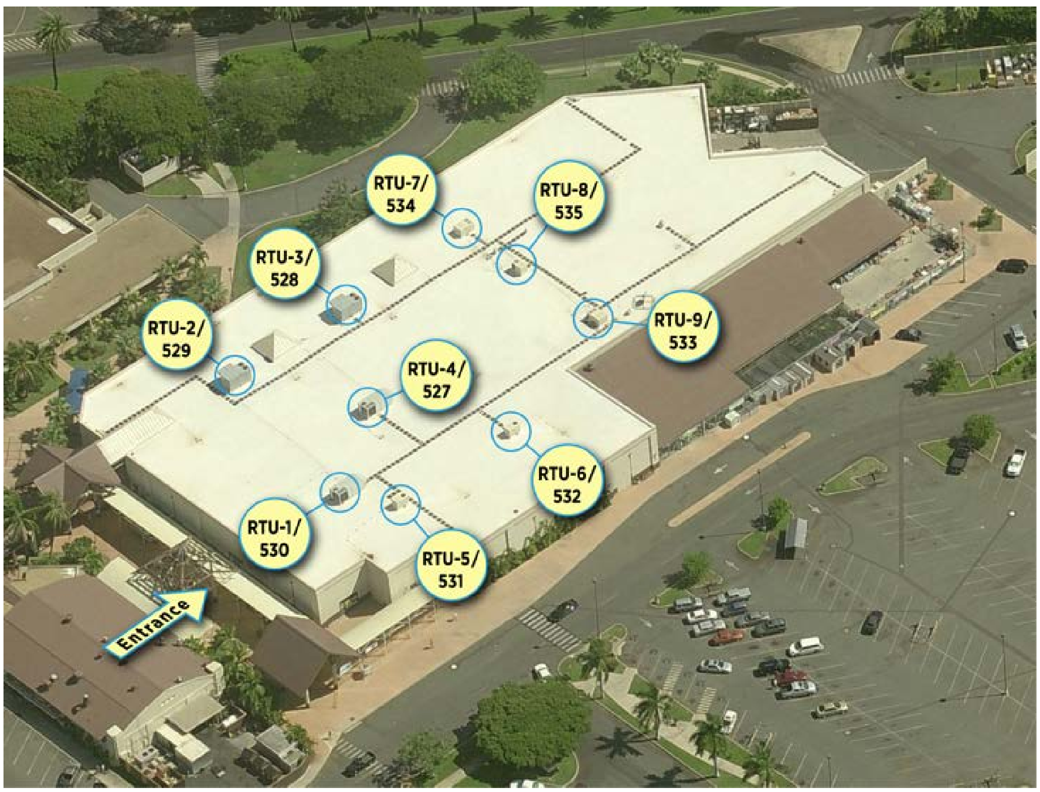

Figure 6. Arial image of the BXtra building with designated RTU locations

3.1.2 Small Office Buildings A13 and C27

An ARC retrofit was installed on the 20-ton RTU serving the west side of building A13, a single-story 7,889-ft^2 office building. The RTU was ducted throughout the entire office space; three other mini-split DX systems served the conference room, north offices, and several cubicles. Each DX system was controlled by its own thermostat.

An ARC retrofit was installed on one of the three RTUs serving building C27, which is also a small office building. The CATALYST was installed only on the 12.5-ton RTU serving 2,706 ft^2 of the total building's 17,285 ft^2. The remaining space is a separate server room that is conditioned by two other RTUs that are not part of this demonstration. Building C27 also has a few mini-split DX systems serving each conference room.

Table 2 summarizes the RTU characteristics serving A13 and C27. Figure 7 shows pictures of the A13 and C27 RTUs.

(a) **(b)**

Figure 7. (a) 20-ton RTU serving Building A13 small office space; (b) 12.5-ton RTU serving Building C27 small office space

Table 2. Buildings C27 and A13 RTU Specifications

EQ_ID [1]	RTU				Supply Fan Motor		Compressor	OA Damper		HVACARMor DX Evaporator and Condenser Coil Coating
	Tons	Brand	Model No.	HP	Motor FLA	Motor Power Factor	Number and Stages	non-ESM Operation	ESM Operation	
A13 Unit 02	20	Trane	TCH240	5	6.3	75%	2 comp 2 stages	All Day 20% Fixed Open	6% @ 90% Capacity 12.5% @ 40% Capacity Open 8:00 a.m.–3:30 p.m. (May–October) weekdays only Open 9:00 a.m.–3:30 p.m. (November–April) weekdays only	Yes
C27 Unit 01	12.5	Carrier	50HJ-014	3	7.5	75%	2 comp 2 stages	All Day 20% Fixed Open	6% @ 90% Capacity 12.5% @ 40% Capacity Open 8:00 a.m.–3:30 p.m. (May–October) weekdays only Open 10:00 a.m.–3:30 p.m. (November–April) weekdays only	No

3.2 Sampling Protocol

The ARC retrofit controller's built-in data acquisition with standard sensors was used for this demonstration. Additional temperature and RH sensors were installed inside each building to monitor their impact on thermal comfort. Throughout the demonstration, the monitored data were collected on a 1-minute time scale. Figure 8 shows a schematic of a typical RTU illustrating the location of each sensor.

Table 3 provides a list of sensors, including manufacturer, model number, and sensor accuracy. Once each day, the monitored data were transferred through a cellular modem connection to TWT's data server on the Amazon cloud. The raw data was then sent to NREL and post-processed via a SQL database. This database was used to clean and roll up data into hourly and daily averages. The cleaning algorithms also corrected the non-ESM energy usage by eliminating the VFD drive loss impacts on fan power. The VFD manufacturer provided drive watt loss data at normal duty (swing PWM equal 3 kHz) for each VFD model. NREL calculated a VFD efficiency that was assumed to be constant at the different fan speeds. The VFD parasitic energy usage was subtracted from the energy use of the non-ESM RTU operation to more accurately represent a baseline RTU with the standard factory drive package.

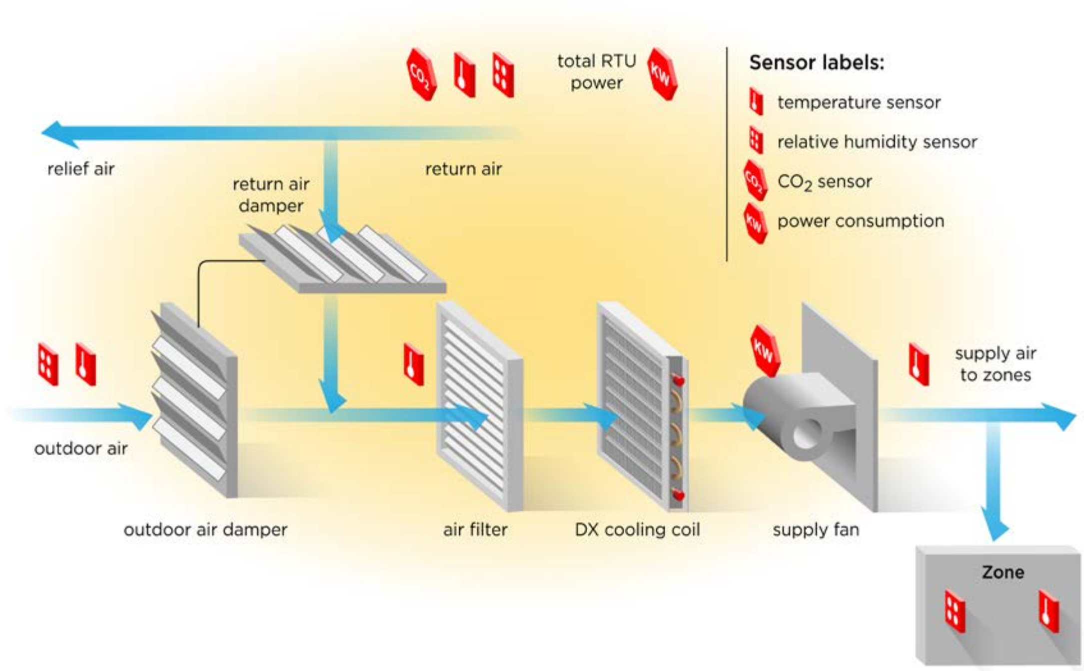

Figure 8. Sample RTU graphic illustrating sensor location

Table 3. Digital and Analog Monitoring Points on Each RTU

Digital or Analog Signal	Monitoring Point	CATALYST Standard Sensor or Demonstration Add	Sensor Manufacturer/ Model	Sensor Accuracy	Sensor Notes
Digital-1	Occupied status	Standard	N/A	N/A	Controller calculated based on programmed schedule
Digital-2	First-stage cooling	Standard	N/A	N/A	Signal from controller
Digital-3	Second-stage cooling	Standard	N/A	N/A	Signal from controller
Digital-4	Supply fan power	Standard	Yaskawa VFD Output	Could not be obtained from Yaskawa	Value is monitor via a communication output on the drive; power is measured internally on the drive.
Digital-5	Total RTU power	Add	Continental Watt-Node WNC-3D with ACT current transducers	± 3% at leading power factor of 0.866	100 Hz resolution Watt-Node; accuracy combines Watt-Node and current transducers (www.ccontrolsys.com/w/Metering_System_Accuracy)
Analog-1	OA temp sensor	Standard	Senva HD-3B	± 2˚C (3.6˚F) Full Range; 0.5˚C (0.9˚F) typ @ 25˚C (77.0˚F)	Resistance Temperature Detector (RTD); positioned inside the OA hood always in the shade
Analog-2	RA temp sensor	Standard	Senva HD-3B	± 2˚C (3.6˚F) Full Range; 0.5˚C (0.9˚F) typ @ 25˚C (77.0˚F)	RTD; Positioned at the RA inlet into the RTU
Analog-3	SA temp sensor	Standard	ACI-AN Series	± .36 F	RTD in SA ductwork
Analog-4	MA temp sensor	Add	ACI-AN Series	± .36 F	Single RTD measurement located at the filter inlet
Analog-5	OA RH sensor	Standard	Senva HD-3B	± 3%, 20-80% Range	Capacitance sensor; Positioned inside the OA hood always in the shade
Analog-6	RA RH sensor	Standard	Senva HD-3B	± 3%, 20-80% Range	Capacitance sensor; positioned at the RA inlet into the RTU
Analog-7	RA CO_2 sensor	Standard	AirTest TR-9291	± 30 PPM; ±3% reading	CO_2 sensor positioned in RA ductwork
Analog-8	Space temperature	Add	ACI A/1K-2W	± 1.1˚C (1.9˚F)	Wall mounted temperature sensor at the existing thermostat location
Analog-9	OA damper controller	Standard	CAT-371	0-10 VDC signal at 8 Bit resolution	Control signal generated by controller CAT-371
Analog-10	Fan speed	Standard	Communicating Modbus signal	N/A	Control signal generated by controller CAT-371

3.3 Equipment Calibration and Data Quality Issues

Prior to the ARC installation at JBPHH, a CATALYST was installed on a 5-ton, 15-seasonal energy efficiency ratio (SEER) Trane RTU at NREL's Thermal Test Facility (TTF). The RTU was outfitted with all the same data monitoring equipment and sensors shown in Figure 8. The Trane RTU was connected to the TTF's HVAC laboratory, which can create MA conditions for the evaporator coil and OA conditions for the condenser to capture any climatic condition in the United States. The TTF's high accuracy temperature, RH, and power sensing equipment were used to verify the accuracy of the CATALYST sensors. The CATALYST manufacturer, Transformative Wave Technologies (TWT), does not calibrate its sensors in the field or purchase single- to multipoint factory calibrations because of the extra cost. The laboratory testing revealed that many of the sensors (except for the ± 3% RH sensors) were within the manufacturer's stated accuracy range. Consequently, NREL had TWT replace three temperature and RH sensors in the field with temperature and RH sensors NREL had verified to meet the manufacturer's specification. Two of the replacement sensors had a ± 3% RH accuracy; one had a ± 2% RH accuracy.

3.4 Baseline (non-Energy Savings Mode) Characterization

Before the ARC was installed, a retro-commissioning process was conducted that included tightening fan belts, ensuring proper refrigerant charge, calibrating temperature sensors, and cleaning condenser coils. This ensured that the baseline and ARC retrofit performance was measured on properly commissioned equipment.

The baseline performance and ARC performance were measured in tandem by alternately operation between two modes: ESM which enabled all the ARC retrofit features and non-ESM. The non-ESM mimicked the original RTU control sequences on a code-compliant RTU. Every other week, the eIQ BMS was remotely controlled to switch between ESM and non-ESM. For the rest of the report, baseline operation is referred to as non-ESM and ARC retrofit operation is referred to as ESM.

3.5 Performance Objectives

Six quantitative and two qualitative performance objectives were created (see Table 4). All the performance objective results are presented in Section 4 except for "Economizing Hours" and "Evaporator Coil and Condenser Coil Coatings," which are discussed in Appendix G and Appendix H, respectively.

Table 4. Performance Objectives

	Performance Objective	Metric	Data Requirements	Success Criteria
1	Annual energy savings	kWh/ton per 1,000 h of NAVFAC-permitted RTU operation	Annualized ESM versus non-ESM RTU energy usage	Minimum energy savings of 80 kWh/ton/1,000 h of NAVFAC permitted RTU operation
2	Interior thermal comfort	ESM versus non-ESM difference between occupied dry bulb and dew point temperatures; RH < 65% for occupied and unoccupied hours	Space dry bulb temperature, RH, and dew point temperature	ESM maintains a lower space dew point temperature profile; ESM and non-ESM maintain similar occupied dry bulb temperature profiles; ESM and non-ESM maintain RH < 65% for occupied and unoccupied hours
3	Ventilation quality	OA flow rate (cfm); RA CO_2 concentration (ppm)	TAB report; RA CO_2 concentration (ppm)	Maintaining sufficient ventilation per ASHRAE 62.1-2010; OA damper opened if DCV enabled
4	Demand response	Total building power draw (kW)	RTU power	Minimum peak demand savings of 15% during scheduled demand events
5	Economizing hours	Time in economizing and integrated economizing (h)	Supply fan speed; OA damper position; compressor on/off status	Minimum of 1,300 h/yr in economizer mode
6	Evaporator coil and condenser coil coatings	Visual comparison of the evaporator and condenser coils with and without the coating	Site visit pictures pre- and post-coil coatings	Measurable energy savings of RTUs that received coil coating compared to RTUs that did not receive coil coatings

3.5.1 Annual Energy Savings

The annual energy savings performance objective was established based on NREL's evaluation of PNNL modeling results that looked at the ARC retrofit technology in Miami (Wang et al. 2011). Because this is the climate closest to Hawaii from that modeling study, NREL used the modeling results to calculate the fan only energy savings for a small office building. The modeling results predicted that the ARC retrofit would provide a fan savings of approximately 80 kWh/ton per 1,000 h of building operation. To be conservative, NREL did not incorporate the DX cooling energy savings. A combination of the DCV and potential economizing hours should provide some DX cooling energy savings. The energy savings for the retail building (BXtra 1235H) should be greater than for the small office buildings (C27 and A13) because it has longer operating hours, is larger and has more varied occupancy.

3.5.2 Interior Thermal Comfort

The interior space temperature and RH were monitored for the duration of the demonstration under ESM and non-ESM operation. ARC retrofit technologies might be able to improve moisture control by further dehumidifying the space, but this had not been evaluated in other field demonstrations. ESM slows the airflow across the evaporative coil and provides a colder and lower dew-point air than non-ESM. ARC operation should maintain a lower space RH with the same temperature profiles (see Appendix A for defining NAVFAC's thermal comfort requirements about space temperature and RH).

3.5.3 Ventilation Quality

By enabling DCV, the ARC retrofit needs to maintain only the OA/ft^2 requirement. It then meets the OA/occupant requirement using a CO_2 sensor in the RA. The ARC retrofit opens the OA damper from its minimum position if the CO2 concentration exceeds 1,000 ppm. The OA flow rates measured during the TAB must show that the baseline and ARC operations meet the minimum ASHRAE 62.1-2010 OA/ft^2 requirement. To meet the OA/occupant requirement, the ARC operation must show that the OA damper is properly operated to maintain the CO_2 concentration under 1,000 ppm. Finally, the NAVFAC AHJ will need to authorize the ARC retrofit to enable CO_2 based DCV according to UFC 3-410-01.

3.5.4 Demand Response

Some utilities employ a peak demand charge in addition to charging for energy consumption. The target was set to measure the ARC retrofit's ability to reduce peak demand during a 2 hour window. Two demand response sequences were implemented, one for the BXtra and one for buildings C27 and A13. For the BXtra building, the peak demand for all nine RTUs was limited to 160 kW between 3:00 p.m. and 5:00 p.m. on Tuesdays, Thursdays, and Saturdays. The BXtra demand response sequence is outlined in detail in Section 0. Buildings C27 and A13 were controlled to prevent both RTUs from operating in second stage cooling simultaneously from 1:30 pm to 3:30 pm. Appendix F reviews the C27-A13 demand response results. For both sequences, the demand response goal was to reduce peak demand by 15% compared to a standard day's operation during the designated 2-hour window.

3.5.5 Economizer Hours

Currently, NAVFAC facilities in Hawaii incorporate no economizing. Based on several site surveys, NREL found the OA dampers operated in a fixed position. Hawaii's humid climate minimizes the number of hours per year that a differential dry bulb temperature with dew point lockout economizing could operate. Yet the enhanced sensing and control provided by an ARC retrofit may be adept enough to enable economizing for sufficient hours across the year. The OA economizer performance objective was set to meet at least 1,300 h/year of operation.

3.5.6 Evaporator Coil and Condensing Coil Coatings

During the spring 2012 site visit to select the demonstration RTUs, many of the aluminum fins on the condenser coils were showing significant corrosion. The marine climate was making the condenser coil aluminum fins brittle. Air conditioning performance was degrading (see Figure 9). Based on discussions with NAVFAC HVAC technicians, new RTUs installed in Hawaii are not ordered with copper fins or with a factory coil/cabinet coating. Instead a local Oahu firm applies a Blygold PoluAl XT coating to the condenser coils when the RTUs arrive on the island before they are shipped to the job site.

Based on its website,[2] Blygold is an aluminum pigmented polyurethane for aluminum and copper substrates. The polyurethane provides protection from UV, salt, and acidic conditions. The aluminum pigment is to mitigate the coating's impact on the coil's heat transfer. Blygold sent NREL third party lab results of an ASTM B117 neutral salt spray test with 4,000 hour exposure and an ASTM G85 acidic salt-spray test with 4,000 hour exposure. The Blygold PoluAl specimens from both tests showed slight discoloration but no corrosion was present. Based on these tests, the Blygold manufacturer states 3,000 hours + protection according to ASTM B117 and ASTM G85. Blygold also provides a limited 5-year manufacturer warranty.

Despite the Blygold coating that was applied when the RTUs were first installed, the condenser coils needed refurbishment. The 1235H BXtra RTUs, installed in 2006, were 7 years old. The A13 RTU, installed in 1998, was 15 years old. The C27 RTU age is unknown as no nameplate data was shown. Based on the age of these RTUs and the condition of the condenser coils, NREL surmised that the Blygold coating will not last the typical 15 year lifetime of an RTU in Hawaii. The typical lifetime of an RTU in Guam is approximately 7 years due to the more extreme marine climate. If NAVFAC was going to invest in ARC retrofit technologies to realize energy savings to existing RTUs, NREL wanted to investigate a field applied coil coating that may extend RTU life expectancy.

[2] For more information, see www.blygold.com/ba/coilcoating.html.

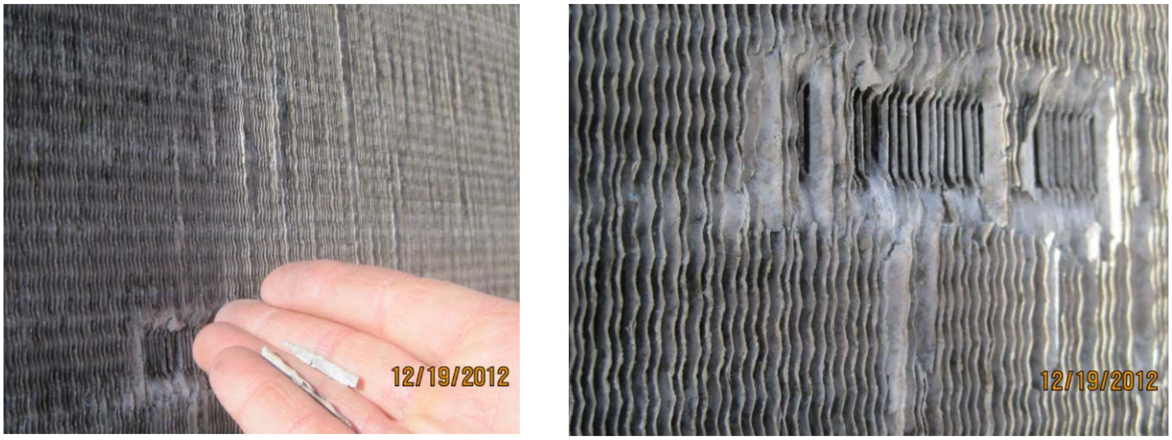

Figure 9. Corrosion and deterioration of the aluminum fins typical of all 11 RTUs*

*Note: Picture of one of the Carrier 50AJ-030CC 30-ton RTUs serving the BXtra 1235H building was installed in 2006 and was labeled to have received a Blygold coil coating before installation.

NREL specified the HVACArmor DX coil coating product since it can be field applied. The evaporator and condenser coils on four of the 1235H BXtra RTUs and the A13 RTU were first cleaned with a solvent and then coated. The remaining six RTUs did not receive the coil coating to provide a control with which to compare the immediate performance impacts. The HVACArmor DX product (also identified as Hempel 55610) is a polyurethane coating marketed to "rejuvenate and restore" marginally deteriorated aluminum coils and copper tubes. It is marketed to provide corrosion and ultraviolet protection with a single coat at a 1 mil thickness to minimize airside pressure drop increases. Similar to the Blygold PolyAl coating, HVACArmor DX is impregnated with aluminum paste to mitigate negatively impacting coil heat transfer. Based on independent lab test results, the HVACArmor DX showed no blistering or red rust and less than 0.1 mm rust creep from a scribe after 1628 hours exposure to ASTM B117 neutral salt-spray test.

Based on the independent lab test results provided to NREL from the respective manufacturers, NREL cannot state that HVACArmor DX will or will not outperform Blygold. Adding a coil coating to the demonstration was to investigate whether a field applied coating can extend the life of an RTU. NREL evaluated the monitored data to determine if statistically significant results indicated that the coil coating improved performance immediately (see Appendix H). In Section 8, NREL recommends comparing the maintenance and lifespan of the RTUs receiving the HVACArmor DX coating with typical expectations for a NAVFAC follow on activity to this demonstration.

4 Technical Performance Analysis and Assessment

The ARC technology reduced RTU energy consumption and improved interior comfort through lower RH. The results for each demonstration objective are summarized in Table 5. Section 4.1 summarizes the initial months of monitoring and configuring the ARC system before the official demonstration periods began. The following subsections go into more detail about each demonstration objective. The economizing and coil coating demonstration objectives are summarized in Appendix G and Appendix H, respectively.

Table 5. Performance Objective Results

	Performance Objective	Success Criteria	Results
1	Annual energy savings	Minimum energy savings of 80 kWh/ton per 1,000 h of NAVFAC-permitted RTU operation	• BXtra 1235H (9 ARCs) met the objective by saving 94 kWh/ton per 1,000 h operation (15% HVAC reduction—Table 11) • Building C27 (1 ARC) did not meet the objective by saving 55 kWh per ton per 1,000 h operation (7% HVAC reduction—Table 14) • Building A13 (1 ARC) did not meet the objective by saving 39 kWh/ton per 1,000 h operation (5% HVAC reduction—Table 17)
2	Interior thermal comfort	• ESM maintains a lower space RH and dew point temperature profile • ESM and non-ESM maintain similar occupied dry bulb temperature profiles • ESM and non-ESM maintain < 65% RH for occupied and unoccupied hours	• All three buildings showed that ESM operation maintained a lower space RH and dew point compared to non-ESM operation; • All three buildings showed negligible difference in the dry bulb temperature profiles • Except for a few hours, all three buildings showed that the occupied and unoccupied space RH never exceeded 65%
3	Ventilation quality	• Maintaining sufficient ventilation per ASHRAE 62.1-2010 • OA damper opened if DCV call	• TAB measurement uncertainty too significant to conclude whether ventilation rates met ASHRAE 62.1 requirements • No RTU CO_2 concentration exceeded 1,000 ppm to initiate the DCV sequence
4	Demand response	Minimum peak demand savings of 15% during scheduled demand events compared to previous day's peak demand	• BXtra demand response sequence achieved the objective by reducing the peak demand 12% to 27% depending on the month • C27 and A13 demand response sequence did not work properly and no conclusive demand reduction could be calculated
5	Economizing hours	Minimum of 1,300 h/yr in economizer mode	Economizer sequence operated properly but infrequently due to Hawaii climate—unlikely 1,300 hours are possible due to climate
6	Evaporator condenser coil coatings	Measurable energy savings of RTUs that received coil coating compared to RTUs that did not receive coil coatings	There was no conclusive difference in performance between the RTUs with and without the HVACArmor DX coating.

4.1 Initial Adjustment Period

Performance monitoring began on January 1, 2013. NREL configured the CATALYST system during the first 4 months of operation to ensure that:

- NAVFAC's standards of service (operational schedules, space temperature, and space RH) were being met.
- Non-ESM versus ESM performance could be clearly distinguished.

Regarding differentiating performance, NREL originally configured the controls to alternate daily between non-ESM and ESM operation. During the initial monitoring, NREL discovered that non-ESM operation was "piggy-backing" on ESM's improved dehumidification for all three buildings. NREL defined the phenomena as *latent cross-talk*. Non-ESM operation was using less energy because it was handed a drier space from the previous day's ESM operation. NREL found that alternating weekly provided a clearer performance distinction between non-ESM and ESM operation. All the demonstration objectives summarized in the following subsections are based on monitored data from alternating weekly between non-ESM and ESM operation.

For the 1235H BXtra (nine of 11 RTUs demonstrated), the official demonstration period was May 3, 2013 through November 9, 2013 (thermostat and operational schedules are summarized in Table 6). The demonstration period had two different daily operational hours because of an error occurred in the ARC optimum start sequence. Before August 22, 2013, the RTUs were incorrectly turning on at 1:00 a.m. for ESM and non-ESM operation and operating for 20 h/day. Once identified, adjustments were made so the RTUs came on correctly at 5:00 a.m. for 16 h/day for the remainder of the demonstration.

The demonstration start dates for the two units on C27 and A13 were later because standards of service issues needed to be addressed. NREL worked with NAVFAC to determine the proper thermostat set points and schedules for buildings A13 and C27. Section 0 outlines how NAVFAC's thermostat set points and operational schedules were defined and applied. During the initial months of monitoring, NREL discerned that high infiltration rates in buildings A13 and C27 caused excessive moisture buildup between 4:00 a.m. and 6:00 a.m. The space RH was exceeding 65%. These hours are before the NAVFAC-approved RTU operational hours, which start at 8:00 a.m. in the summer and 10:00 a.m. in the winter.

Over the course of several weeks, NREL applied various control strategies with the aim of mitigating energy usage and maintaining NAVFAC's approved comfort standards for non-ESM and ESM operation. The selected control strategy was to turn the RTUs on at 6:00 a.m., before NAVFAC-approved summer operating hours. During this "morning dehumidification period," the OA dampers remained fixed at 20% open under non-ESM operation but remained closed under ESM operation. NREL found that early RTU operation from 6:00 a.m. to 8:00 a.m. sufficiently drove the space RH below 65% before occupancy for both operational modes. The RTUs were then able to maintain proper moisture control throughout the occupied period of 8:00 a.m. to 3:30 p.m.

Building C27 started the demonstration period on July 1, 2013 (thermostat and operational schedules are summarized in Table 8). Maintenance issues unrelated to the CATALYST system delayed building A13's official start date to August 1, 2013 (thermostat and operational schedules are summarized in Table 7). Buildings A13 and C27 had the optimum start sequence replaced with the "morning dehumidification period" discussed above.

A demand response sequence was applied to ESM and non-ESM operation for all three buildings on Tuesdays, Thursdays, and Saturdays (if there was weekend operation) and is summarized in Section 0.

Table 6. Building 1235H BXtra Thermostat and Operational Schedule during the Demonstration Period

Space Type	Large Retail
Area served by 9 RTUs*	69,576 ft^2
May 1 to August 8, 2013 Set point = 74°F Setback = N/A (RTU off per NAVFAC Hawaii Region Energy Instruction)	1:00 a.m. to 9:00 p.m. every day 20 h × 365 days = 7,300 h/yr
August 9 to November 9, 2013 Set point = 74°F Setback = N/A (RTU off per NAVFAC Hawaii Region Energy Instruction)	5:00 a.m. to 9:00 p.m. every day 16 h × 365 days = 5,840 h/yr
RH Constraints	Maximum of 65% RH including occupied and unoccupied hours
Scheduled Demand Report Event	3:00 p.m. to 5:00 p.m. every Tuesday, Thursday, Saturday both ESM and non-ESM operation
Total Tonnage/Conditioned Area	398 ft^2/ton

Table 7. Building A13 Thermostat and Operational Schedule during the Demonstration Period

Space Type	Small Office
Area served by RTU	7,834 ft^2
August 1 to November 9, 2013 Set point = 76°F Setback = N/A (RTU off per NAVFAC Hawaii Region Energy Instruction)	Summer (May–October): Monday–Friday 6:00 a.m. to 8:00 a.m. "Morning Dehumidification Period" (2 h/day) 8:00 a.m. to 3:30 p.m. NAVFAC Approved Operation (7.5 h/day) Winter (November–April): Monday–Friday 7:00 a.m. to 9:00 a.m. "Morning Dehumidification Period" (2 h/day) 9:00 a.m. to 3:30 p.m. NAVFAC-approved Operation[a] (6.5 h/day)
RH Constraints	Maximum of 65% RH including occupied and unoccupied hours
Annual Operational Hours	2,340 h
Scheduled Demand Report Event	1:30 p.m. to 3:30 p.m. every Tuesday and Thursday ESM and non-ESM operation
Total Tonnage/Conditioned Area	392 ft^2/ton

[a] Based on Bonnie White, building energy manager for A13, occupants were permitted to have the RTU turn on 1 hour before NAVFAC-approved operation at 10:00 am for winter months.

Table 8. Building C27 Thermostat and Operational Schedule during the Demonstration Period

Space Type	Small Office
Area served by RTU	2,706 ft^2
Set point[a] = 75°F Setback = N/A (RTU off per NAVFAC Hawaii "Region Energy Instruction")	Summer (May–October): Monday–Friday 6:00 a.m. to 8:00 a.m. "Morning Dehumidification Period" (2 h/day) 8:00 a.m. to 3:30 p.m. NAVFAC-approved operation (7.5 h/day) Winter (November–April): Monday–Friday 8:00 a.m. to 10:00 a.m. "Morning Dehumidification Period" (2 h/day) 10:00 a.m. to 3:30 p.m. NAVFAC-approved operation (5.5 h/day)
RH Constraints	Maximum of 65% RH Including occupied and unoccupied hours
Annual Operational Hours	2,210 h
Scheduled Demand Report Event	1:30 p.m. to 3:30 p.m. every Tuesday and Thursday ESM and non-ESM operation ESM and non-ESM operation
Conditioned Area/Total Tonnage	216 ft^2/ton

[a] Based on Bonnie White, building energy manager for C27, occupants were permitted to drop the thermostat temperature to 75°F from accepted interpretation of NAVFAC approved set point 76°F.

4.2 Annual Energy Savings

The principal goal of this demonstration was to quantify the ARC retrofit technologies' energy savings in hot-humid climates. Measurements of daily non-ESM and ESM energy usage at buildings 1235H, A13, and C27 were rolled up from 1-minute monitored data. The results are presented in two ways:

- Measured energy usage in each operational mode for each building's demonstration period. Processing consisted of grouping the data into ESM and non-ESM sets and totalizing the energy use, and calculating daily average energy consumption for ESM and non-ESM operation; the difference equals the energy savings of the ARC retrofit technology.
- Calculated annual average energy savings using a linear regression model with Honolulu International Airport (HNL) Typical Meteorological Year (TMY3) weather data to calculate annual ESM and non-ESM energy usage; the difference equals the energy savings. For details on the regression method and models see Appendix B.

The results from both methods are presented below for each of the three buildings.

4.2.1 BXtra Energy Savings

The measured data from the official demonstration period from August 3, 2013 through November 9, 2013 were cleaned by eliminating 32 days when known maintenance issues impacted daily energy usage. The main maintenance issue was that Unit 01 lost wireless communication for 28 days (August 9, 2013 to September 5, 2013). Table 9 shows that across the clean 159-day sample, ESM operation saved a daily average of 335 kWh; a 17% reduction in total HVAC energy usage. Yet this is a not a true apples-to-apples comparison, because the ESM sample experienced a 0.5°F lower average daily temperature, a known predictor of daily energy usage. Table 10 shows that most ESM savings consisted of a 55% reduction in supply fan energy compared to a 5% reduction in the compressor and condenser fan energy. The supply fan energy savings met NREL's expectations. Yet NREL anticipated larger compressor and condenser fan energy savings from the DCV feature.

Table 9. BXtra 1235H Demonstration Period (8/3/13–11/9/13) Sample Set Summary

	Total Raw Sample (Days)	Maintenance Issues (Days)	Cleaned[a] Sample (Days)	Average OA Temp[a]	Total Energy Usage[a]	Average Daily Usage[a]
Non-ESM Operation	86	17	69	78.5°F	138,049 kWh	2,001 kWh
ESM Operation	105	15	90	78.0°F	149,891 kWh	1,665 kWh
	191 total	32 total	159 total	0.5°F delta	287,940 kWh total	335 kWh (17%) savings

[a] From the raw sample, NREL eliminated days when known maintenance issues impacted daily energy usage. The BXtra 1235H operated on weekends, which were included in the sample set.

Table 10. Building BXtra 1235H Monitored Energy Usage Separated between Fan and Remaining End-Uses (Compressors, Condenser Fans, Controller) Broken Down by ESM and Non-ESM Operation

	Fan Energy[a]	Comp/Cond Fan/Controller Energy[a]	Fan Average Daily Usage[a]	Comp/Cond Fan/Controller Average Daily Usage[a]
Non-ESM Operation	31,824 kWh (23% of total)	106,225 kWh (77% of total)	461 kWh	1,539 kWh
ESM Operation	18,489 kWh (12% of total)	131,402 kWh (88% of total)	205 kWh	1,460 kWh
			256 kWh (55%) ESM Savings	79 kWh (5%) ESM Savings

[a] From the raw sample, NREL eliminated days when known maintenance issues impacted daily energy usage. The BXtra 1235H operated on weekends, which were included in the sample set.

Figure 10 provides a time series visual of the total daily energy usage in each operational mode across the entire demonstration period. The figure also includes the daily average dry bulb temperature, which was the second most statistically significant predictor in the regression model. The most significant predictor was the daily hours of operation, 20 h/day before August 22, 2013 compared to 16 h/day for the remainder of the demonstration. Figure 10 shows a noticeable reduction in daily energy usage for ESM and non-ESM operation after August 22, 2013, when the RTUs were operating 4 fewer h/day.

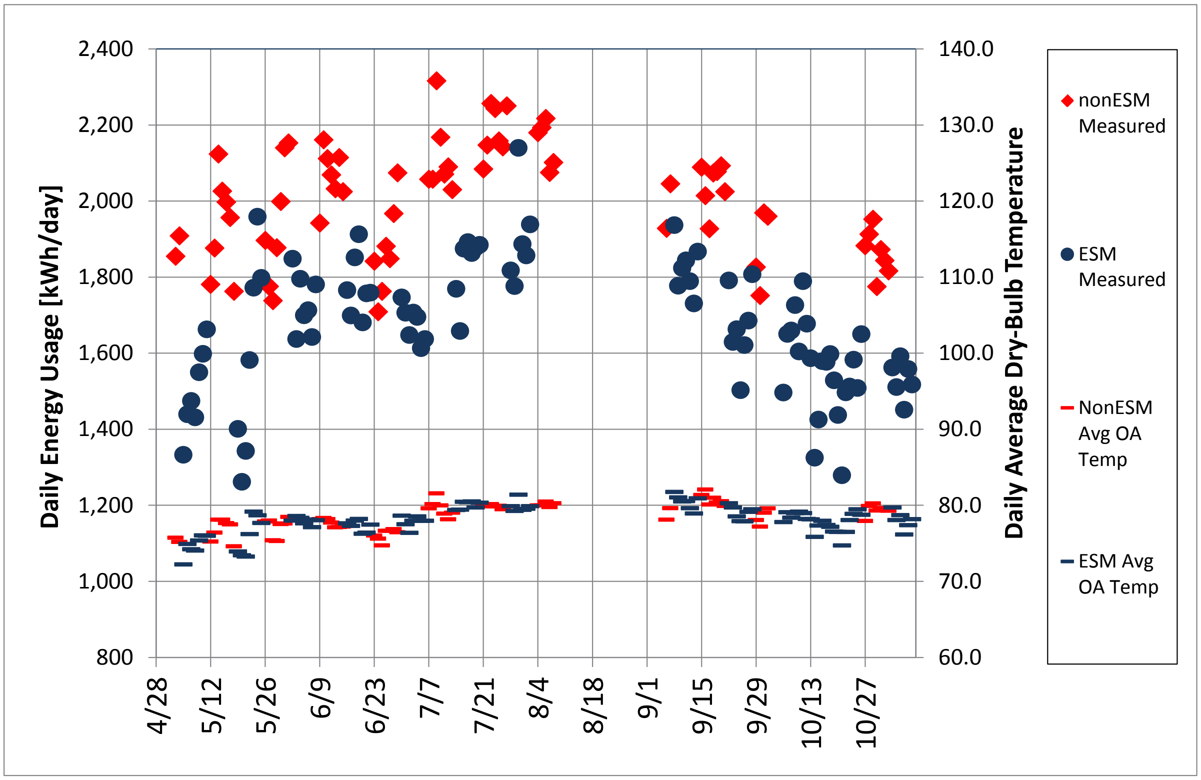

Figure 10. BXtra 1235H time series of measured ESM and non-ESM energy usage (excluding known maintenance days) and average ambient dry bulb temperature. Note that no data are shown from August 9, 2013 to September 5, 2013 when Unit 01 lost wireless communication.

Figure 11 and Figure 12 provide more details about the daily energy usage for each of the nine RTUs for non-ESM and ESM operation, respectively. In both operational modes, the BXtra 01 (Unit 01) consumes the most daily energy. During the demonstration NREL surmises that the temperature sensor for BXtra 01 was impacted by the infiltration load because of its proximity to the main entrance (Figure 6).

During the writing of this report, it turned out that the temperature sensors was reading 2-3°F higher than a calibrated handheld temperature sensor. Each temperature sensors was supposed to be calibrated during the commissioning process before the construction was closed out. Either the sensor went out of calibration during the demonstration period or the temperature sensors were never calibrated. NREL is uncertain that the energy savings would be larger or smaller if Unit 01 had a calibrated temperature sensor. If Unit 01 behaved like Unit 04, the savings would have been larger. This is a significant finding and shows the importance of ensuring calibrated sensors. In Appendix J, NREL includes this finding as a practical lesson learned for future ARC installations.

Another observation is the unequal RTU loading that could create maintenance issues. Unit 04 and probably Unit 01 with a calibrated sensor would provide more conditioning compared to the other identical 30 ton Carrier RTUs, Units 02 and 03. In Appendix J, NREL recommends that for follow-on ARC installations, the duty cycle of the RTUs be monitored after the installation and that the sequence be adjusted to equalize the loading across the RTUs.

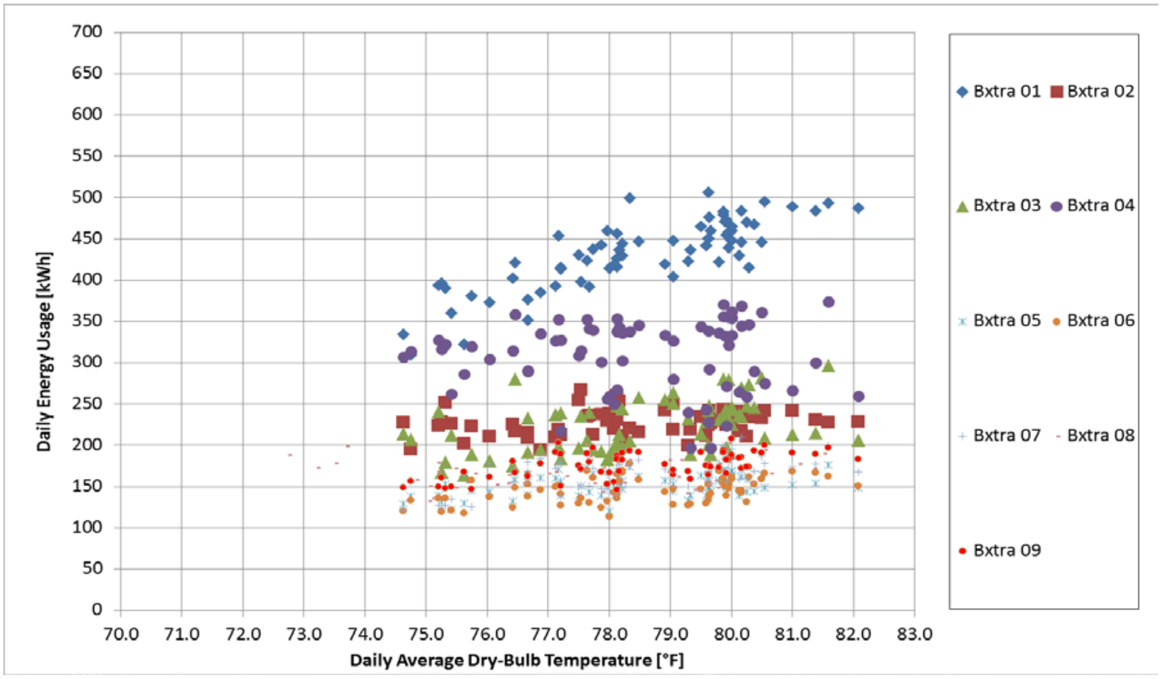

Figure 11. BXtra 1235H non-ESM operation daily energy usage for each RTU versus daily average ambient dry bulb temperature

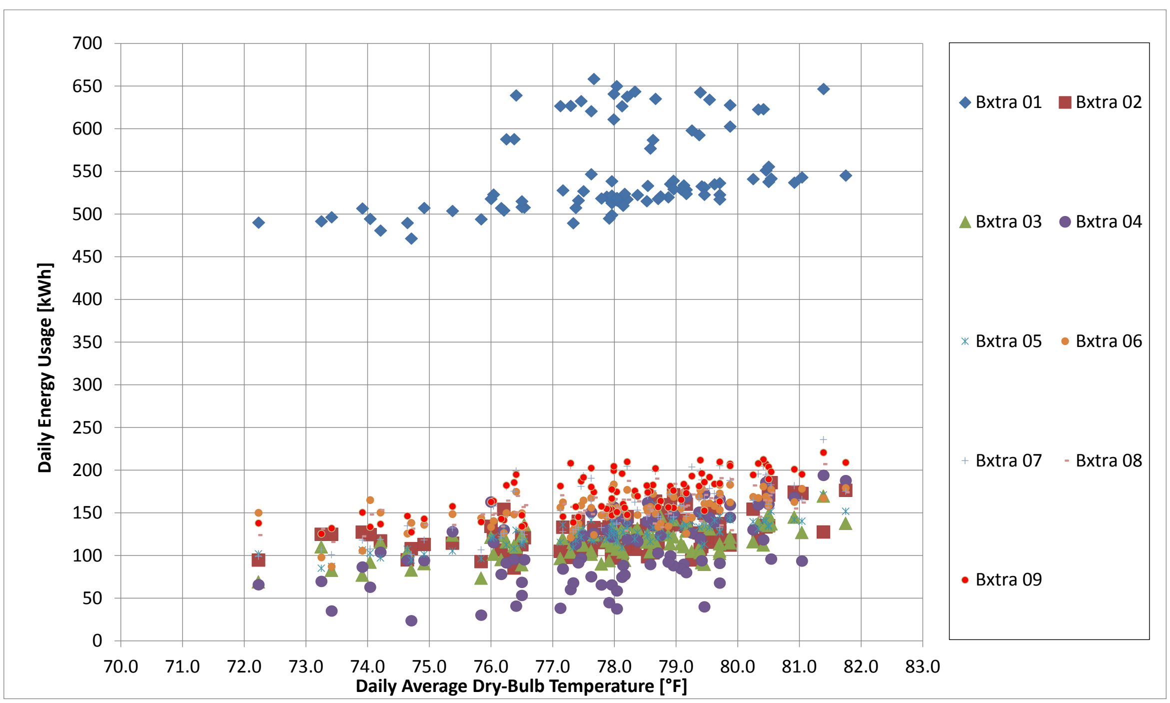

Figure 12. BXtra 1235H ESM operation daily energy usage for each RTU versus daily average ambient dry bulb temperature

Table 11 shows the annual energy usage and savings of the regression model applied to HNL TMY3 weather (for details on the regression method and models see Appendix B). ESM operation saved 15% of the total HVAC energy, which normalized to 94 kWh/ton per 1,000 h of operation at 16 h/day and 7 days/week. The hour of operation used to normalize the energy savings is based on the total annual hours the RTU is operating. For the BXtra, the annual operating hours is 5,840 h/yr for 365 days and 16 h per day (see Table 6).

Table 11. BXtra 1235H Linear Regression Energy Usage and Savings Applied to HNL TMY3 Weather Data

	Energy	Normalized Energy
Non-ESM Annual Energy Usage	627,061 kWh	614 kWh/ton per 1,000 h operation
ESM Annual Energy Usage	530,564 kWh	519 kWh/ton per 1,000 h operation
Annual Energy Savings	96,498 kWh (15%)	94 kWh/ton per 1,000 h operation

Figure 13 plots the daily energy usage between ESM and non-ESM operation based on TMY3 weather data. For a visual comparison of the regression model versus the actual measured data, Figure 14 and Figure 15 show non-ESM and non-ESM operation, respectively. The ARC retrofit technology applied to the BXtra exceeded the energy savings performance objective of 80 kWh/ton/1,000 h of operation.

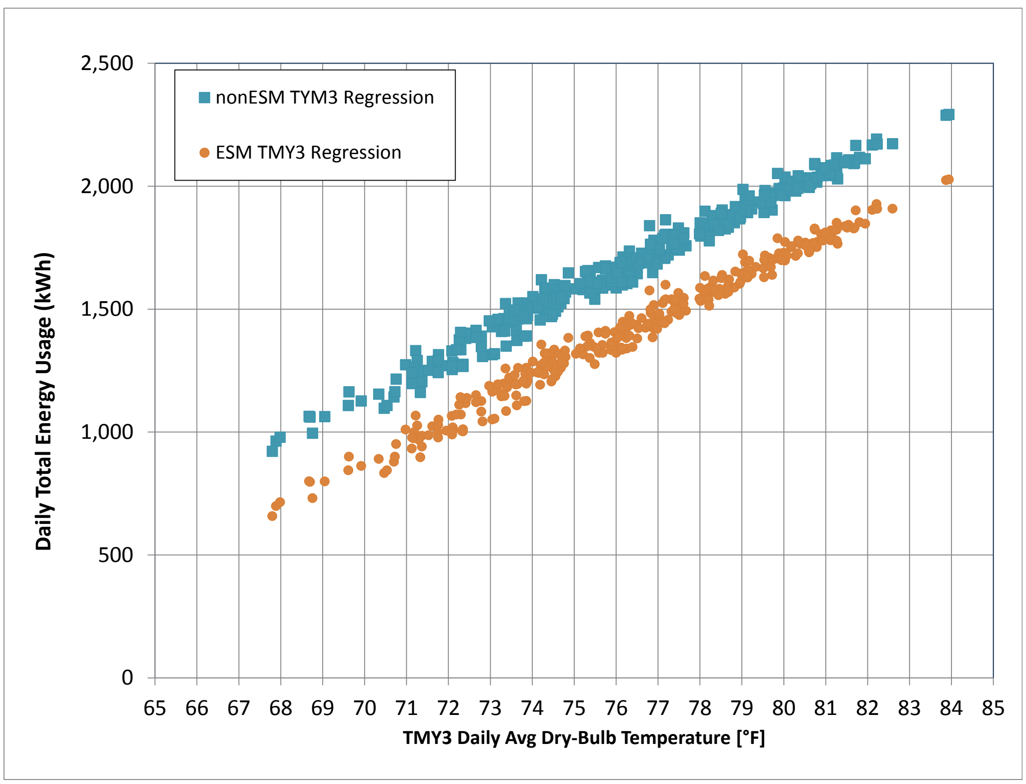

Figure 13. BXtra 1235H linear regression model applied to HNL TMY3 weather data

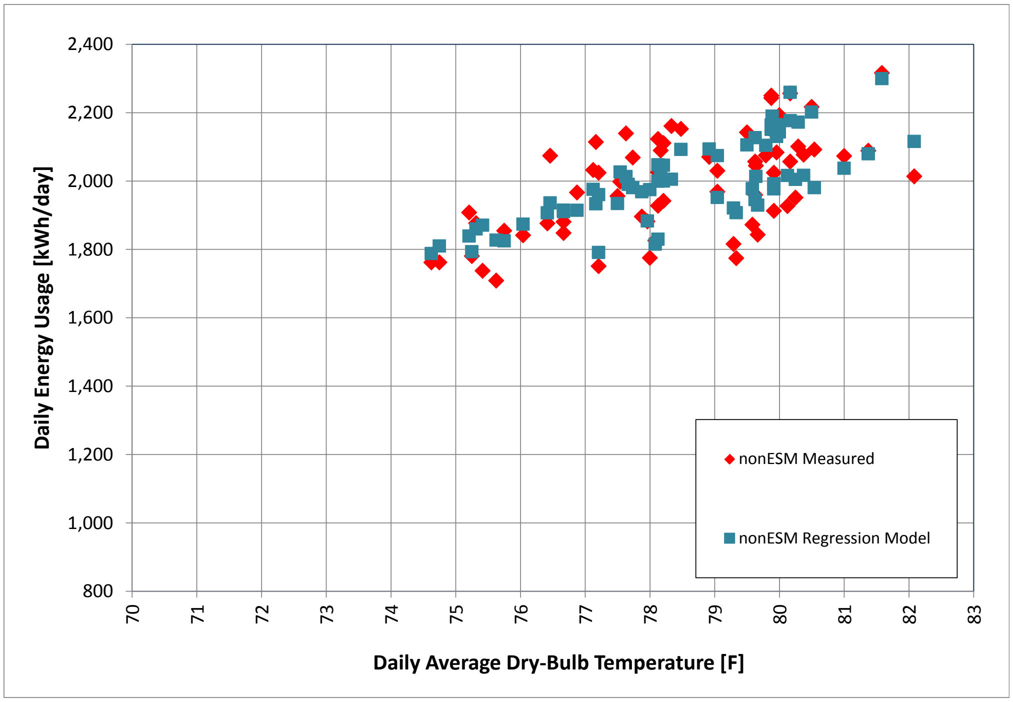

Figure 14. BXtra 1235H comparison of non-ESM daily energy usage between measured data and the regression model

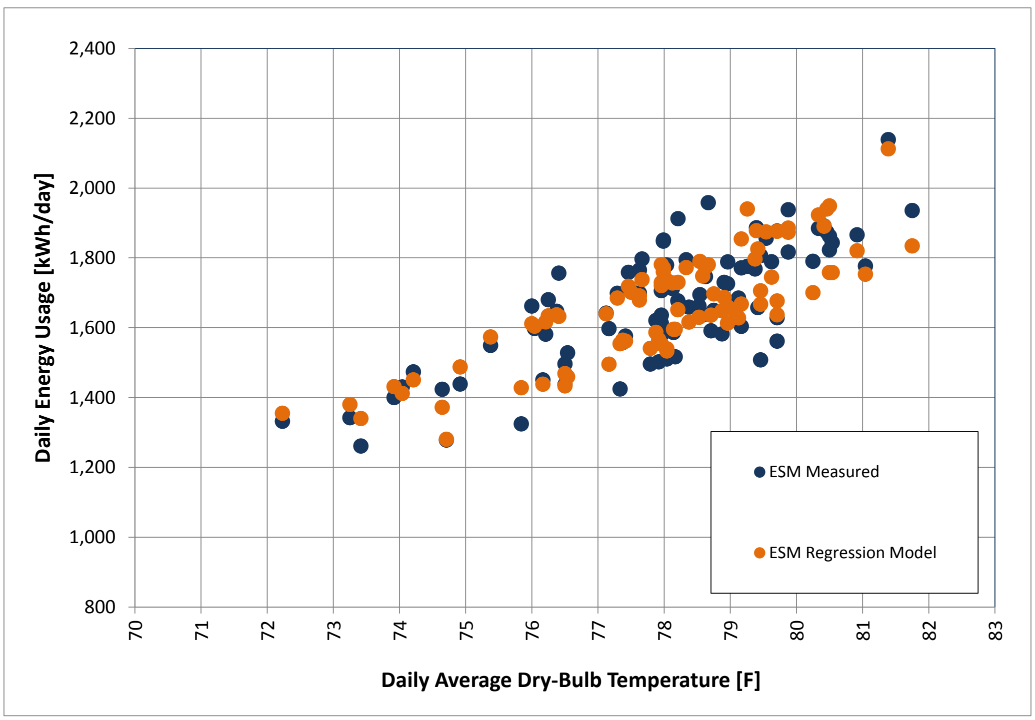

Figure 15. BXtra 1235H comparison of ESM daily energy usage between measured data and the regression model

4.2.2 C27 Energy Savings

From the raw sample of days, NREL eliminated weekend days (not occupied on weekends) and days with known maintenance issues (see Table 12). Based on the 87 cleaned sample days, ESM operation saved on average 13 kWh/day (11%) compared to non-ESM operation. Yet this is a not a true apples-to-apples comparison, because the ESM sample experienced a 0.9°F lower average daily temperature, a known predictor of daily energy usage. Table 13 provides a breakdown of the energy usage between the fan and remaining components (compressors, condenser fans and controller). Similar to the BXtra results, the supply fan constituted most of the savings, although the BXtra fan percentage savings were considerably greater at 55%. Also similar to the BXtra results, building C27 ESM operation saved 5% for the non-fan energy usage.

Table 12. Building C27 Demonstration Period (July 1, 2013 to November 9, 2013) Measured Energy Usage between ESM and non–ESM Operation

	Total Raw Sample (Days)	Maintenance Issues (Days)	Weekends	Cleaned[a] Sample Days	Avg OA Temp[a]	Total Energy Usage[a]	Avg Daily Usage[a]
Non-ESM Operation	57	6	16	35	79.9°F	4,016 kWh	115 kWh
ESM Operation	77	3	22	52	79.0°F	5,290 kWh	102 kWh
	134 total	9 total	38 total	87 total	0.9°F delta	9,307 kWh total	13 kWh (11%) savings

[a] Based on cleaned data eliminating weekend days and days when known operational issues impacted daily energy usage.

Table 13. Building C27 Monitored Energy Usage Separated between Fan and Remaining (Compressors, Condenser Fans, Controller) Broken Down by ESM and non-ESM Operation

	Fan Energy[a]	Comp/Cond Fan/Controller Energy[a]	Fan Avg Daily Usage[a]	Comp/Cond Fan/Controller Avg Daily Usage[a]
Non-ESM Operation	755 kWh (19% of total)	3,261 kWh (81% of total)	22 kWh	93 kWh
ESM Operation	704 kWh (13% of total)	4,586 kWh (87% of total)	14 kWh	88 kWh
			8 kWh (37%) ESM savings	5 kWh (5%) ESM savings

[a] Based on cleaned data eliminating weekend days and days when known operational issues impacted daily energy usage.

For a visual of the cleaned sample days, NREL plotted the time series of the measured daily energy as well as average and minimum ambient dry bulb temperatures shown in Figure 16. At the beginning of the demonstration, the hotter summer months masked the energy usage difference between ESM and non-ESM operation. Yet, toward the end of the demonstration period (after mid-October), the ESM operation clearly shows a lower daily energy usage at cooler ambient conditions.

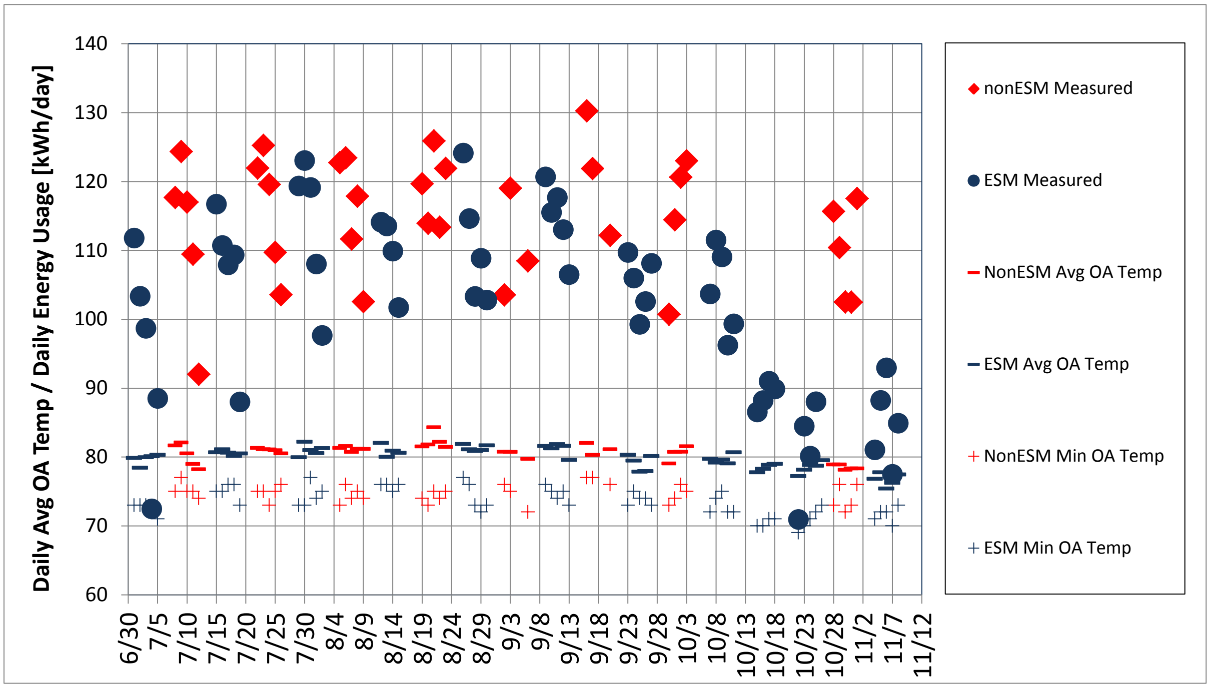

Figure 16. Building C27 time series plot of measured ESM and non-ESM energy usage (excluding weekends and known maintenance days) and average OAT and minimum OAT. Note that due to an error in the weekly alternating schedule, ESM operated an extra week in mid-October.

The building C27 linear regression was applied to HNL TMY3 weather data to calculate the annualized energy usage for ESM and non-ESM operation. Across the year, operating Monday–Friday, the regression model calculates that ESM operation saves 1,526 kWh at a 7% total RTU energy reduction (Table 14).

Building C27 energy savings did not meet the performance objective of 80 kWh/ton/1,000 h operation. NREL expected building C27 (and similarly building A13) to experience less savings compared to the BXtra, but the savings of 55 kWh/ton per 1,000 h operation shown in Table 14 were even lower than expectations. For C27, the annual operating hours is 2,210 h/yr based on weekday only operation (see Table 8). NREL looked deeper into the monitored data to determine whether an operational issue impacted RTU operation and hence ESM energy savings.

Table 14. Building C27 Linear Regression Energy Usage and Savings Applied to HNL TMY3

	Energy	Normalized Energy
Non-ESM Annual Energy Usage	23,185 kWh	839 kWh/ton per 1,000 h operation
ESM Annual Energy Usage	21,658 kWh	784 kWh/ton per 1,000 h operation
Annual Energy Savings	1,526 kWh (7%)	55 kWh/ton per 1,000 h operation

Figure 17 shows the resultant ESM and non-ESM daily energy usage versus TMY3 daily average ambient dry bulb temperature. Figure 18 provides confidence that the regression model accurately reflects most of the variance of measured non-ESM daily energy usage versus average ambient dry bulb temperature. Figure 19 provides similar confidence in the regression model to capture ESM operation. See Appendix B for more details about the building C27 regression model.

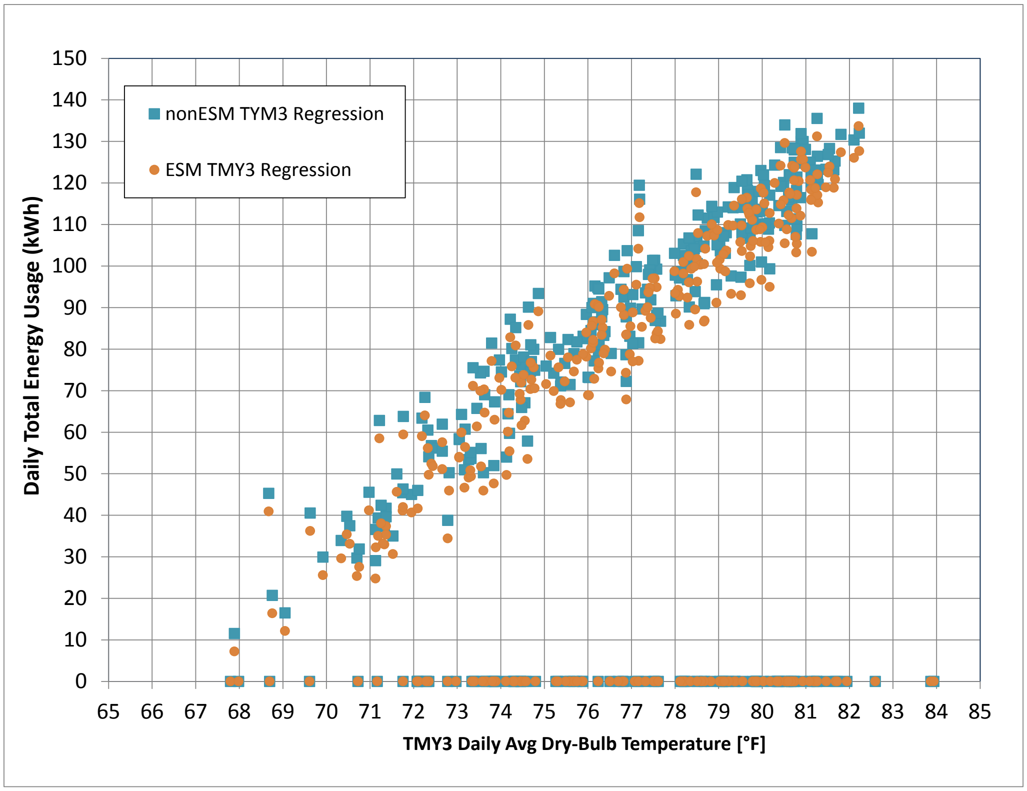

Figure 17. Building C27 linear regression model applied to HNL TMY3 weather data; zero energy values are for weekends when the RTUs are off per NAVFAC operational requirements

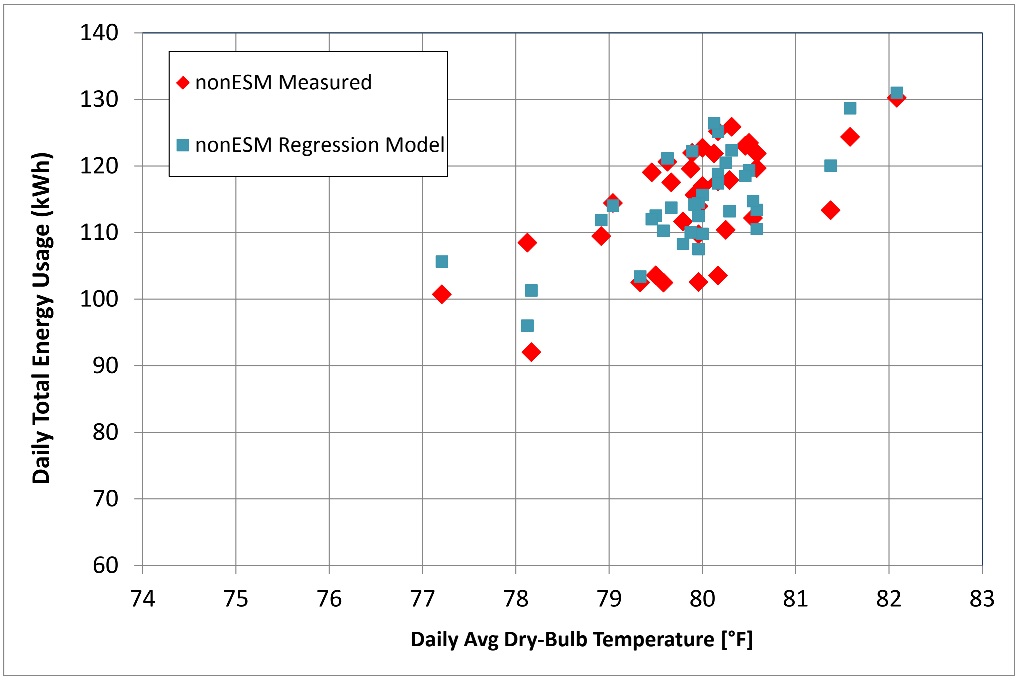

Figure 18. Building C27 comparison of non-ESM daily energy usage between measured data and the regression model

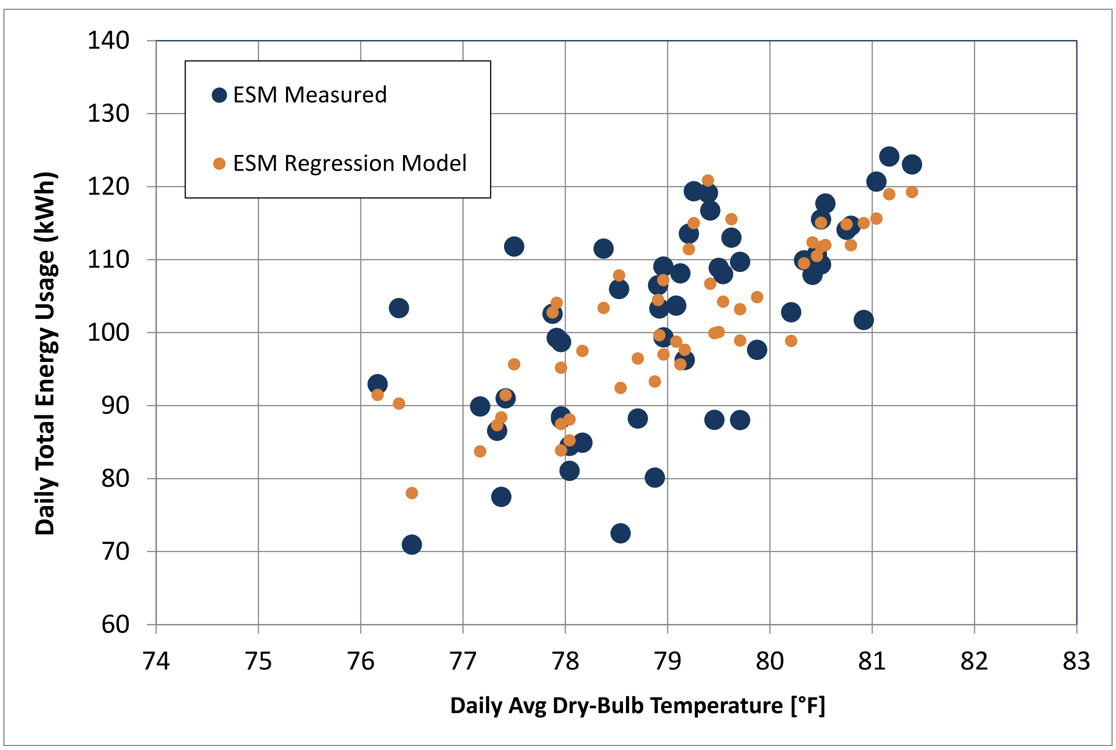

Figure 19. Building C27 comparison of ESM daily energy usage between measured data and the regression model

Compared to BXtra and building A13, the C27 RTU operated in second-stage cooling for almost the entire operational period of 6:00 a.m. to 3:30 p.m. Figure 20 provides an example on September 9, 2013 (Monday); except for 0700-0800, the second-stage cooling was always operational indicated by the purple squares. At first NREL thought that the RTU was undersized relative to the load. The infiltration load in these small offices must be significant, because as soon as the RTU shuts off at 3:30 p.m., the space temperature increases beyond the OAT in about 4 hours (see Figure 21). The confusing part was that the 216 ft2/ton RTU size to conditioned floor area parameter shown in Table 8 indicated that the RTU was oversized. A typical size of 300–400 ft2/ton would be expected.

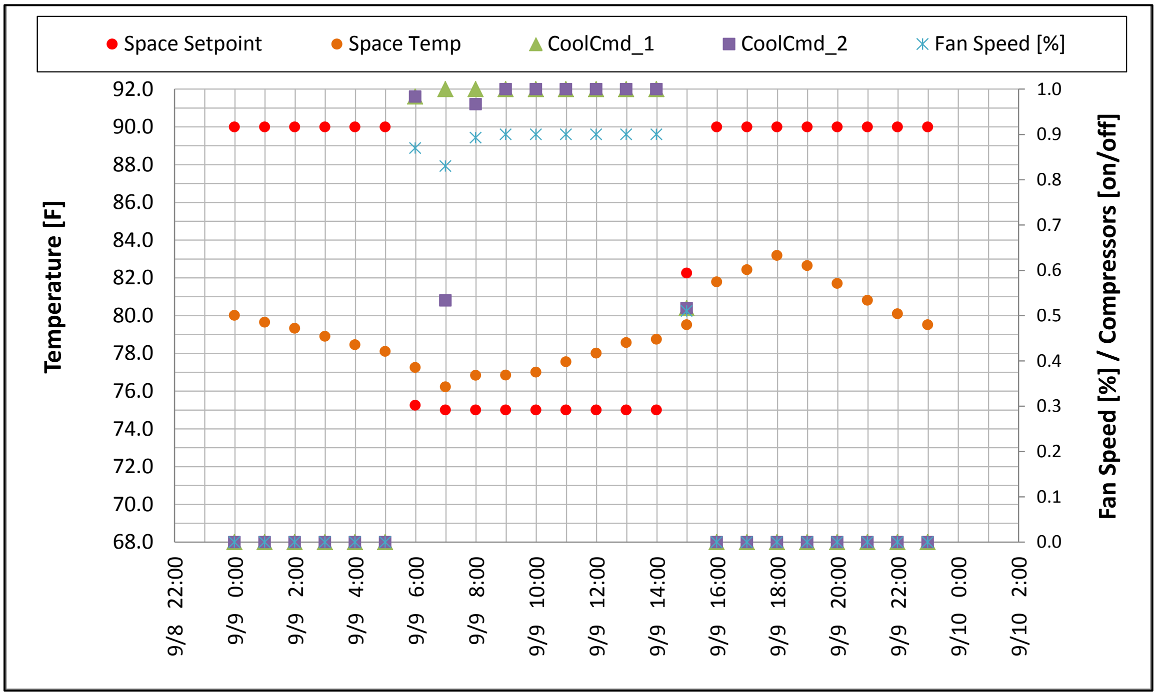

Figure 20. C27 RTU operation (9/9/2013)

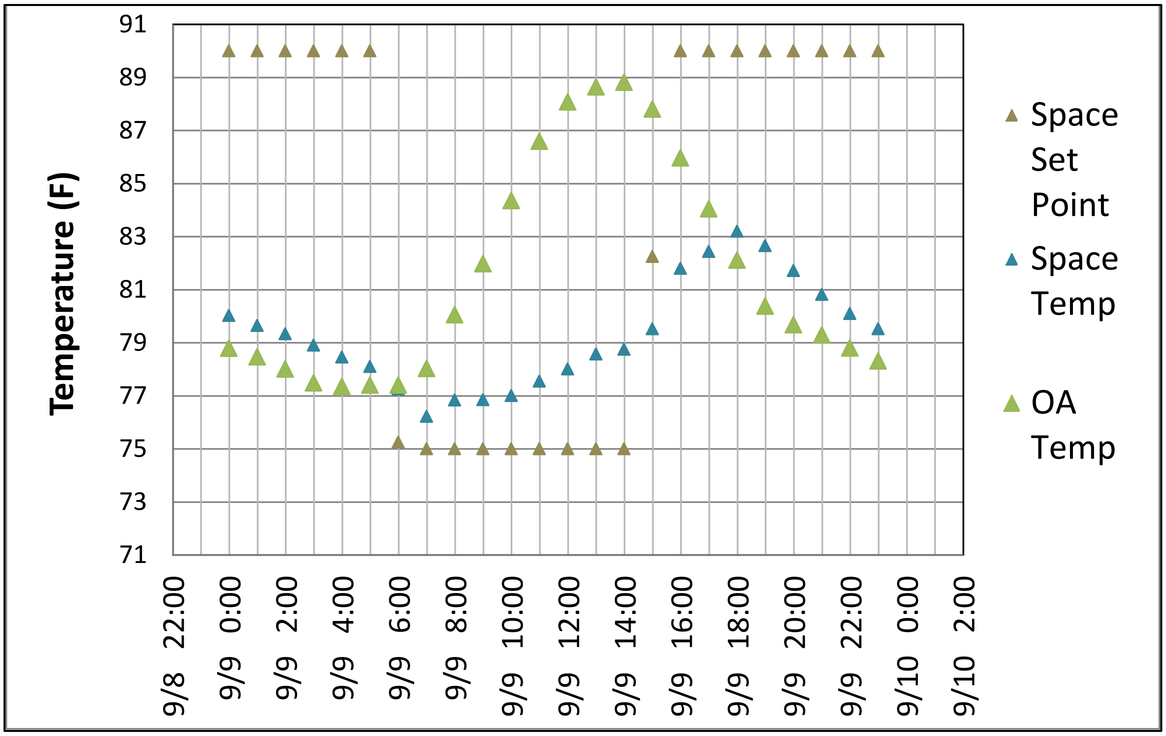

Figure 21. C27 space temperature versus space temperature set point (9/9/2013)

NREL is confident that the location of the temperature sensor immediately next to an exit door (see Figure 22) was reason the RTU operated improperly. The temperature sensor is influenced by the infiltration at the door and is not representative of the average air temperature across the space. During a site visit to building C27, NREL used a calibrated field temperature sensor to measure a 6°F temperature difference from the temperature sensor location to the furthest cubicle still inside the RTU's conditioned area. As a lesson learned for follow-on ARC retrofit installations in Appendix J, NREL recommends that temperature sensors be located near the center of the conditioned space and at least 4 feet from any doors if along the same wall or 20 feet if along a wall perpendicular to the door. For an ARC retrofit with a properly located temperature sensor, the energy savings will have a higher probability of exceeding the 55 kWh/ton per 1,000 h operation measured in this field test.

Figure 22. Building C27 improperly located temperature sensor immediately next to the side exit door

4.2.3 A13 Energy Savings

Because of maintenance issues unrelated to the CATALYST system, building A13 experienced the shortest demonstration period (August 1, 2013 to November 9, 2013). ESM operation saved 22 kWh/day at a 12% reduction in HVAC usage for the cleaned sample set shown in Table 15. Like building C27, this energy savings does not provide a true apples-to-apples comparison because ESM sample experienced a 1.0°F lower average daily temperature.

Table 16 shows that the supply fan provides the most energy savings. Figure 23 provides a time series of the measured daily energy use across the demonstration period. Unfortunately, the sample days do not extend past October 22, 2013 through the end of the demonstration on November 19, 2013. An error in the demand response sequence caused the first-stage compressor to come on and never shut off from October 22, 2013 through November 15, 2013. Consequently, during the days when the first-stage compressor was operating 24 h/day, the daily energy usage was inflated such that those days needed to be eliminated from the sample set. The error occurred because building A13's demand response sequence was modified and caused operational errors during demand response and non-demand response days. In Appendix J, for follow-on ARC retrofits, NREL recommends conducting a post-construction meeting to review ARC system operation and using the monitored data to identify similar operational issues.

Table 15. Building A13 Demonstration Period (8/1/13–11/9/13) Measured Energy Usage between ESM and Non-ESM Operation

	Total Raw Sample (Days)	Maintenance Issues (Days)	Weekends (Days)	Cleaned[a] Sample (Days)	Avg OA Temp*	Total Energy Usage[a]	Avg Daily Usage[a]
Non-ESM Operation	41	13	11	17	80.0°F	3,268 kWh	192 kWh
ESM Operation	60	15	15	30	79.0°F	5,103 kWh	170 kWh
	101 total	28 total	26 total	47 total	1.0°F delta	8,371 kWh total	22 kWh (12%) savings

[a] Based on cleaned data eliminating weekend days and days when known operational issues impacted daily energy usage.

Table 16. Building A13 Energy Usage Separated between Supply Fan and Remaining End Uses (Compressors, Condenser Fans, Controller) Broken Down by ESM and non-ESM Operation

	Fan Energy[a]	Comp/Cond Fan/Controller Energy[a]	Fan Avg Daily Usage[a]	Comp/Cond Fan/Controller Avg Daily Usage[a]
Non-ESM Operation	465 kWh (14% of total)	2,803 kWh (86% of total)	27 kWh	165 kWh
ESM Operation	462 kWh (9% of total)	4,641 kWh (91% of total)	15 kWh	155 kWh
			12 kWh (44%) ESM savings	10 kWh (6%) ESM savings

[a] Based on cleaned data eliminating weekend days and days when known operational issues impacted daily energy usage.

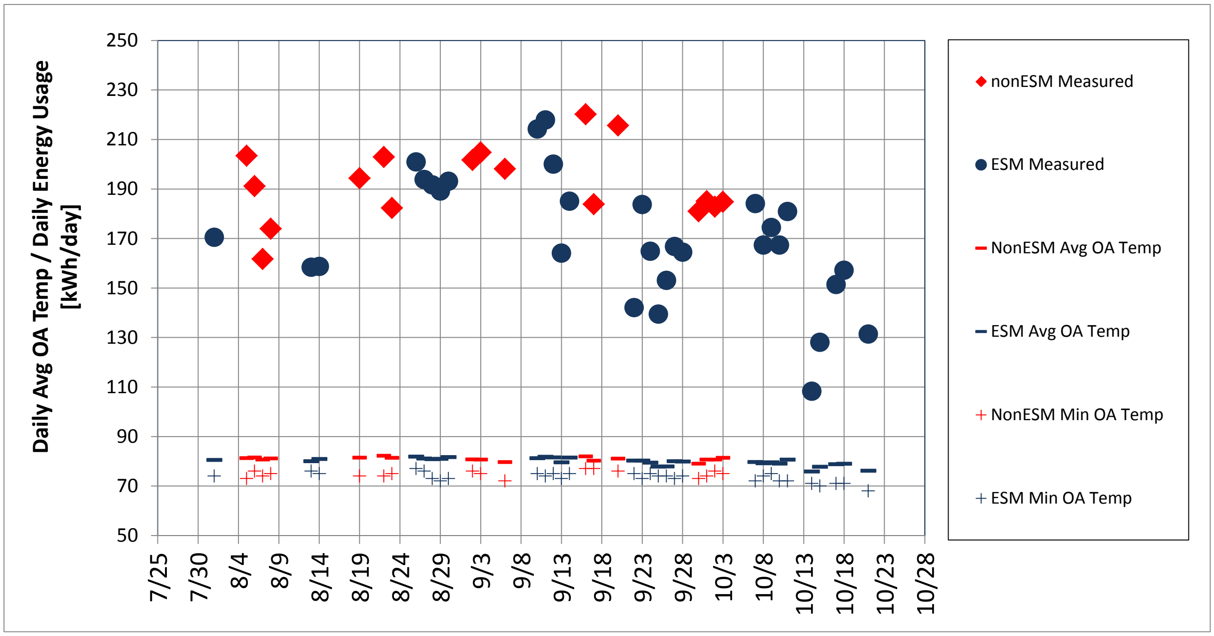

Figure 23. Building A13 time series plot of measured ESM and non-ESM energy usage (excluding weekends and known maintenance days) and average OAT and minimum OAT. Note that due to an error in the weekly alternating schedule, ESM operated an extra week in mid-October.

Table 17 shows the building A13 regression model applied to HNL TMY3 weather data. ESM operation saved 1,803 kWh annually, resulting in a 5% HVAC energy reduction. Building A13 (with a 20-ton RTU) experienced smaller absolute and percentage energy savings compared to the 12.5-ton RTU serving building C27. The normalized energy savings was 39 kWh/ton per 1,000 h of operation. For A13, the annual operating hours is 2,340 h/yr for weekday only operation (see Table 7).

Table 17. Building A13 Linear Regression Energy Usage and Savings

	Energy	Normalized Energy
Non-ESM Annual Energy Usage	38,612 kWh	825 kWh/ton per 1,000 h operation
ESM Annual Energy Usage	36,809 kWh	787 kWh/ton per 1,000 h operation
Annual Energy Savings	1,803 kWh (5%)	39 kWh/ton per 1,000 h operation

NREL believes that had building A13's demonstration period been longer, the energy savings would be been greater than building C27's. A longer demonstration would also have incorporated the impacts of larger humidity ratio (HR) ranges and diluted human behavior-based impacts. Figure 24 shows the non-ESM and ESM daily energy usage versus TMY3 weather data. Figure 25 and Figure 26 compare the regression model versus the measured data. Again, had the demonstration period been longer, the regression model would have most likely incorporated HR and possibly Friday as statistically significant predictors, which would have explained some of the scatter in Figure 25 and Figure 26.

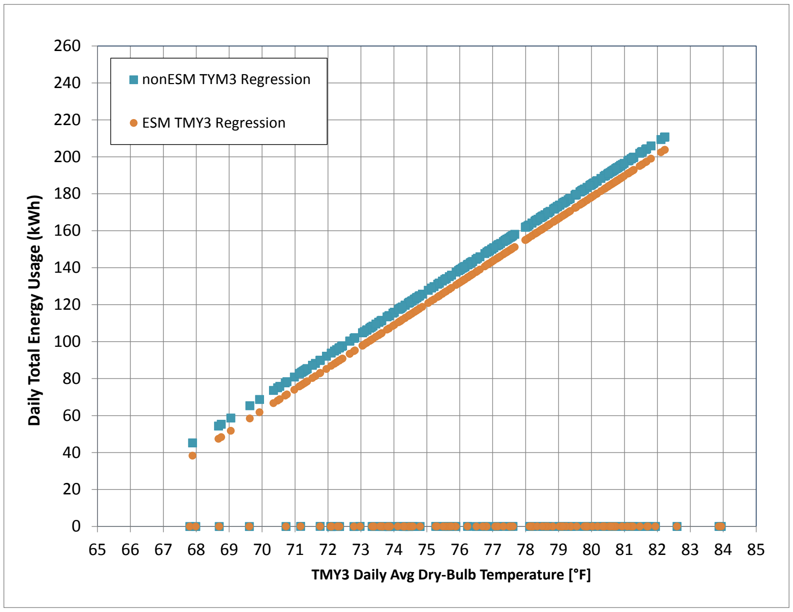

Figure 24. Building A13 linear regression model daily total energy based on TMY3 weather data; note zero energy values are for weekends when the RTUs are off per NAVFAC operational requirements

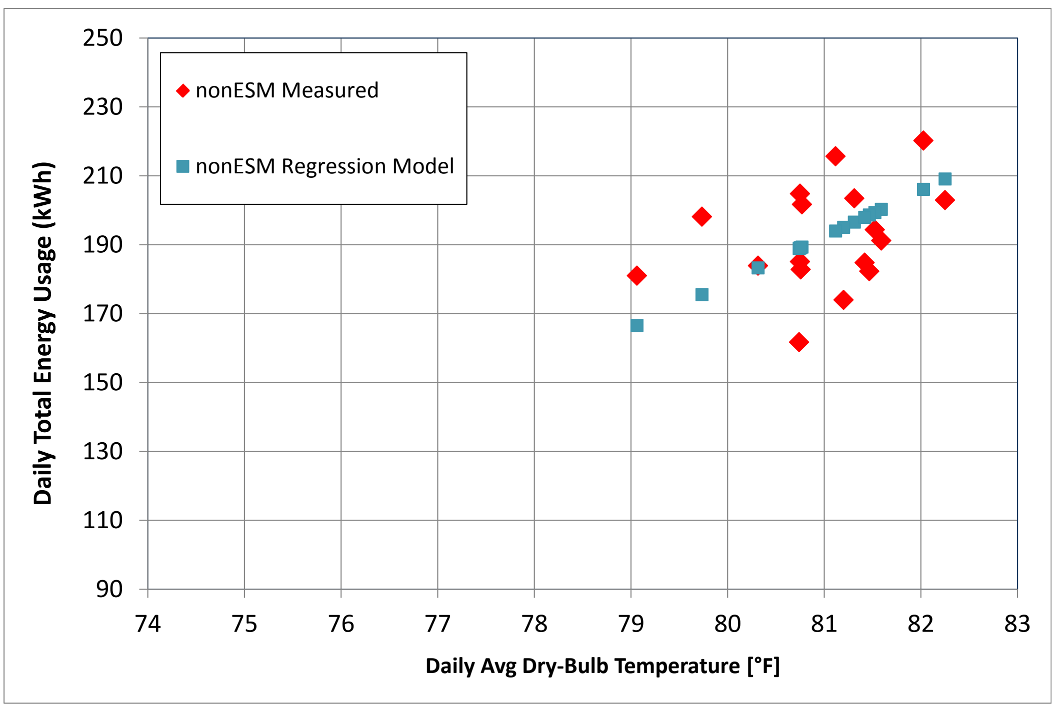

Figure 25. Building A13 comparison of non-ESM daily energy usage between measured data and the regression model

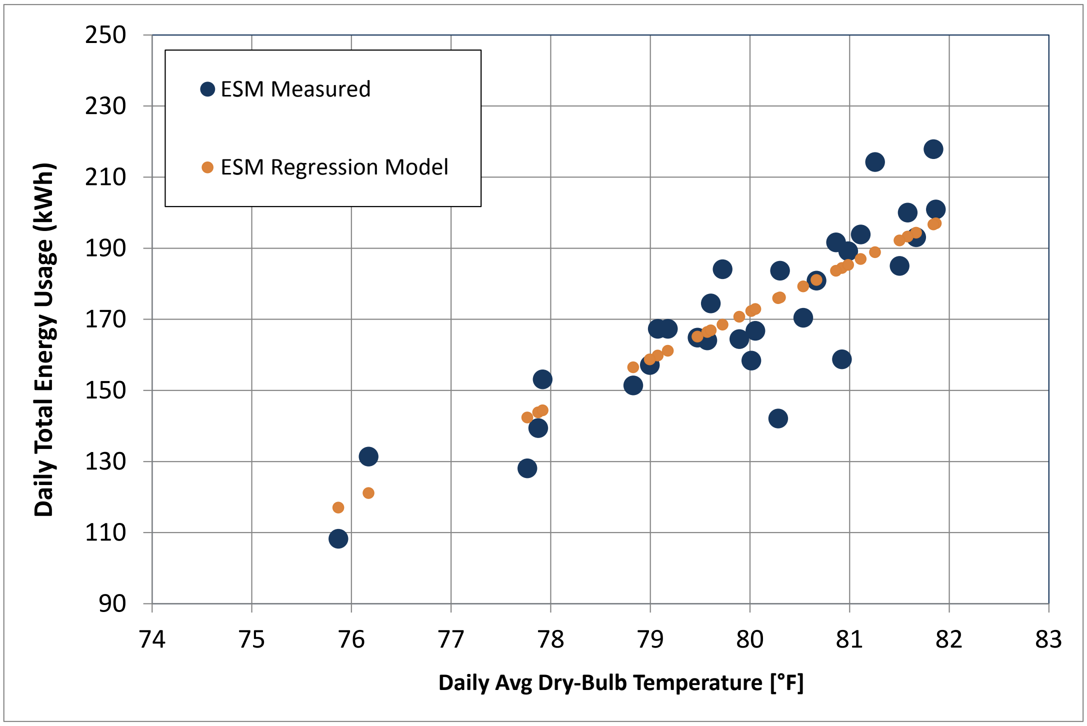

Figure 26. Building A13 comparison of ESM daily energy usage between measured data and the regression model

NREL will continue to monitor building A13's performance through January 2014 and will provide an addenda report with updated energy usage and savings. NREL chose the A13 RTU because it has larger capacity (20 tons) than other RTUs on the potential demonstration list. NAVFAC technicians stated that it was not experiencing uncharacteristic levels of maintenance. In hindsight, building A13's RTU should not have received the ARC retrofit but should have been replaced. The RTU was 15 years old and at the end of its life based on the reoccurring maintenance issues during the demonstration period. At the end of the demonstration period, NAVFAC told NREL that it was going to replace the A13 RTU with a new high efficiency unit in early 2014.

4.3 Interior Thermal Comfort

The interior space temperature and RH were monitored in all three buildings for the duration of the demonstration to characterize the impact of ARC system operation on interior thermal comfort. At the onset of the demonstration, NREL determined that the NAVFAC-approved thermostat set points and allowable RTU on/off times caused the RH to exceed 65% for buildings A13 and C27. In addition to thermal discomfort, NREL was concerned about mold. The moisture problem was exacerbated when NREL was directed in April 2013 to increase the space temperature set point to 80°F based on Commander Navy Installations Command (CNIC) direction to operate at Common Output Level Standards (COLS) level 4 until further notice.

NREL brought the moisture issue and imminent COLS level 4 directive to NAVFAC Hawaii's and NAVFAC Headquarters' attention. From April through June 2013, NREL held weekly conference calls to identify concerns and establish NAVFAC's standards of service regarding thermal comfort and allowable RTU on/off times. Appendix A reviews how NAVFAC and

NREL established the final demonstration thermostat set points, RH constraints, and required RTU on/off times. Table 6, Table 7, and Table 8 summarizes these operational parameters for buildings 1235H, A13, and C27, respectively.

RTUs provide thermal comfort through sensible cooling (maintaining space temperature near set point) and latent cooling (maintaining space RH lower than a predefined threshold). ASHRAE standard 55 recommends the space RH be maintained at < 65% for thermal comfort and mold concerns. ARC retrofits will improve the latent cooling capability of an RTU. Space RH will reduce and comfort will improve especially for the humid Hawaii climate. ARC retrofits improve latent cooling two ways: (1) the slower fan speeds under first- or second-stage cooling supplies colder air at a lower dew point temperature, which will drive the space dew point lower; and (2) ARC retrofits can close the OA damper during unoccupied operation and leverage DCV to reduce the ventilation flow rate during occupied operation.

For the latent cooling analysis, NREL included both space dew point and RH. RH was evaluated to determine whether both ESM and non-ESM operation maintained the space at < 65% RH for occupied and unoccupied hours. Yet RH is not solely a measure of moisture content but is also a function of dry bulb temperature, which was impacted by the operational mode. Therefore, dew point temperature was used to compare the latent cooling capability of ESM versus non-ESM operation.

Histograms of hourly average space temperature and dew point are shown in Figure 27 through Figure 32. All three facilities demonstrated a reduction in space dew point under ESM operation; the BXtra shows the greatest reduction. The relatively larger infiltration loads on buildings C27 and A13 reduced the dew point difference between ESM and non-ESM operation. The differences in space temperature were less defined and varied by building. The BXtra ESM operation showed a slightly warmer temperature. Building C27 showed ESM operation maintaining a slightly cooler temperature. Building A13 showed a negligible difference in space temperature.

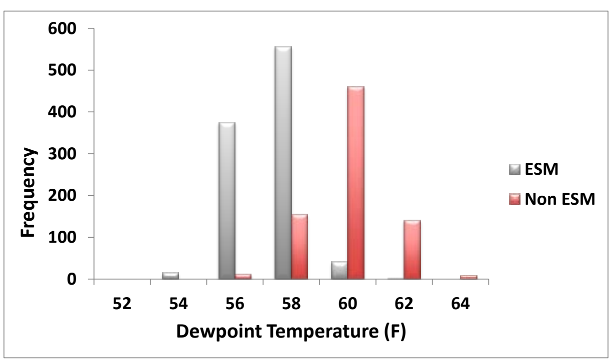

Figure 27. BXtra dew point temperature histogram

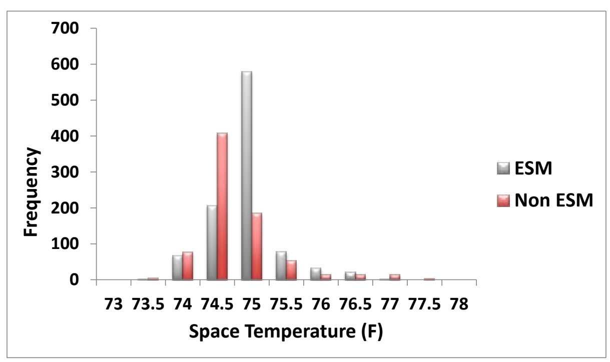

Figure 28. BXtra space temperature histogram

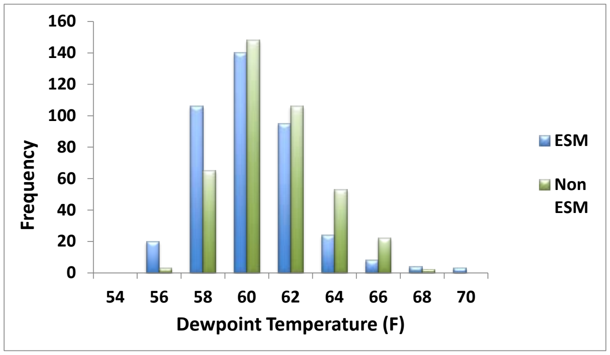

Figure 29. A13 dew point temperature histogram

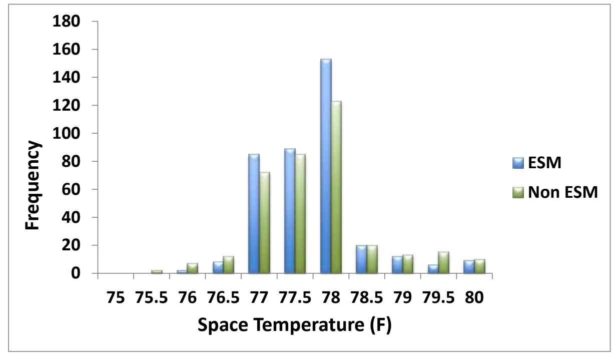

Figure 30. A13 space temperature histogram

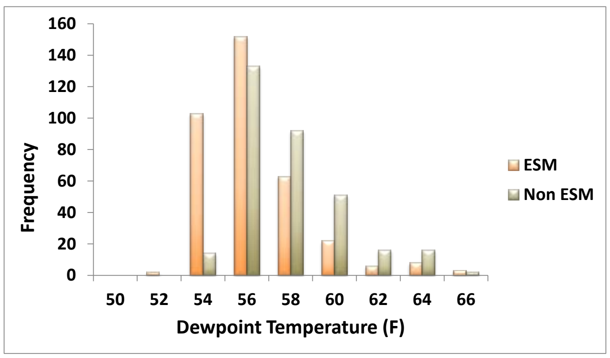

Figure 31. C27 dew point temperature histogram

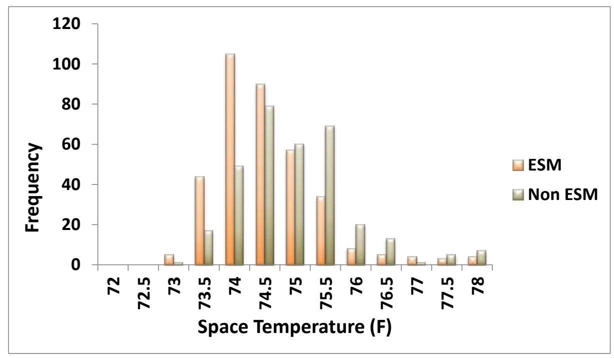

Figure 32. C27 space temperature histogram

NREL found that both ESM and non-ESM maintained the space RH at < 65% except for a few hours for all three buildings. Figure 33 shows the hourly average space RH for the BXtra as a function of OA HR in ESM and non-ESM during occupied hours. Reinforcing the dew point histogram in Figure 27, ESM clearly maintains a drier space. Over the course of the demonstration, the average RH for the BXtra in non-ESM was 58% compared to 53% in ESM.

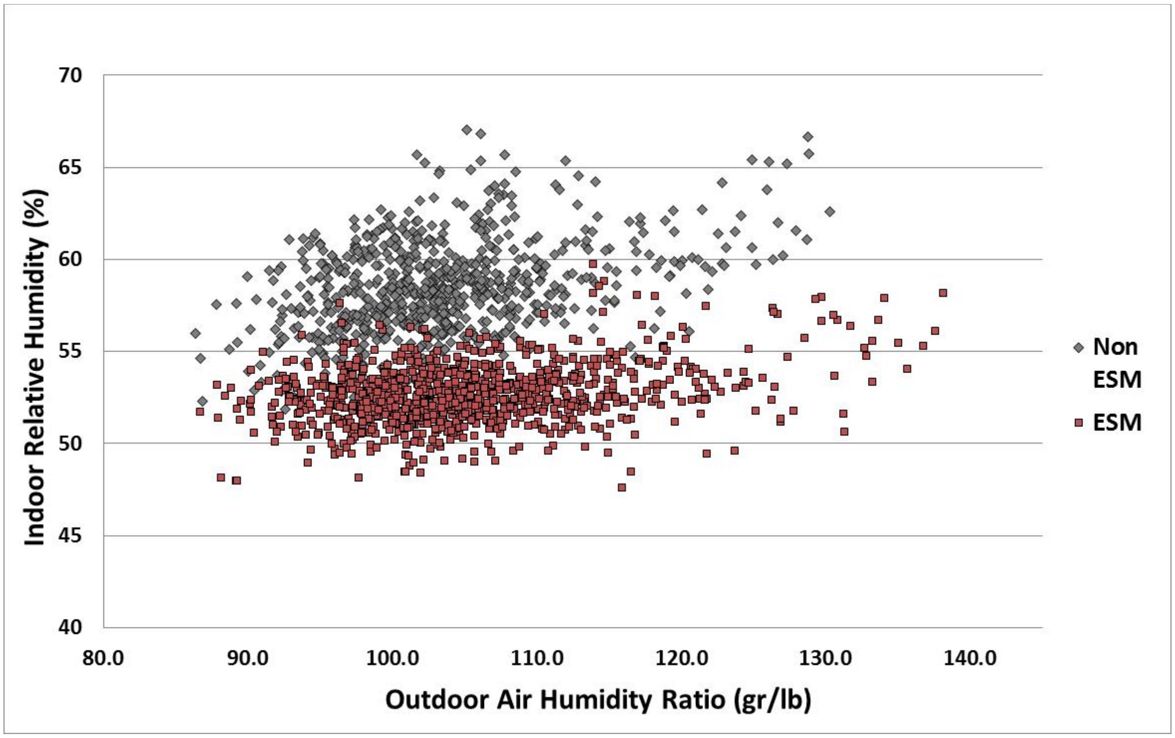

Figure 33. BXtra space hourly average RH including occupied and unoccupied hours versus hourly average ambient HR

4.4 Ventilation Quality

None of the CO_2 sensors in the three buildings measured a concentration > 1,000 ppm such that the CATALYST needed to initiate its DCV sequence and open the OA dampers. In fact, the CO_2 concentrations never exceeded 700 ppm. There were no reports of occupant complaints about air quality. Based on work with other retail type buildings, NREL found that CO_2 rarely achieves the DCV limit except under extreme conditions such as Black Fridays in retail buildings. Office spaces rarely if ever achieve the DCV limit because their occupancy density never reaches their design occupancy level throughout the year.

NREL was not concerned about over-ventilation since the CO_2 ppm levels were within expected ranges; 400-450 ppm during unoccupied times (close to ambient CO_2 concentration at 400 ppm) and 450-700 during occupied times for all 3 buildings. NREL did not want to close the dampers further until the CO_2 concentration reached 1,000 ppm since the ventilation flow rate still needed to meet the minimum ASHRAE 62.1 cfm/ft^2 requirement for material off-gassing. NREL determined that the OA damper configurations during the demonstration period maintained acceptable CO_2 concentrations and therefore met the ASHRAE 62.1 cfm/occ requirement.

Table 18 shows the ASHRAE Standard 62.1 minimum ventilation requirements for all three buildings. By enabling DCV, the ARC system can reduce the minimum ventilation rate by 48% for retail buildings and 29% for office buildings. Yet to practically apply these ASHRAE 62.1 minimum requirements, NREL found the TAB results had too significant an uncertainty. NREL decided to maintain the CATALYST default OA damper sequence at 6% open at 90% fan speed and 12% open at 40% fan speed. The following paragraphs summarize the uncertainty in the TAB measurements and why this decision was made.

Table 18. ASHRAE Standard 62.1-2010 Minimum Ventilation Rates for the 1235H BXtra, C27, and A13 Buildings

Building	Area Served	Space Type	Occ Vent Rate	Default Occ Density	Area Vent Rate	Min Req'd Vent Rate (No DCV Operation)	Min Req'd Vent Rate (DCV Operation Only)
1235H BXtra	69,576 ft^2	Retail Sales	7.5 cfm/occ	15 occ/ 1,000 ft^2	0.12 cfm/ft^2	16,176 cfm	8,349 cfm (48% reduction)
C27	2,706 ft^2	Office	5.0 cfm/occ	5 occ/ 1,000 ft^2	0.06 cfm/ft^2	230 cfm	162 cfm (29% reduction)
A13	7,834 ft^2	Office	5.0 cfm/occ	5 occ/ 1,000 ft^2	0.06 cfm/ft^2	666 cfm	470 cfm (29% reduction)

NREL had a TAB conducted per UFGS 23 05 93 to verify that actual ventilation rates were meeting the minimum requirements shown in Table 18. The TAB measured the total supply and OA flow rates at 90% fan speed (CATALYST second-stage cooling mode) and 40% fan speed (CATALYST fan only mode). The uncertainty for the total supply flow rate NREL determined to be +/-15 to 20% based on the +/-3% sensor accuracy at each air velocity measurement of the duct traverse. Yet the uncertainty of the ventilation flow rates NREL determined to be significantly more.

The TAB procedure implemented a pitot tube traverse of the OA intake velocities at the damper. Directly measuring OA with a pitot tube is actually recommended by NEBB TAB procedure standards as referenced by UFGS 23 05 93. Compared to built-up air handling units, RTUs provide so little ventilation that the air velocities at the damper are well below the 50 fpm threshold at which pitot tube accuracy significantly diminishes. The Short Ridge AirData Multimeter ADM-860 used for the TAB has a stated air velocity accuracy of +/-3% from 50 to 8,000 fpm. The TAB report showed the OA damper traverse velocity readings ranging from 0 to 225 fpm.

The resultant OA flow rates based on these velocity readings did not make intuitive sense. Identical RTUs with the same OA damper configuration were reported as having drastically different ventilation. For example, at a 90% fan speed and 6% OA damper, BXtra Unit 05 and Unit06 ventilation flow rates were reported at 2,406 cfm and 168 cfm, respectively. In some cases, the same RTU was reported as providing significantly more ventilation at 40% fan speed with a 12% OA damper than 90% fan speed with a 6% OA damper. BXtra Unit01 reported a 1,316 cfm at the 40% fan speed configuration and 613 cfm at the 90% fan speed configuration. Most of the other RTUs showed the opposite trend.

NREL determined that a combination of sensor error (air velocities below 50 fpm) and environmental air (impacts of wind) were the causes. While not the recommended method, NEBB TAB procedure accepts a pitot tube traverse of the total supply minus the total return to calculate OA flow rate. The TAB should have implemented this procedure considering that measuring the return air would have been at velocities over 50 fpm and minimally influenced by the wind. While there is additional uncertainty of subtracting two calculated air flows, the uncertainty would have been significantly reduced.

This demonstration showed that despite extensive evaluation of the TAB results, no definitive conclusions could be drawn about whether the ARC systems were maintaining sufficient DCV minimum ventilation per ASHRAE 62.1-2010. NREL still recommends that the TAB activity includes balancing the ventilation rates at different fan speeds. Yet to maintain confidence in the TAB measurements, the ventilation flow rates should be calculated based on the measured SA flow minus the measured RA flow. The OA damper should be configured accordingly at each fan speed. The CO_2 sensor will then enable the ARC system to respond appropriately if occupancy (cfm/occ) based ventilation is needed.

The following subsections summarized how NREL interpreted the TAB results acknowledging the significant uncertainty of the measurements. For buildings A13 and C27, the ventilation measurements were not valid for the demonstration period. Based on scheduling complications, the TAB took place before the electronic actuators were installed in these RTUs. The TAB report indicated that the measurements were taken with the OA damper manually adjusted to 50% open. To simplify the installation process and ensure the TAB is conducted at the correct time, NREL recommends that the ARC installs, not a third party TAB certified contractor, balance the supply and ventilation flow rates. This recommendation along with NREL's recommendation for how to conduct the TAB is summarized further in Appendix J. Appendix E summarizes the sensor and environmental uncertainty as well as the detailed TAB results.

4.4.1 1235H BXtra

The aggregated ventilation rate measured for all nine RTUs at 90% fan speed was 7,346 cfm, which is slightly less than the DCV minimum required at 8,349 cfm but well within the uncertainty of the TAB measurement. At 40% fan speed, the aggregated ventilation rate was 3,871 cfm, much less than the minimum required but again within the uncertainty of the TAB measurement.

4.4.2 Building C27

The 176 cfm ventilation rate at the 90% fan speed indicated that the minimum ventilation rate was meeting the DCV minimum required at 162 cfm. Yet at 40% fan speed, the RTU was under ventilating at 53 cfm yet within the uncertainty of the TAB measurement. These measurements were made before the electronic actuator was installed. The TAB report stated that the OA damper was manually adjusted to 50% open.

4.4.3 Building A13

Compared to the DCV minimum requirement of 470 cfm, the 851 cfm ventilation rate at the 90% fan speed indicates overventilation. The 335 cfm at 40% fan speed indicates slight underventilation but within the uncertainty of the TAB measurement. These measurements were made before the electronic actuator was installed. The TAB report stated that the OA damper was manually adjusted to 50% open.

4.5 Demand Response

Demand response events can be triggered by a schedule or a communication signal. The CATALYST ARC can respond to any method of communication. The Navy demonstration demand event was scheduled through the ARC's BMS function. Scheduled demand events are set up to occur between 3:00 p.m. and 5:00 p.m. every Tuesday, Thursday, and Saturday for the

BXtra in ESM and non-EM and between 1:30 p.m. and 3:30 p.m. for A13 and C27 in ESM. The BXtra demand response results are summarized below. Buildings C27 and A13 demand response results are summarized in Appendix F.

The BXtra sequence of operation is set up to limit the maximum demand across all nine RTUs to 160 kW during a demand event. The peak power draw of all nine RTUs is approximately 194 kW. To maintain the demand level, the sequence targets equipment with the lowest cooling load based on space temperature versus set point. As the cooling load changes, the available electric capacity is passed to units with highest demand based on the following rules:

- If the cooling load is greater than 60% (based on the difference between the temperature set point and current space temperature) a minimum of one compressor will run.
- The unit will be locked into an operating mode for 15 minutes following a demand call.

A temperature set point shift is used before the demand event. The cooling set point temperature is lowered by 2°F before the demand period. During the demand event, the space temperature is allowed to float up 2°F above set point. At the end of the demand event, the space temperature is reset to its normal set point temperature. The monthly peak demand savings over a 4-month period are provided in Table 19 for the BXtra building.

Table 19. BXtra Monthly Demand Savings

Month	Maximum Demand 3:00 p.m. to 5:00 p.m. Non Demand Response Day (kW)	Maximum Demand 3:00 p.m. to 5:00 p.m. Demand Response Day (kW)	Demand Savings During Demand Response Event (kW)	Maximum Daily Demand on Demand Response Day (W)	Maximum Daily Demand Non Demand Response Day (kW)	Demand Reduction (kW/Ton)	Demand Reduction (Watt/ft^2)
July	117.7	96.5	21.2 (18%)	127.9	119.9	0.12	0.30
August	153.8	112.1	41.7 (27%)	186.8	154.3	0.24	0.60
September	152.0	125.8	26.2 (17%)	199.6	170.0	0.15	0.38
October	151.2	132.4	18.8 (12%)	196.2	160.0	0.11	0.27

The peak demand savings during the demand response period ranged from 41.7 kW in August to 18.8 kW in October. Although the demand was reduced during the demand response period, the precool sequence increased overall demand for the demand response days (Figure 34).

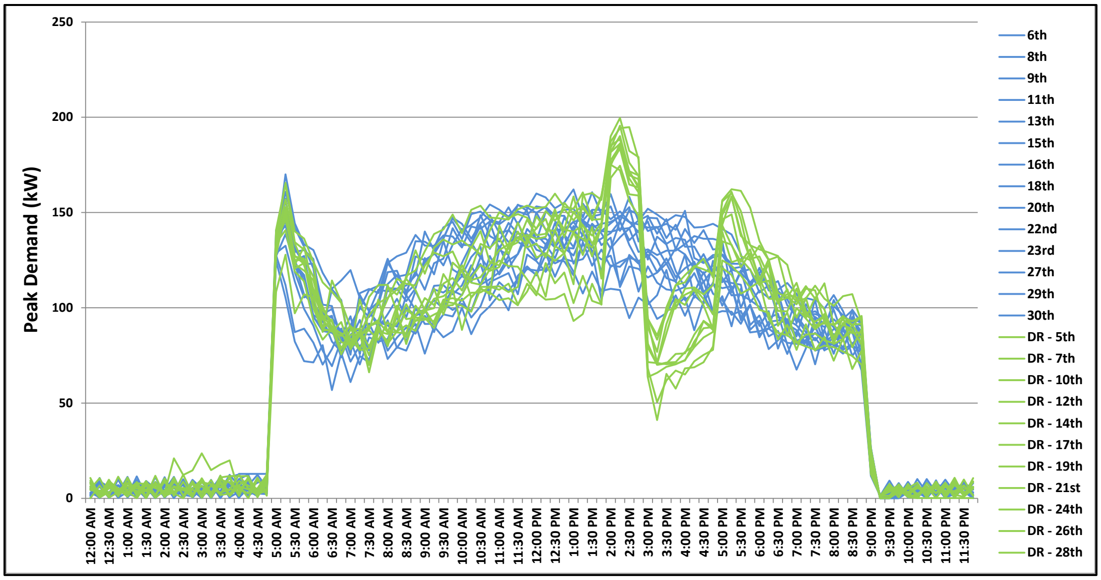

Figure 34. BXtra demand response for September

During September, when the units were operating 16 h/day, the increased peak demand associated with precooling the space before the demand event increased overall demand by an amount that is roughly equivalent to the reduction in demand during the demand event. Yet, based on NREL's work with utilities, the main focus is on the peak power during the demand event. Utilities are less concerned with the peak demand that occurs before the demand event.

The demand response analysis also indicated that the overall demand for the BXtra is sensitive to the operational schedule. When the units operate 16 h/day, the baseline peak increases by about 30 kW over the baseline peak when the units are operating 20 h/day. When the schedule was changed to 16 h/day, the baseline peak occurred first thing in the morning rather than around 1:00 p.m. (Figure 35).

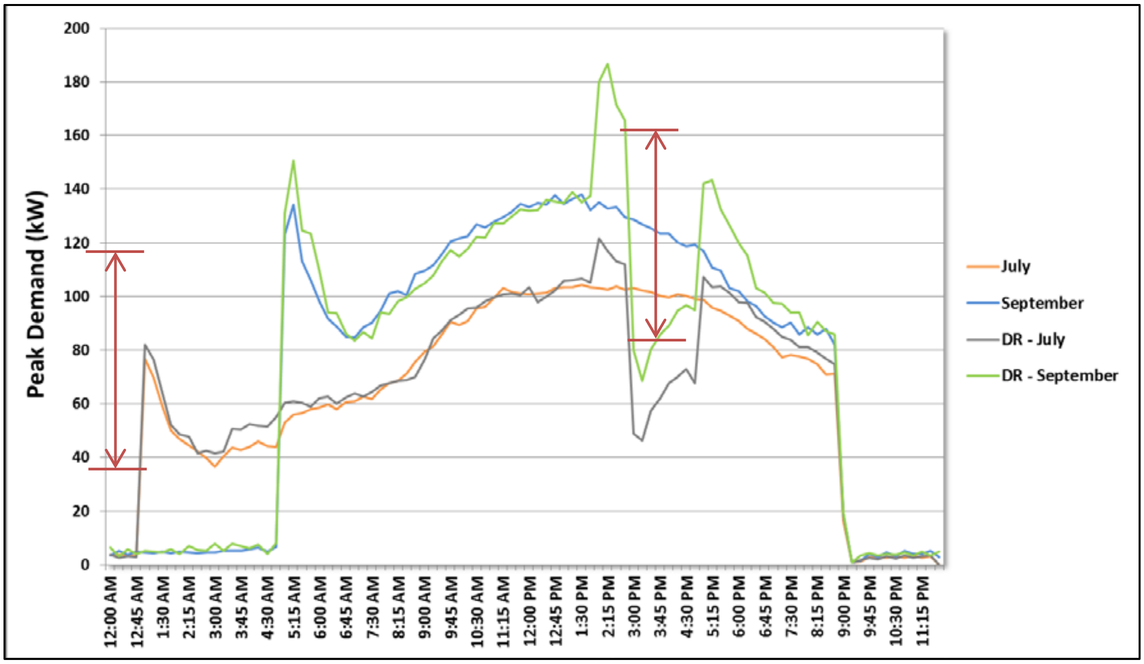

Figure 35. BXtra demand response for July and September

In addition to the baseline peak shifting to the beginning of the day, the reduced operation of the unit also caused a larger spike in energy use to precool the space. The peak demand analysis for the BXtra provided valuable insights into the complexities of trying to maintain space comfort and simultaneously shift peak demand without increasing overall demand. The sequence successfully shifted peak demand, but the analysis revealed that the peak demand profile is sensitive to the operational schedule of the RTUs and the space load before the demand event.

The expectation that an RTU can maintain a comfortable space while shifting demand is a challenging goal. More work is needed to determine general procedures that can effectively meet this goal. A simpler sequence that simply shifts demand or turns off a series of compressors based on a control signal from a utility is easy to implement, but commercial building owners are not universally open to sacrificing thermal comfort during these demand events. Further peak demand analysis should be conducted to determine a truly optimal strategy for this location that can maintain acceptable space temperatures and shift the peak demand.

The demand response feature of ARC technologies is not recommended for NAVFAC currently. This demonstration of demand response was to show the magnitude of the peak reduction. Since it will typically increase building energy consumption, utilities will need to provide building owners like NAVFAC rebate incentives to enable a demand response feature for ARC systems. NREL is currently working with utilities to evaluate these demand response capabilities further and determine if additional utility rebates can incentive the ARC technology as a combined demand response and energy efficiency asset. With prescriptive based rebates, ARC systems would realize an improved ROI.

5 Economic Performance Analysis and Assessment

Economic results of the demonstration indicate application of the ARC technology in Hawaii can yield appreciable energy and cost savings. Demonstration actual net savings are projected at $170,000 over a 10-year operational life, with a savings to investment ratio (SIR) of 1.9. Results are promising and indicate the U.S. Navy, on an economic basis, should consider further investment and deployment of ARC retrofit technologies in the Pacific region.

Further, there may be additional, improved savings for follow-on deployments. Comparing per-unit results between facilities, BXtra building performance was appreciably better than small office buildings A13 and C27. These results indicate selecting facilities with multiple RTUs and longer building operating hours will improve energy efficiency and economic return. Assuming follow-on deployments apply the demonstration's lessons learned for improved facility and RTU selection, energy savings for 11 RTUs could increase to 120 MWh/yr (16% increase) resulting in $270,000 savings over the same 10-year economic life. Assuming pricing efficiencies will also be realized in transitioning from a demonstration to deployment scale activity, economic return is expected to increase more significantly.[3]

Table 20 provides a full summary of the economic results, in addition to key analysis inputs. Key economic results were calculated using the latest version of the National Institute of Standards and Technology (NIST) developed Building Life-Cycle Cost (BLCC) Program. eROI values were provided using the latest available version of the Neptune eROI calculator, as provided by NAVFAC.[4] Appendix K includes a detailed accounting of the economic analysis performed.

Economic results were reviewed to evaluate performance sensitivities and potential sources of error in the estimates provided. Four key factors were identified:

1. **Performance dependency on facility selection.** Proper selection of facilities presents a key factor in energy and cost savings performance. As presented in Table 21, per-unit energy and economic yields were significantly greater for the BXtra building than for buildings C27 and A13. Of specific note, the SIR for BXtra is significantly greater than unity, whereas C27 and A13 are significantly lower. For future deployments, careful consideration should be given to facility and RTU types, with best performance yields coming from large facilities with multiple RTUs and operating hours exceeding 50 h/week.

[3] See Appendix K for facility price savings assumptions.

[4] eROI is a Navy-specific metric for evaluating benefits of investment in energy technologies. The benefit figure reflects the present value of the project's anticipated contribution to energy as well as it contribution, in dollar-equivalent terms, to other Navy objectives such as improving energy reliability for critical infrastructure, reducing greenhouse gas emissions, meeting regulatory mandates, and so on. An eROI greater than 1.0 indicates the project's benefits are anticipated to exceed its costs. The higher the eROI value, the more attractive the project.

Table 20. Economic Analysis Results

	DD1391 Estimate[a]	Demo Actuals[a]	Projected Follow-On Deployment[a]
Economic Analysis Results			
eROI Value	3.6	5.2	6.9
Net Savings	$75,000	$170,000	$270,000
SIR	1.3	1.9	2.8
Simple Payback	in 7th year	in 5th year	in 3rd year
Adjusted Internal Rate of Return	6%	10%	14%
Key Analysis Inputs			
Annual Energy Savings	168 MWh	100 MWh	120 MWhc
Electricity Price[b]	$0.24/kWh	$0.425/kWh	$0.425/kWh
Initial Investment Cost	$221,130	$166,624	$136,000[c]
Economic Life	10 years	10 years	10 years
Units Installed	11	11	11

[a] DD1391 estimate column reflects analysis as performed as part of site approval/DD1391 process in September of 2012. Demonstration Actuals column reflects economic results based on actual, realized costs of procurement and installation and measured energy savings results. Project follow-on column reflect estimated results for future installations of this technology using a more efficient acquisition strategy and refined RTU selection.

[b] Electricity pricing for demo actuals and projected follow-on reflect the average price of FY13 and FY14 rates at JBPHH.

[c] For follow-on activity, per RTU energy savings are assumed consistent with BXtra building, i.e. selection is optimized for best energy savings results. Detail of cost reductions presented in Appendix K.

Table 21. Normalized Savings Comparison Between Demonstration Facilities

	BXtra	C27	A13
Annual Energy Savings per RTU	10,722 kWh/yr	1,526 kWh/yr	1,803 kWh/yr
Normalized Annual Energy Savings[a]	94 kWh/ton per 1,000 h operation	55 kWh/ton per 1,000 h operation	39 kWh/ton per 1,000 h operation
Annual Cost Savings per RTU	$4,557/yr	$649/yr	$766/yr
SIR per RTU	2.3	0.2	0.3

[a] Total annual energy savings normalized based on nominal tonnage and annual hours of operation; BXtra has 5,840 annualized hours; C27 has 2,210 annualized hours; A13 has 2,340 annualized hours.

2. **Utility electricity rate volatility.** Significant volatility in JBPHH utility rates from FY 2013 to FY 2014 indicate analysis results as presented may be susceptible to uncertainty in projecting future year utility rate pricing. More specifically, utility rates have jumped from $0.24/kWh in FY 2013 to $0.58/kWh in FY 2014. The expectation, based on discussions with NAVFAC Hawaii personnel, is for utility rates to decline in FY 2015, but an exact value remains uncertain. This volatility in pricing must be considered in evaluating economic results of the CATALYST technology, as applied to JBPHH.

   A preliminary sensitivity analysis was performed to evaluate the effect of electricity pricing uncertainty on economic yield. Figure 36 shows net savings estimates for a 15-year economic yield across an electricity price range of $0.325–$0.525/kWh. This range encompasses a ± $0.10/kWh sensitivity band around the nominal rate applied to our economic analysis.[5] As indicated by the figure, electricity pricing has a significant impact on savings. CATALYST technology savings, however, remain appreciable, even at a conservative price of $0.325/kWh.

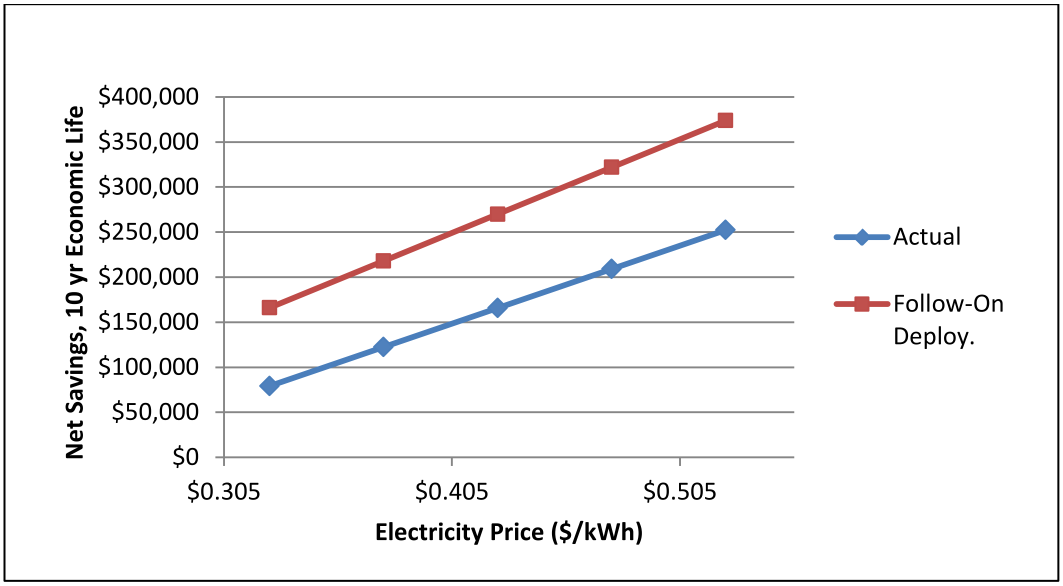

Figure 36. Sensitivity analysis on electricity pricing

3. **Economic life of the ARC technology.** Estimation of the economic life of the ARC technology depends on several factors such as the operational life of the ARC device, the operational life and maintenance of the RTU on which it is installed, and the age of the RTU when the retrofit is performed.

   For this report, the CATALYST system's average economic life was estimated at 10 years. This estimate was based on simple assumptions of an average RTU operational life of 15 years in Hawaii. The CATALYST unit is then utilized, on average, for 10 years of the RTU's lifetime. Reinstallation of half of the CATALYST units was assumed at 7.5 years (half of RTU average operational life), to account for retrofitted RTUs being decommissioned and CATALYST units being reused.

   The actual, realized economic life of the deployed ARC technology will have a significant impact on aggregate energy savings and realized economic yield. Depending on the age criteria used in selecting RTUs, the ARC's economic life may easily vary by several years. In selecting RTUs for ARC retrofits, careful consideration should be given to estimated ARC economic life in this climate zone because RTU lifetimes are much shorter in marine environments, and related factors such as RTU operational life and the technical/price viability of reusing ARCs on progressively decommissioned RTUs.

4. **Results are region specific.** Electricity pricing, weather patterns and climate, and regional pricing for construction costs are key input parameters in estimating energy and

[5] The nominal rate of $0.425/kWh is the average rate between FY 2013 and FY 2014 known rates.

cost savings. Hawaiian values for these parameters, although reasonably attributable to other areas of the Pacific, deviate considerably relative to other applicable regions such as the continental United States. Therefore, energy and cost saving estimates as presented, although promising, are not directly translatable to other geographic regions.

6 Project Management Considerations

Execution of this technology demonstration was programmatically straightforward. Most commercially available ARC technologies are packaged based on a “kit” concept for ease in specification, procurement, and installation. Consequently, acquiring and deploying ARC technologies require minimal time and resources. Table 22 provides a summary of programmatic elements of this project and a high-level timeline of events.

Table 22. Summary of Programmatic Elements of This Project

	Programmatic Summary
Implementation Method	Design-build contractor, minor construction
Key Contractor	TWT
Period of Performance	1 year, 8 months
Project Timeline	Site identification: March 2012–May 2012 Site approval: June 2012–September 2012 Procurement/installation: September 2012–January 2013 Demonstration: February 2013–November 2013

The project life cycle consisted of four sequential tasks:

1. **Identify the site.** To initiate the project, NREL provided NAVFAC the criteria, summarized in Section 3.1, to identify candidate RTU equipment to receive the ARC technology. Based on an established list, the Integrated Product Team (IPT) visited each site and narrowed the list to 11 RTUs.
2. **Approve the site.** Once the site was selected, the IPT approved the site (DD1391), and performed National Environmental Policy Act (NEPA) determination activities.
3. **Procure and install the equipment.** The design-build contractor, TWT, procured and installed the equipment. Design activities were negligible, and overall acquisition was straightforward with few challenges.
4. **Demonstrate the equipment.** As discussed in Section 4, after the ARC was installed and commissioned, the demonstration period began with troubleshooting and evaluation of Navy standards of service. Once operational schedules were finalized, the demonstration monitoring period started.

Programmatic challenges experienced on this project were minimal from an acquisition/technology implementation perspective. Challenges were, however, evident in operation of the ARCs during the demonstration period because of unexpected adjustments to Navy COLS in tandem with ensuring that space comfort and humidity requirements were properly defined and implemented. A key takeaway was that additional, formalized guidance on operational space condition requirements is needed. Valuable lessons learned about moisture control (e.g., morning charge to mitigate interior space moisture) and operational schedules used in this demonstration may also apply to future ARC deployments.

In summary, this technology was acquired in a straightforward manner, executed quickly, and presented minimal challenges. Proper operation did cause appreciable delays. These challenges, however, were not attributable to the ARC technology. Rather, they related to time delays associated with developing a full interpretation of facility space comfort requirements and subsequent translation to ARC operational requirements.

6.1 Site Selection and Approval

6.1.1 Site Selection

Careful selection of facilities and RTUs is a key factor in ensuring optimal ROI for ARC technologies. For the demonstration, selection of facilities and RTUs was initiated by screening RTUs against a short list of technical criteria and identifying candidate options. RTU options were prioritized, accounting for the technical screening criteria, estimated energy savings, and pragmatic factors such as accessibility and client-facility interest. The IPT then performed a site survey of best candidate options, which led to final selection of RTUs. Overall, the site selection activity encompassed a 3-month period, with coordination between NREL, NAVFAC, and site personnel.

Lessons learned from the demonstration, recommended for consideration in site selection for future deployments, follow:

- The RTU supply fan must use a three-phase motor because the VFD that comes with the TWT ARC package works on three-phase motors only.
- Facility use is an important factor in RTU screening. More specifically, screening RTUs by energy savings potential depends on occupancy schedules, temperature and RH set points, and maximum allowable humidity levels.
- RTUs that are undersized for the intended facility are not recommended for ARC applications because the system will almost always operate in second-stage cooling. This significantly reduces fan savings. The RTU must be controlled to have the fan constantly on during occupied hours to meet ASHRAE 62.1-2010 ventilation requirements per UFGS 23 81 00.0020 paragraph 1.6. RTUs that provide ventilation and that operate in auto mode will cycle the supply fan based on a heating or cooling call which is not code compliant. These RTUs will also have a reduced energy savings from an ARC technology, because the ARC operates the fan at a partial speed during ventilation mode, rather than completely turning the unit off.
- The estimated remaining operational lifetime of the RTU should be longer than the estimated payback period of the ARC retrofit. Newer RTUs are therefore more attractive for ARC applications. NREL recommends RTUs under 10 years old for the ARC technology.
- The larger the RTU capacity (particularly the supply fan motor size), the greater the savings and the quicker the payback.

6.1.2 Site Approval

Site approval, NEPA, and DD1391 activities were required for this demonstration. All these activities presented minimal administrative burden and were performed over a few months. For the NEPA evaluation, the NAVFAC Hawaii Environmental Program determined a categorical exclusion (CATEX) in accordance with OPNAVINST 5090.1C CH-1.

For future deployments of the ARC technology, it should be noted that physical and aesthetic impacts to the site are negligible. Most ARC technology elements are housed in the RTU cabinet. In the specific instance of the ARC technology offering demonstrated in this project, a small NEMA 4 electrical box was also installed on the exterior of the RTU housing containing the controller and wireless modem (see Figure 2).

Site communication and ARC monitoring and control options should also be considered during site approval activities in deploying this technology. For this demonstration, a remote monitoring package using a Web-based interface and cellular modem was used for offsite monitoring and control of the ARC units. Before deploying these packages, the IPT worked with JPBHH communications personnel to develop an appropriate communications plan for remote access. Several other ARC technology offerings provide remote BMS solutions (see Table 25), making military communications requirements relevant for future deployments. Before implementing a remote BMS solution, the DOD communications requirements for the specific installation need to be understood and the impacts of applicable approval processes and security issues evaluated. The local NAVFAC CIO should be consulted regarding these communication requirements.

6.2 Contracts and Procurement

The implementation strategy for this project used a design-build contract, awarded to the provider of the ARC technology. Although structured as design-build, this contract had minimal design requirements and focused largely on procurement, installation, and commissioning. As executed, direct acquisition of this technology via the provider presented minimal challenges, largely because it was easy to install and had few site requirements and impacts.

This project used applicable Division 01, General Requirements. These requirements and related follow-on activities are presented in Table 23.

Table 23. UFGS—General Requirements

UFGS	
Division 01—General Requirements	
01 14 00	Work Restrictions
01 30 00	Administrative Requirements
01 33 00	Submittal Procedures
01 35 26	Governmental Safety Requirements
01 42 00	Sources for Reference Publications
01 45 00.10 20	Quality Control for Minor Construction
01 78 00	Closeout Submittals

A summary of lessons learned from the demonstration, which should be considered when acquiring equipment for future ARC deployments, follows:

- **Facility set points and schedules.** Facility thermal comfort, ventilation needs, and operational schedules should be well articulated and included in the acquisition. For each RTU, temperature set point schedule, maximum allowable RH (or dew point), OA damper open schedule (when ventilation should be provided), and required RTU on/off times should be clearly defined.

- **Pre-proposal/solicitation site visit.** Solicitations should benefit from a pre-proposal site walkthrough by potential offerors. Accurate pricing will likely depend on the offerors' ability to evaluate supply fan motor size and other RTU design features that are relevant to their specific ARC offerings. Eagerness to bid will likely also depend on an evaluation of the general condition of the RTUs and determination of necessary maintenance work.

6.3 Design

Packaged ARC technologies have been developed as turnkey product solutions. Integration of ARC technologies with standard RTUs requires a negligible level of site design. For this project, significant design activities comprised a detailed field investigation to evaluate the RTUs for any maintenance issues before the ARC units were installed.

UFGS facility construction/technical design specifications were developed as presented in Table 24.

Table 24. UFGS—HVAC

UFGS	
Division 23—Heating, Ventilating, and Air Conditioning	
23 05 93	Testing, Adjusting, and Balancing for HVAC
Division 26—Electrical	
26 00 00.00 20	Basic Electrical Materials and Methods
26 20 00	Interior Distribution System

For future deployments, site design requirements should be minimal. Technical specifications will need to be developed; however, the list of UFGS specifications should not be extensive. Some care and client attention should be given to tailoring UFGS 23 05 93 "Testing, Adjusting, and Balancing for HVAC" to ARC installation activities. TAB testing, if not specified carefully, may be overprescribed and present unnecessary escalations in cost and schedule. Specific considerations for TAB specifications follow:

- The ARC technology is applicable to a single-zone control. Balancing should be limited to the SA and OA flow rates only. Balancing the air distribution system (diffusers) has minimal value.
- OA flow rates should be verified to meet ASHRAE 62.1-2010 ventilation requirements at various ARC fan speed sequences. OA flow rate should be calculated by subtracting the RA from the SA as acceptable by NEBB procedures.
- Maximum SA flow rates should be verified to meet the operating window of the RTU, which is typically 350–450 cfm/ton. Based on the ARC sequence of operation, the TAB should validate that under any DX operation (first stage, second stage, etc.) the supply fan is providing at least 300 cfm/ton. Slower flow rates will only decline over time as filters clog, and may cause icing of the DX coil.

6.4 Installation and Construction (Include Permitting, Interconnect Agreements, Factory Acceptance Testing, Commissioning)

ARC installation was straightforward and easily executed through a series of sequential work activities. Outstanding RTU maintenance issues were addressed first. The CATALYST systems were installed. Remote communication was established. System commissioning and TAB were performed. Maintenance and ARC installs were completed within a 3-week period. Commissioning/TAB required an additional month of work because the independent TAB contractor had a schedule conflict. Total construction time took approximately 2 months.

After the construction was finished, several months of evaluation were needed to accommodate thermal comfort requirements. The driver behind this prolonged evaluation was an unexpected adjustment to the Navy's COLS. The COLS directly regulate thermostat set-points. CNIC changed from COLS 3 to COLS 4 shortly after the installation. Determining the proper ARC operation to meet these standards required significant time and resources. For effective ARC implementation, NAVFAC should clearly articulate the facility comfort requirements to the ARC provider and ensure that these requirements are met.

Other considerations for future ARC installs are as follows:

1. **HVAC unit downtime.** RTUs will need to be shut down during installation. Acceptable downtime relative to facility thermal comfort and temporary cooling requirements will need to be considered.
2. **Crane requirements.** At least one ARC product presented in Table 25 will require a crane for access.
3. **Commissioning.** The commissioning process should, at a minimum, include:
    a. A functionality test to ensure that all the modes of operation (first-stage cooling, fan-only, etc.), are operating according to the sequence of operation.
    b. Validation of system performance relative to facility thermal comfort and ventilation requirements (temperature set points, RH maximum, OA damper schedule, and RTU hours of operation).
    c. Temperature, RH and CO_2 sensors should be calibrated.

6.5 Operation and Maintenance

TWT oversaw O&M of the installed ARC units and retrofitted RTUs for almost 1 year. NAVFAC routine maintenance procedures are shown in Appendix D. Routine maintenance requirements of the ARC technology are generally minimal and should be fulfilled by standard inspections.

ARC technologies should improve O&M when packaged with a BMS solution. Like some of the other ARC-BMS packages listed in Table 25, TWT developed the eIQ BMS to integrate with its CATALYST ARC system. NREL found mixed results for the ARC-BMS package improving O&M.

The following subsections divide the ARC-BMS package impacts on O&M into two categories: unforeseen maintenance and routine maintenance. The impact on routine maintenance is neutral in the worst-case scenario. The impact on unforeseen maintenance depends on the maintenance staff's acceptance of the Web-based monitoring and alarming through automated FDD. Although the online dashboards can always become more intuitive and automated FDD algorithms more sophisticated, the adoption of ARC-BMS as a maintenance avoidance and troubleshooting tool depends on the training.

6.5.1 Automated Fault Detection and Diagnostic and Remote Monitoring Addressing Unforeseen Maintenance

Unforeseen maintenance refers to the inevitable issues related to failures of RTU components such as fan belts and compressors. The automated FDD capabilities built into most ARC-BMS packages should alert HVAC service technicians of potential maintenance issues that should be inspected and possibly addressed before components fail. During the demonstration, NREL saw distinct examples where the ARC-BMS package improved RTU O&M and where it did not.

- **Positive impact on O&M.** The BXtra 1235H RTUs had only one known maintenance issue. The automated FDD worked as expected by identifying a fan belt that showed signs of potential failure. TWT sent a service technician to fix the belt before it failed.
- **Neutral impact on O&M.** The RTU serving A13 had multiple maintenance issues, one of which was related to the CATALYST system. The first issue was that the supply fan was left in a manual override mode during the TAB. It did not run when the compressors were turning on. Both DX stages iced up the coils and building A13 was not conditioned for 1½ days. An automated FDD should have alerted personnel when the compressors were coming on but the supply fan was not. Unfortunately, this automated FDD did not occur.
- The subsequent six maintenance failures were not due to the CATALYST but to typical field issues and the fact that the A13 RTU is 15 years old and at the end of its life. For four of the issues, TWT was alerted based on automated FDD, yet too late; the office space in A13 had become uncomfortable such that the NAVFAC HVAC technicians were already on site before TWT responded. In two cases NAVFAC HVAC technicians had already addressed the issues before TWT learned about them.

One solution is to improve the automated FDD algorithms to acknowledge a broader array of failure mechanisms. Yet the more important obstacle to ARC-BMS packages improving O&M is having buy-in by the NAVFAC HVAC technicians. These technicians will bring another tool into their arsenal only if it is intuitive to use and enables them to work more nimbly. Although the eIQ dashboard can always be made more user friendly, the obstacle to adoption is with the training of NAFAC HVAC technicians. (See Section 6.6 for a summary of the training conducted during the demonstration and how that should be improved.) For future ARC installations, NAVFAC should emphasize the training and buy-in by the HVAC technicians.

6.5.2 Routine Maintenance

Some of the automated FDD algorithms may improve routine maintenance procedures, such as when filters need to be changed. For future ARC installations, NAVFAC should not consider ARC-BMS packages as having any impact on routine maintenance. NAVFAC HVAC service technicians should continue their routine maintenance schedules.

6.6 Training

After the installation was complete, TWT held a training session for HVAC technicians with the Hickam, Pearl Harbor, and NAVFAC Hawaii ACEM shops. The training started with 1 hour in the classroom, including a presentation of the CATALYST and eIQ systems followed by questions and answers. TWT also provided reference materials organized in binders for each HVAC technician present. The training concluded with an in-field overview of the CATALYST hardware on the C27 RTU.

After the training, TWT visited the NAVFAC Hawaii ACEM shop to ensure that its computers were capable of logging into the eIQ webpage. TWT put together a comprehensive service guide covering how to access and use the Web-based BMS system and diagrams of the entire hardware configuration. Unfortunately, TWT was unable to provide website access because of what is most likely a NAVFAC firewall. At the writing of this report, TWT was still trying to obtain access for the NAVFAC Hawaii ACEM shops to the Web-based BMS.

For on-site access to the CATALYST system, TWT provided each ACEM shop a handheld computer tablet that can plug directly into the controller and enable read-write capability. This way NAVFAC HVAC technicians can communicate with the CATALYST to troubleshoot and override operation. Also through technical support over the phone, TWT can remotely connect to the RTUs and provide troubleshooting advice as well as override operation.

7 Commercial Readiness Qualitative Assessment

The commercially available ARC systems should be evaluated from three perspectives: (1) straightforward design and specification; (2) ease and speed of installation; and (3) seamless integration into NAVFAC's O&M procedures.

7.1 Commercial Readiness

The ARC retrofit technology is commercially available from multiple vendors and manufacturers. Although it is a relatively new product type (less than 10 years old), ARC systems are composed of very mature components. NREL assessed the ARC technology at technology readiness level (TRL) 9 (Figure 37).

NREL performed a cursory product survey and identified several commercially available ARC solutions that are summarized in Table 25. Each ARC technology includes slightly different energy-saving features. The table is not a comprehensive list. Some big box retailers with large RTU portfolios have engaged energy service companies and HVAC original equipment manufacturers to provide custom-built ARC solutions. These solutions do not have significant standalone intelligence since they are integrated into the retailer's BMS.

These ARC products require services to install the unit, perform O&M, and deliver BMS functionality (if applicable). There is no single business model for accomplishing this, and some ARC manufacturers work through local HVAC providers for installation and O&M services. As discussed in Section 6, the demonstration showed the importance of procuring the monitoring services to ensure long-term savings and potentially improved O&M via automated FDD and enhanced troubleshooting.

Table 25. Commercially Available ARC Technologies

Primary Manufacturer	Variable-Speed Supply Fan Control	Web-Based BMS or EMS Control	DCV	Demand Response	Advanced Economizing	Automated FDD
Feature Priority for Realizing Energy Savings in Hawaii/Guam	1	2	3	NA	N/A[b]	5
TWT CATALYST http://transformativewave.com	Yes	Yes TWT's eIQ BMS[a]	Yes	Yes	Yes	Yes
NexRev DrivePak www.nexrev.com	Yes	Yes NexRev's FREEDOM EMS[a]	No[e]	Yes	No[e]	Yes
Enerfit[c] www.enerfit.com	Yes	No	Yes	No	Yes	Yes
Bes-Tech Digi-RTU[d] www.bes-tech.net	Yes	Yes Bes-Tech's EMCS	Yes	No	Yes	No
Trane SZVAV Retrofit	Yes	Yes[f]	Yes	Yes	Yes	No

[a] The BMS solution provided by TWT and the EMS solution provided by NexRev are compatible through open protocols: BACnet, LonWorks, and ModBus.

[b] The field demonstration results, summarized in Section 4.8, showed minimal energy savings potential with economizer operation in Hawaii because of its high humidity levels. Similarly, Guam will realize no benefit from installing economizers. Yet many Navy locations, particularly on the West Coast, may save significant energy with advanced economizer operation integrated into ARC technologies.

[c] The Enerfit ARC solution also includes another actuated damper that is added to control the OA and RA before they enter the evaporator coil. This unique damper configuration is used to enhance the RTU's dehumidification capability. NREL has not tested—or seen test results of—this feature and therefore cannot state whether it would improve dehumidification or save energy.

[d] The Digi-RTU technology also retrofits the lead compressor from constant to variable-speed. NREL has not tested or seen third-party testing of the energy savings associated with incorporating variable-speed compressor control.

[e] NexRev DrivePak does not control the OA damper and therefore does not provide DCV capability or advanced economizing. Based on correspondence, NexRev stated that most of its clients have already used a BMS to enable DCV and advanced economizer control. Consequently NexRev has not integrated these features into DrivePak.

[f] Trane offers this retrofit only on Trane RTUs that already have a Trane BMS.

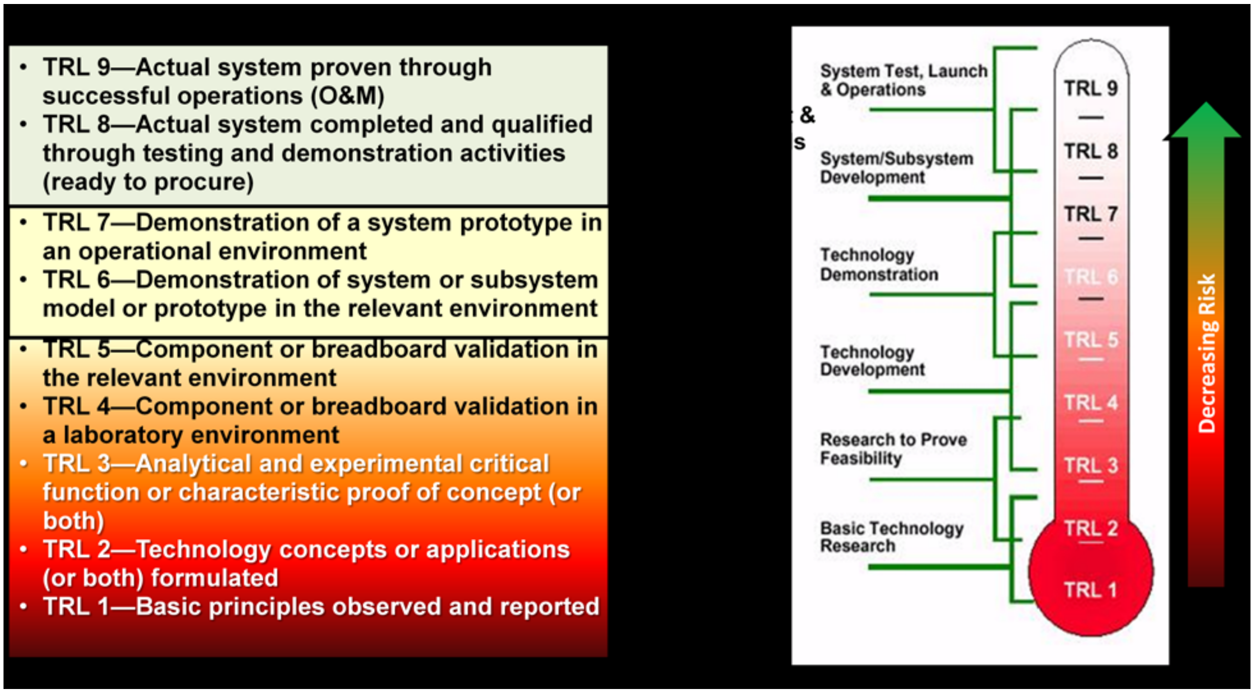

Figure 37. Technology Readiness Level (TRL)
Source: DOD Defense Acquisition Guidebook (DAG) and NASA TRL Thermometer

7.2 Market Opportunities and Barriers

The ARC market addresses retrofitting code-compliant RTUs 5 tons and larger. It is a cost-effective alternative to replacing the RTU with a more efficient unit when the RTU has at least 5 years of remaining life. ARCs deliver the best returns where electricity prices are high, in climates with significant swing seasons (spring and fall), in building types that experience highly variable occupancies, and in buildings that require 50 or more hours of operation each week. Larger RTUs also save more energy relative to the installed cost, which improves the ROI.

To expedite the market adoption of ARC technologies and high efficiency RTUs, the DOE Federal Energy Management Program, ASHRAE, and the Retail Industry Leaders Association have formed the "Advanced RTU Campaign" (www.advancedrtu.org). The campaign is "a recognition and guidance program designed to encourage building owners and operators to take advantage of savings opportunities from high efficiency RTUs."

Utility, state, and local incentive programs help to drive retrofits and high efficiency replacements. In the continental United States, particularly the in Pacific Northwest and along the West Coast, companies that provide ARC technologies work extensively with utilities to conduct field demonstrations to develop prescriptive rebate programs. (For example, see Appendix C for a list of utilities and energy efficiency organizations TWT has worked with to develop CATALYST-specific rebates.) For certain utilities such as Snohomish Public Utilities District, the rebate program covers up to 60% of the installed cost.

Hawaiian Energy Company's (HECO) current incentive program administrator is Hawaii Energy. Based on its website, www.hawaiienergy.com/hvac, the current prescriptive rebate for adding VFDs to HVAC fan motors is $50/hp. At the request of NAVFAC, NREL will provide the field demonstration results to HECO and Hawaii Energy to see if they would be interested in developing a prescriptive ARC rebate program beyond the current VFD program. HECO will likely be interested in ARC technologies because they couple energy savings and demand response capabilities into a single packaged solution.

As described above, the technology presents many near-term opportunities. Longer term, the need for the technology may change as codes and standards "raise the bar" on energy consumption. ASHRAE Standard 90.1-2013 requires new RTUs in certain applications to have SZVAV control (variable-speed supply fans), DCV, and economizing. Consequently, the ASHRAE 90.1 standard is now driving beyond energy efficiency ratio and integrated energy efficiency ratio requirements and essentially mandating that most ARC features be fully integrated into new RTU equipment. ARC retrofits enable building owners to realize RTU energy savings now rather than having to wait until their equipment ages to the point where it needs replacing.

7.3 Usability and Functionality

The usability and functionality of ARC systems should be evaluated from three perspectives: (1) straightforward design and specification; (2) ease and speed of installation; and (3) seamless integration into NAVFAC's O&M procedures.

- **Straightforward specification.** ARC systems are simple to specify, regardless of size. The VFD size and electrical service would be based on the evaporator fan motor size. In the case of the Bes-Tech Digit-RTU technology (see Table 25), the compressor size and electrical service would need to be known as well. The remaining components such as the controllers and sensors would be the same regardless of the RTU size or manufacturer. Consequently, ARC systems can be configured quickly based on a 1- to 2-hour site inspection per RTU to determine component health and the RTU's nameplate, supply fan motor nameplate, and OA damper configuration. The main part of this site inspection is determining the maintenance costs to retro-commission the RTU before the ARC is installed.
- **Ease and speed of installation.** ARC technologies can be considered "kits" that a certified HVAC technician can install quickly and easily. For example, two HVAC technicians trained to install the CATALYST ARC system can complete an installation, including the eIQ BMS, in less than 8 hours depending upon the RTU size. Then the TAB and commissioning process would take one HVAC technician another 4 hours to complete. Based on the "kit" concept, local HVAC contractors or NAVFAC's HVAC technicians can install ARC technologies. Compared to a bulk purchasing concept on which an energy service company or HVAC original equipment manufacturer-based custom-built ARC product focuses, packaged ARC "kits" can be purchased individually or in bulk.
- **Seamless integration into NAVFAC's O&M procedures.** The ACEM shops in Hawaii and Guam are severely overloaded and struggle to maintain the HVAC equipment in their jurisdictions. Beyond correcting equipment malfunctions, each ACEM has its own routine O&M schedule (see Appendix D). Unfortunately, at the onset, NAVFAC's HVAC technicians viewed the energy-saving features of an ARC technology as another

system to troubleshoot and that could malfunction. Instead, an ARC system paired with an integrated BMS with Web-based monitoring can provide automated alarming (FDD) of potential malfunctions, remote troubleshooting leveraging a Web-based dashboard, and improved on-site troubleshooting by enabling technicians to remotely communicate with the controller. In fact, the Enerfit ARC technology (see Table 25) provides a handheld device for HVAC technicians that will talk via Bluetooth with their controller. The CATALYST ARC technology can use a handheld tablet to communicate with the controller via an Ethernet cable. Figure 4 provides an example screenshot of TWT's eIQ BMS solution that can be accessed over the Web and shows the user real-time operation. Of course, a new system always presents a learning curve, but the Web-based dashboards are user friendly enough to allow HVAC technicians to leverage these features to reduce the site visits and troubleshooting time for RTU O&M.

8 Recommended Next Steps

The most immediate next step will be for NREL to monitor ESM versus non-ESM performance through January 2014 and provide an addenda report to the Navy that reflects updated, more accurate annual savings estimates. The regression model for all three buildings will be updated to include monitored data during Hawaii's cooler winter months. The final normalized energy savings metric, kWh/ton/1,000 h of operation, will be recalculated for all three buildings.

Based on the results to date, other near-term actions are recommended, both for tropical climates and for almost any other climate type. ARC retrofit technologies are TRL 9 and commercially available. For tropical climates, NAVFAC should adopt ARC retrofits on large buildings where multiple standard efficiency RTUs less than 10 years old serve a single space to realize significant energy savings. The ARC retrofit on the BXtra exchange building showed a 15% HVAC annual energy reduction savings of 96,498 kWh (94 kWh/ton/1,000 h of operation). Although this is a big box retail facility, the energy savings implications would be applicable to other large buildings, including exchange stores, recreation centers (bowling alleys, gymnasiums), conditioned hangers or warehouses, cafeterias, and commissaries.

For buildings smaller than 20,000 ft^2 where one RTU serves a single space, the tropical application recommendations are less clear. NREL's addenda report should offer better near-term guidance, and NAVFAC could conduct additional performance monitoring of additional units being installed in early 2014. NREL procured and will install additional CATALYST ARC systems for 19 RTUs at JBPHH (Table 26). At the time of writing this report, 7 CATALYST were pending approval for installation in Guam (Table 27).

These RTUs provide a comprehensive cross-section of the NAVFAC building types in Guam and Hawaii. For all 26 RTUs, NREL included the Web-based BMS eIQ system that will provide remote monitoring to NAVFAC. The statement of work states that "The Subcontractor shall ensure all remote monitoring capabilities are furnished for a period of three years (3) post completion of all installation activities, including eIQ online and wireless network access." NAVFAC could use this monitoring capability to assess the energy savings on a broader base of building types if interest and resources allow.

Based on successful field test results in nontropical climate zones, NAVFAC should consider transitioning the ARC technology to its facilities in other climate zones to realize even greater savings. Unlike tropical climates, most continental U.S. climates enable the ARC system to save more energy from enhanced economizing, greater DCV savings, and more operational hours in ventilation mode. Appendix I includes a summary of other ARC retrofit demonstrations in U.S. climates and how those results can be applied for NAVFAC facilities. For future ARC installations, NREL developed practical lessons (see Appendix J).

Table 26. Follow-on ARC Retrofit Installation on 19 RTUs at JBPHH

Count	Building Type	Bldg #, Name, and Location	Size	Model	Condition
1	Medium Office	284 Federal Fire Station, JBPHH	20 tons	Carrier 50TM-025	Very Good
2			18 tons	Carrier 50TM-020	Very Good
3			25 tons	Carrier 50TM-028	Very Good
4	Medium Mixed Use	1750H Chapel, JBPHH	10 tons	Carrier 50HJ-012	Good
5			12.5 tons	Carrier 50HJ-014	Good
6			12.5 tons	Carrier 50HJ-015	Good
7			20 tons	Carrier 50AY-020	Good
8			7.5 tons	Carrier 50HJ-008	Very Good
9	Large Retail	1232H Exchange, JBPHH	6	Carrier 50TC	Very Good
10			NA–chilled water coil	Reliance Frame 256T, Type P, Design B	Very Good
11			NA–chilled water coil	Carrier 39MW03C011K7Z11XPS	Very Good
12			NA–chilled water coil	Carrier 39MW03C011K7Z11XPS	Very Good
13			NA–chilled water coil	Carrier 39MW03C011K7Z11XPS	Very Good
14			NA–chilled water coil	Carrier 39MW03C011K7Z11XPS	Very Good
15			NA–chilled water coil	Carrier 39MW03C011K7Z11XPS	Very Good
16			NA–chilled water coil	Carrier 39MW03C011K7Z11XPS	Very Good
17	Recreation Center	1859H Makai Recreation Center, JBPHH	40	York Y14FC02A	Fair/Good
18	Medium Office	1200H Base Engineer Administration, JBPHH	30	Carrier 50EW-034	Good
19	Cafeteria	1860H Hale Aina Dining Facility, JBPHH	18	Carrier 50HJ-020	Very Good

Table 27. Follow-on ARC Retrofit Installation on 7 RTUs at AAFB

Count	Building Type	Bldg #, Name, and Location	Size	Model	Condition
1	Recreation Center	1605 Teen Center, AAFB	20 tons	Carrier 50TC-D24	Good
2	Small Office	23010 Mobility Response Sq., AAFB	10 tons	Carrier RAS121H	Good
3			10 tons	Carrier 50TFF	Fair
4	Small Office	20011 Communications Sq., AAFB	18 tons	Trane TCH180	Good
5	Terminal	17002 Passenger Terminal, AAFB	10 tons	Carrier 50TC-A12	Good
6	Small Office	18001 36 CEs Motor Pool Building, AAFB	10 tons	Carrier 50TC-A12	Good
7	Recreation Center	1622 Youth Center Gym, AAFB	20 tons	Carrier 50TC-D2	Very good

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Appendix A: NAVFAC-Defined Thermal Comfort

During the initial monitoring months, NREL determined that the RH in buildings A13 and C27 exceeded 65% and caused thermal comfort issues and mold concerns. NREL brought this to the attention of NAVFAC Hawaii and NAVFAC Headquarters. This appendix summarizes the outcome of the weekly conference calls from April through June 2013, which identified NAVFAC standards of service for temperature set points, RH thresholds, and allowable RTU on/off times. The appendix also includes recommendations for incorporating ASHRAE Standard 55-2010 thermal comfort criteria into UFC and UFGS for HVAC sizing and operational requirements. The last subsection summarizes how ARC retrofit systems provide lower space RH so proper thermal comfort can be maintained even with warmer COLS temperature set points.

Defining NAVFAC Thermal Comfort and Operational Requirements

NAVFAC establishes thermal comfort and HVAC operational requirements through a combination of criteria and mandates. For NAVFAC's energy teams, building energy managers, and HVAC technicians, reconciling these requirements to determine the proper temperature set points and schedules can be cumbersome and confusing. Thus, the actual temperature set points and schedules applied are not consistent across buildings and do not always adhere to the latest NAVFAC requirements.

These criteria and mandates are summarized below. In addition to the conflicting temperature requirements, none of these requirements properly define what the operational (not design) RH thresholds should be.

COLS. To control energy usage in real time, Commander Navy Installations Command (CNIC) established four COLS levels. Summarized in Table A-1, the underlined and bolded text highlights the verbiage that applies to HVAC and thermal comfort. (The text shown in Table A-1 was not edited from the version sent to NREL.) In addition to each COLS level, CNIC provided an appendix on the specific actions needed to meet these requirements.

Table A-1. Navy Defined Utilities COLS

COLS 1. Utility is available to meet all mission requirements. Commodity availability has no risk to mission, quality of life, or routine station operations. Energy and water efficiency and awareness are utilized and ***no forced reduction measures are required.*** Other services are available to meet all mission requirements.
COLS 2. Utility is available to substantially meet mission requirements with minor difficulty. Utilities funding status and/or weather conditions present LOW risk to customer operational requirements. ***Building occupants and supported tenants forced to make minor operational adjustments to meet mission requirements in accordance with health/safety regulations.*** Minimal forced reduction measures include (but are not limited to): (1) Reduction measures resulting in LOW risk to warfighter support and operational requirements of host activity and tenant commands. Suggested measures are listed in Appendix. (2) Heating and Air Conditioning delayed/interrupted no more than two weeks (3) ***Operation of climate control systems is reduced to lower energy consumption. Goal is to reach average temperatures that have minimum impact on warfighter support: 68 or 69 degrees in heating season (68<avg temp<70) and 77 or 78 degrees in the cooling season (78>avg temp>76)*** (4) 5% or less reduction required for electrical service delivery facilities without direct support function to the

warfighter (e.g., ball field lighting, decorative lighting) (5) 5% or less reduction required for steam service delivery facilities without direct support function to the warfighter (e.g., warehouses, gymnasiums) (6) 5% or less reduction required in water use for facilities without direct support function to the warfighter (e.g., irrigation, car washes) (7) Water rationing for no more than seven days

COLS 3. Utility is available to marginally meet mission requirements with major difficulty. Utilities funding status and/or weather conditions present MODERATE risk to customer operational requirements. ***Building occupants and supported tenants forced to make minor operational adjustments to meet mission requirements in accordance with health/safety regulations.*** Forced reduction measures include (but are not limited to): (1) Reduction measures resulting in MODERATE risk to warfighter support and operational requirements of host activity and tenant commands. Suggested measures are listed in Appendix. (2) Heating and Air Conditioning availability delayed/interrupted no more than four weeks (3) ***Operation of climate control systems is reduced to lower energy consumption. Goal is to reach average temperatures that have moderate impact warfighter support: 66 or 67 degrees in heating season (66<avg temp<68) and 79 or 80 degrees in the cooling season (80>avg temp>78)*** (4) 6% to 10% reduction required for electrical service delivery facilities without direct support function to the warfighter (e.g., ball field lighting, decorative lighting) (5) 6% to 10% reduction required for steam service delivery facilities without direct support function to the warfighter (e.g., warehouses, gymnasiums) (6) 6% to 10% reduction required in water use for facilities without direct support function to the warfighter (e.g., irrigation, car washes).

COLS 4. Utility is not available to marginally meet mission requirements due to funding shortfalls and/or weather/climate conditions even after making significant mission adjustments. Program requires additional resources to meet basic customer requirements. ***While meeting bare minimum health/safety regulations, building occupants and supported tenants will experience significant hardships that include:*** (1) Reduction measures resulting in HIGH risk to warfighter support and operational requirements of host activity and tenant commands. Suggested measures are listed in Appendix. (2) Heating and AC availability delayed/interrupted more than four weeks (3) ***Operation of climate control systems reduced to prevent equipment failure/breakdown, regardless of impact on warfighter support. May achieve average temperatures less than 66 degrees in heating season, and greater than 80 degrees in cooling season*** (4) Greater than 10% reduction in all utilities service to all facilities without direct warfighter support function (5) Imposed 2 or more brief rolling blackout of utilities services in order to reduce consumption.

APPENDIX: SHORE ENERGY REDUCTION ACTIONS

This is a list of specific actions that can be implemented to reduce an installation's consumption of utilities. ***Taking actions like these will generally require building occupants to make adjustments to their standard daily operations.*** As a result, if an installation/region takes enough of these actions, there will be some risk to building occupants' ability to accomplish their mission. ***Additionally, Installation Managers should be careful instituting these types of actions measures to ensure they do not create costs in other areas (ie. undue excessive equipment wear and tear, requirements to pay labor overtime, etc.)***

- Reduce delivery of Installation Services that are not direct warfighter support functions including (but not limited to): MWR, Chaplain/ministry services, Fleet and Family Support, etc.
- Adopt, where practical, Alternative Work Schedules (AWS)/Compressed Work Schedule (CWS) to reduce commuting costs and installation energy usage.
- Institute large scale AWS/CWS across entire commands, entire sites or entire installations.

· ***Mandate night-time operations as a peak-shaving effort and as an energy consumption reduction measure.***
· ***Prohibit all use of energy intensive personal appliances such as space heaters and electric fans.***
· ***Implement drastic evening and weekend setbacks for HVAC systems.***
· Limit travel to mission essential requirements. Substitute use of video and telephone conferencing.
· ***Provide command attention to energy management training and awareness***
· Encourage turning off computers after hours or when not in use
· ***Ensure that lights are turned off in buildings at night***
· Contract for Resource Efficiency Managers dedicated to lowering energy consumption
· Maximize use of training simulators
· ***Identify load-shedding techniques to cut electricity consumption in buildings and facilities. Examples of these techniques include:***
· ***Adjust equipment controls to reduce hours of operation, e.g. air compressors, water heaters, air handling equipment***
· ***Restrict use of window air-conditioning***
· ***Turn off unneeded lights with motion sensors and separate lighting circuits***
· ***Disconnect vending machine lights***
· ***Remove portable electric heaters and fans***
· Reduce street and parking lot lighting where safety considerations permit
· ***Tune up boilers and HVAC.***
· Make sure steam traps functioning properly.
· Replace incandescent light bulbs with compact fluorescent in buildings and housing.
· Advise family housing residents to run clothes and dish washers only when full.

NAVFAC Hawaii "Region Energy Instruction." In addition to the Navy-wide COLS requirements, NAVFAC Hawaii issued its own energy reduction instruction. Shown in Table A-2, the highlighted text shows the mandate of not lower than 78°F thermostat temperatures from 10:00 a.m. to 3:00 p.m. winter hours (November 01 to April 30) and 8:00 a.m. to 4:00 p.m. summer hours (May 1 to October 31).

Table A-2. NAVFAC Hawaii "Region Energy Instruction" Issued September 2011

UNCLASSIFIED////
REROUTE DETECTED ADMINISTRATIVE MESSAGE
ROUTINE
R 122119Z SEP 11 ZYB PSN 317101H13
FM COMNAVREG PEARL HARBOR HI
TO ALL NAVACTS HAWAII
INFO ZEN/COMNAVREG PEARL HARBOR HI
ZEN/HQ PACAF HICKAM AFB HI
ZEN/15AW HICKAM AFB HIBT
UNCLAS
ALL NAVACTS HAWAII 114/11MSGID/GENADMIN/MIL-STD-6040(SERIES)/B.0.01.00
/COMNAVREG PEARL HARBOR HI/-/-/-/-/-/-//
SUBJ/ENERGY CONSERVATION//
REF/A/DESC:DOC/COMNAVREGHIINST/4101.1D/21JUL2010//
REF/B/DESC:DOC/SECNAVINST/4100.9A/01OCT2001//
NARR/REF A IS THE NAVY REGION HAWAII ENERGY MANAGEMENT PROGRAM INSTRUCTION. REF B IS THE DEPARTMENT OF THE NAVY (DON) SHORE ENERGY MANAGEMENT INSTRUCTION.//POC/STEHN, KRISTA/CIV/UNIT:NAVFAC/NAME:PEARL HARBOR HI/TEL:808-471-0440/EMAIL:KRISTA.STEHN(AT)NAVY.MIL//
GENTEXT/REMARKS/

1. YOUR CONSERVATION EFFORTS THIS FISCAL YEAR WITHIN NAVY REGION HAWAII HAVE SAVED THE NAVY 7.61 MILLION

DOLLARS AND IS VERY MUCH APPRECIATED, HOWEVER WE MUST DO MORE. GIVEN CURRENT TRENDS OF UTILITY CONSUMPTION, WE WILL NOT MEET MANDATED FEDERAL REDUCTION GOALS FOR FISCAL YEAR 2011. THE ENERGY INDEPENDENCE AND SECURITY ACT OF 2007 REQUIRES REGION HAWAII TO ACHIEVE AN 18 PERCENT ENERGY REDUCTION IN FISCAL YEAR 2011; WE HAVE ONLY ACHIEVED A 12 PERCENT REDUCTION, A DIFFERENCE OF APPROXIMATELY 20,000 MEGAWATT HOURS.

2. LEADERSHIP FROM ALL COMMANDS, LARGE AND SMALL, ARE STRONGLY URGED TO REVIEW AND RE-ENERGIZE THE FOLLOWING CONSERVATION POLICIES PROMULGATED REF (A):

A. AIR CONDITIONING (AC) OPERATING HOURS FOR ALL FACILITIES WITHIN REGION HAWAII ARE LIMITED TO BETWEEN 1000 TO 1500 HOURS FROM 01 NOVEMBER TO 30 APRIL AND 0800 TO 1600 FROM 01 MAY TO 31 OCTOBER.

B. PER REF (B), THERMOSTATS FOR CENTRAL AC AND WINDOW AC UNITS MUST BE SET NO LOWER THAN 78 DEGREES FAHRENHEIT. FOR AC UNITS WITHOUT THERMOSTATS, CONTACT YOUR BUILDING ENERGY MANAGER FOR A WALL MOUNTED THERMOMETER AND ADJUST THE AC UNIT TO ACHIEVE 78 DEGREES FAHRENHEIT SPACE COOLING.

C. AC SHALL BE SET NO LOWER THAN 76 DEGREES FAHRENHEIT IN SERVER ROOMS AND NAVY/MARINE CORPS INTRANET (NMCI) POINTS OF PRESENCES (POP), OR INTERMEDIATE DISTRIBUTION FRAME (IDF) ROOMS.

D. PERIMETER WINDOWS AND DOORS SHALL BE KEPT CLOSED WHEN AC IS OPERATING.

E. SECURE OUTDOOR LIGHTING DURING DAYLIGHT HOURS AND ENCOURAGE OTHERS TO TURN OFF LIGHTS AS NEEDED.

F. DURING UNOCCUPIED HOURS, TURN OFF LIGHTING SYSTEMS, OFFICE EQUIPMENT, AIR CONDITIONERS, AND COMPUTERS.

G. REPORT MALFUNCTIONING PLUMBING FIXTURES, SUCH AS LEAKING FAUCETS, DEFECTIVE TOILET FLUSH VALVES, AND LEAKING SHOWER HEADS TO YOUR BUILDING FACILITY MANAGER.

H. KITCHEN APPLIANCES; INCLUDING BUT NOT LIMITED TO REFRIGERATORS, COFFEE MAKERS, MICROWAVES, AND TOASTERS; SHALL NOT BE PERMITTED IN PERSONAL WORK SPACES. REFRIGERATORS SHALL BE LIMITED TO ONE FOR EVERY 20 FULL TIME EMPLOYEES.

I. ONLY ENERGY-STAR RATED OR ENERGY EFFICIENT EQUIPMENT AND APPLIANCES SHALL BE USED.

J. WHERE IDENTIFIED, COMMANDS ARE REQUESTED TO AGGRESSIVELY MAKE RECOMMENDATIONS TO IMPROVE BUILDING ENERGY AND WATER EFFICIENCY TO THE REGION ENERGY TEAM AT 471-0440.

3. IT IS OUR OBLIGATION, ESPECIALLY IN THIS FISCAL ENVIRONMENT, FOR EACH OF US TO BE RESPONSIBLE STEWARDS OF TAXPAYER DOLLARS AND OUR ENVIRONMENT. WE MUST BE SENSITIVE TO THE LIMITED ENERGY RESOURCES AVAILABLE AND THE ENVIRONMENTAL AND FISCAL IMPACTS OF OVERUSE. BY FOLLOWING PRESCRIBED POLICIES, WE WILL SIGNIFICANTLY IMPACT AND REDUCE NAVY REGION HAWAII ENERGY AND WATER USAGE. MAHALO FOR YOUR CONTINUED EFFORTS TO ENSURE THAT WE BUILD A STRONG ENERGY CONSERVATION CULTURE THROUGHOUT NAVY REGION HAWAII.

4. RDML SMITH SENDS.

5. THIS ALL NAVACTS HAWAII IS IN EFFECT UNTIL FURTHER NOTICE.//

UFC 3-410-01. UFC 3-410-01 is the only specification throughout UFCs and UFGSs that acknowledges both space temperature and RH. Section 3-4.3.1 stipulates that cooling HVAC equipment should be sized to meet 78°F (26°C) dry bulb and a maximum of 55°F (12.8°C) dew point (equates to 45% RH) and account for the moisture gain in the space. These requirements apply only for sizing HVAC system purposes. Even the old UFC 3-400-10N "Mechanical Engineering" criterion, which was replaced by UFC 3-410-01, provided operational and sizing thermal comfort guidance, stating: "Space Design conditions shall be 76 Fdb & 50% RH, during the Design Cooling Day outside air conditions. At all other than design day, occupied times, maintain the space within the 'Summer' conditions shown in the latest edition of ASHRAE Handbook of Fundamentals, but not less than 76 Fdb." Again, this guidance was for sizing purposes only.

During the April through June 2013 conference calls, NAVFAC established that buildings A13 and C27 temperature set points and schedules would adhere to NAVFAC Hawaii "Region

Energy Instruction," and NAVFAC obtained a temporary waiver to the current COLS level 4 mandate that CNIC issued in April 2013. Two additional items were clarified.

1. Shown in Table A-2, the "Region Energy Instruction" mandates "*THERMOSTATS FOR CENTRAL AC AND WINDOW AC UNITS MUST BE SET NO LOWER THAN 78 DEGREES FAHRENHEIT*." Yet NREL was directed to use 76°F as the set point and told that the "Region Energy Instruction" was interpreted to allow the temperature set point to be below 78°F to maintain the warmest area of the conditioned space at approximately 78°F.

2. NAVFAC Hawaii procedure allows each building to have its energy managers apply to REGCOM for exceptions to the "Region Energy Instruction." Because building C27 was allowed to reduce its set point, NREL was directed to use a 75°F set point. Similarly, building A13 was allowed to have the RTU operate starting at 9:00 a.m. instead of 10:00 a.m. during the winter months.

Once the temperature set points and operational schedules were established, NREL and NAVFAC focused on the RH issue. Because none of the criteria or mandates addressed RH, NREL proposed—and NAVFAC agreed—to use 65% RH as the threshold for the space, including occupied and unoccupied times. A maximum RH of 65% is based on ASHRAE Standard 55-2010 (discussed further in the following subsection), meets thermal comfort requirements, and mitigates mold issues. NAVFAC agreed to let NREL evaluate different control strategies over several weeks to determine an RTU on/off schedule that would maintain buildings C27 and A13 at < 65% RH and not significantly impact daily energy usage. NREL found that a "morning charge" with the RTUs starting operation at 6:00 a.m. (2 hours before approved operation) sustained the RH to < 65%. NREL then received approval from REGCOM to turn the RTUs on at 6:00 a.m. for buildings C27 and A13.

Section 0 summarizes a recommendation to NAVFAC to streamline its temperature set point and schedule requirements, include RH requirements, and establish how NAVFAC defines thermal comfort according to ASHRAE Standard 55-2010. Beyond improving HVAC efficiency with new or retrofit technologies, NAVFAC can realize significant energy savings by enforcing these strict operational mandates. Most of the infrastructure is there and the building energy manager's role is clearly defined. Yet NAVFAC currently does not realize those savings because the direction for the building energy managers is not clear. The questions, "How can these mandates be interpreted?" and "Which mandates take precedence?" need to be answered.

The wrap-up of this demonstration provides a great example of the confusion that has arisen about the interpretation and application of these mandates. While writing this document, NREL realized that the 3:30 p.m. RTU off times for A13 and C27 during the demonstration period did not follow NAVFAC's "Region Energy Instruction," which stipulates 4:00 p.m. in the summer months and 3:00 p.m. in the winter months. NREL asked the NAVFAC Hawaii energy office and the building energy manager why 3:30 p.m. was the directed off time for summer and winter operation. Both parties replied that there was no official reason for that direction. This example shows the importance of streamlining these HVAC energy mandates and providing clear direction to appropriate NAVFAC personal for enforcement.

The following subsection summarizes how ASHRAE Standard 55-2010 defines thermal comfort and how NAVFAC should implement this methodology when establishing HVAC operational requirements. The final subsection in this appendix summarizes how ARC systems can help NAVFAC achieve warmer temperature set points while balancing thermal comfort and mitigating mold issues.

Applying ASHRAE Standard 55 to NAVFAC Operational Requirements

ASHRAE Standard 55-2010 uses the Fanger Comfort Method to define thermal comfort as a function of dry bulb temperature, RH, mean radiant temperature, clothing (defined by the metric "clo"), metabolic rate (defined by the metric "met"), and air velocity. The Fanger Comfort Method is used to calculate the People Percentage Dissatisfied (PPD). PPD establishes the percentage of building occupants who would be uncomfortable based on a given set of the aforementioned parameters. In mechanical design, it is considered almost impossible to make all occupants comfortable given the variations in clothing and metabolic rates, especially between women and men. As defined in ASHRAE standard 55, the space conditions were considered comfortable when the PPD was < 10%.

Neither the UFCs nor the UFGSs establish how NAVFAC defines thermal comfort in terms of space temperature and RH. During the weekly conference calls, NAVFAC headquarters relayed some guidance from a Mechanical Engineering Criteria Manager who in an email stated:

> We do say to stay within the 'summer' (clo=0.5) or 'winter' (clo=1.0) conditions of the 'ASHRAE Summer and Winter Comfort Zones' chart in the ASHRAE Fundamentals Handbook chapter on 'THERMAL COMFORT'. The chart is better shown in ASHRAE Standard 55. Using the summer "clo" factor of 0.5 would require a humidity below 65%. The ASHRAE Comfort zones have no minimum humidity requirement but we call for no lower than 30% in the winter. Low humidity is not a problem in the summer season.

NREL recommends that similar verbiage be added to the appropriate UFC and UFGS regarding applying ASHRAE Standard 55-2010 summer (0.5 clo) and winter (1.0 clo) comfort criteria when sizing HVAC equipment and establishing operational temperature set points and RH thresholds.

Table A-3 calculates the PPD for each NAVFAC temperature requirement using the Fanger Comfort Method and ASHRAE Standard 55-2010 summer thermal comfort metrics of 0.5 clo, 1.2 metabolic rate (office work), and 50 fpm air velocity. NREL used the 65% RH as the peak acceptable moisture condition except for the UFC 3-410-01 requirement, which identifies the acceptable moisture condition as 55°F dew point. As shown, the maximum 65% RH along with even the COLS level 4 space temperature mandates of 80°F still maintain the PPD at < 10%. Table A-4 shows the calculated PPD for all three buildings in the demonstration applying the ASHRAE Standard 55-2010 0.5 clo summer conditions.

Table A-3. Thermal Comfort PPD Based on Different NAVFAC Temperature Requirements and Maximum 65% RH[a]

	Dry Bulb Temperature	RH	Dew Point Temperature	PPD
UFC 3-410-01 Section 3-4.3.1 Design to 78°F db and 55°F dp	78°F	45%	55°F	6%
NAVFAC Hawaii "Region Energy Instructions"	78°F	65%	65°F	5%
CNIC COLS Level 1	Not Specified	65%	–	–
CNIC COLS Level 2 78>avg temp>76	77°F	65%	64°F	6%
CNIC COLS Level 3 80>avg temp>78	79°F	65%	66°F	6%
CNIC COLS Level 4 > 80	80°F	65%	67°F	8%

[a] Thermal comfort parameters based on ASHRAE Standard 55-2010 summer conditions with 0.5 Clo, 1.2 metabolic rate (office work), and 50 fpm air velocity.

Table A-4. ASHRAE Standard 55-2010 0.5 clo Summer Conditions Applied to All Three Buildings

	BXtra	A13	C27
Calculated PPD	6	8	12
Thermostat Set Point	74°F	76°F	75°F
RH Limit	< 65% RH	< 65% RH	< 65% RH
Clothing (clo)	0.5	0.5	0.5
Metabolic Rate (met)	1.7 (walking about)	1.2 (seated, filing)	1.2 (seated, filing)
Air Velocity	130 fpm (1.5 mph)	50 fpm (0.6 mph)	50 fpm (0.6 mph)

Figure A-1 plots the ASHRAE Standard 55 summer and winter comfort zones on a psychrometric chart compared to NAVFAC Hawaii and COLS requirements. The checkered pattern represents NREL's recommended thermal comfort zone for NAVFAC based on a minimum 30% and maximum 60% RH.

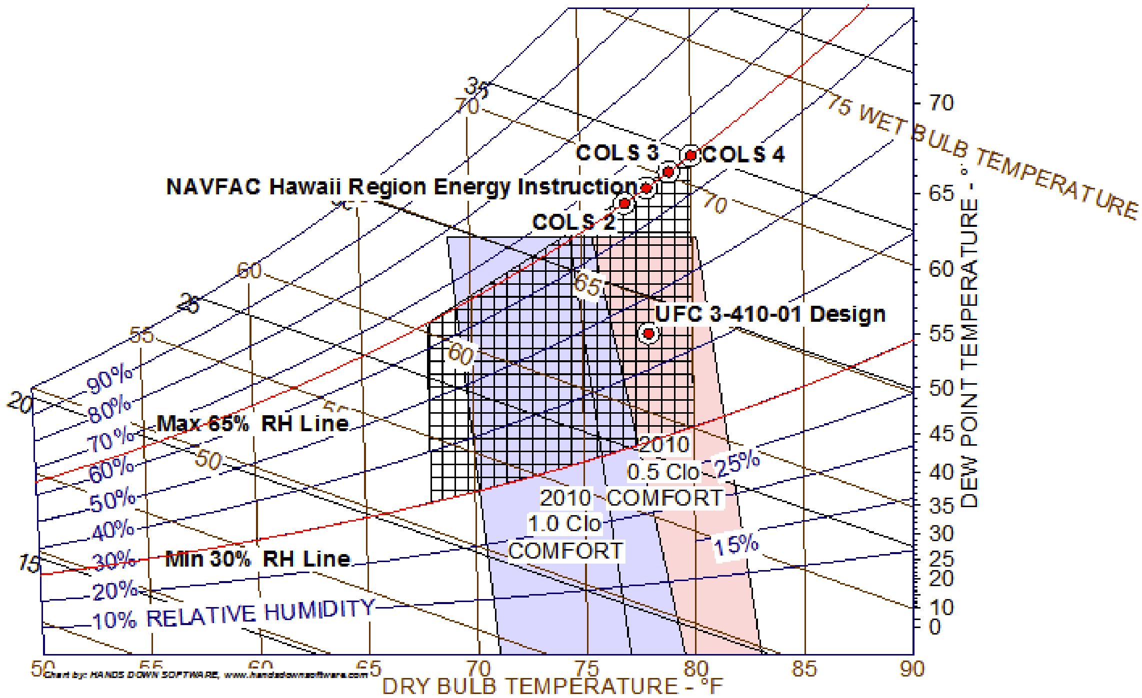

Figure A-1. ASHRAE Standard 55-2010 summer (0.5 clo) and winter (1.0 clo) thermal comfort zones compared with NAVFAC Hawaii and COLS requirements

Appendix B: Linear Regression Method and Results

Previous ARC retrofit technology demonstrations in drier climates (most notably Wang et al. 2013) showed a strong correlation between daily energy usage and daily average ambient dry bulb temperature. Consequently, these demonstrations created linear regression models using daily average ambient dry bulb temperatures as the sole predictor of energy consumption and energy savings. For this demonstration, NREL found significant scatter in the daily energy usage versus the average ambient dry bulb temperature. Therefore, NREL included additional predictors in the regression analysis to account for this scatter.

- **Daily average HR.** Because buildings C27 and A13 had a combination of high ambient humidity and high infiltration rates, NREL included daily average ambient HR as a predictor.
- **Demand response days.** Because the demand response sequence may have impacted daily energy usage, NREL included a separate predictor of "–1" for days when the demand response sequence was on and "+1" when it was not.
- **Friday operation.** For buildings A13 and C27, the predictor for demarking Friday or not was introduced because the data indicated that Fridays have a lower daily energy usage, most likely from reduced occupancy.
- **Daily minimum ambient dry bulb temperature.** NREL found that despite different days experiencing the same average dry bulb temperature and similar HR, the daily minimum dry bulb temperature impacted energy usage throughout the day.
- **Daily maximum ambient dry bulb temperature.** Because the daily minimum was included, NREL also included the daily maximum ambient dry bulb temperature.

For each building, NREL started with the linear model shown in Equation 1. The initial model included first-order predictors, second-order predictors (squared terms), and interaction predictors with mode ("mode · avgOAT", "mode· avgHR"). NREL first evaluated whether the ESM or non-ESM predictor was statistically significant; in other words, whether ESM operation changed the energy usage signature. For all the initial regressions for all three buildings, NREL found that ARC retrofit's impact on daily energy usage was statistically significant.

(1) $Daily\ Energy\ Use = c_0 + (c_1 \cdot mode) + (c_2 \cdot Friday) + (c_3 \cdot DR) + (c_4 \cdot avgOAT) + (c_5 \cdot avgOAT^2) + (c_6 \cdot avgOAT \cdot mode) + (c_7 \cdot avgHR) + (c_8 \cdot avgHR^2) + (c_9 \cdot avgHR \cdot mode) + (c_{10} \cdot avgOAT \cdot avgHR) + (c_{11} \cdot minOAT) + (c_{12} \cdot minOAT^2) + (c_{13} \cdot minOAT \cdot mode) + (c_{14} \cdot maxOAT) + (c_{15} \cdot maxOAT^2) + (c_{13} \cdot maxOAT \cdot mode)$

where: mode = mode of operation that day [–1 = non-ESM or +1 = ESM]

Friday = whether day is Friday [–1 = Friday or +1 = not Friday]

DR = demand response sequence initiated that day [–1 = DR initiated or +1 = no DR]

avgOAT = coded daily average ambient dry bulb temperature [–1 = min to +1 = max]

avgHR = coded daily average ambient humidity ratio [–1 = min to +1 = max]

minOAT = coded daily minimum ambient dry bulb temperature [–1 = min to +1 = max]

maxOAT = coded daily maximum ambient dry bulb temperature [–1 = min to +1 = max]

NREL then reduced the model by eliminating predictors that would definitely not be significant in the final regression model where all the predictors have p-values < 0.05. As a rule, NREL eliminated predictors when their p-values were > 0.25. NREL chose the final regression model when all the predictors were statistically significant. For all three buildings, NREL applied the final regression model to Hawaii International Airport TMY3 weather data to calculate the annual energy usage for ESM and non-ESM operation and thereby energy savings. The energy savings were normalized based on cooling-ton/1,000 h of RTU operation (kWh/ton/1,000 h).

As shown in the following subsections, the final regression model for each of the three buildings is different. At initial observation, the statistically significant predictors should be the same so the final regression model equation should be the same for at least buildings A13 and C27. Further investigation showed that each building had different energy use behavior, which consequently identified different predictors for explaining these variances. The following subsections also explain why the final regression model was different for each building.

BXtra Linear Regression

Table B-1 and Equation 2 show the BXtra final regression model. The demand response predictor was found to be statistically significant. As expected, average ambient dry bulb temperature and HR predictors were found to be statistically significant, as was the day-hours predictor. Figure B-1 plots the measured versus predicted energy usage. Although the regression model does not account for the entire scatter, an adjusted R-squared of 0.899 provides sufficient confidence that the model explains the monitored data.

Table B-1. BXtra 1235H Final Linear Regression Model Parameters

R-Squared	0.899	
Intercept	1,752 coefficient	0.0000 p-value
mode	–132 coefficient	0.0000 p-value
Day_Hours	97 coefficient	0.0000 p-value
DR	–17 coefficient	0.0064 p-value
avgOAT	356 coefficient	0.0000 p-value
avgHR	89 coefficient	0.0000 p-value

(2) $Building\ 1235H\ Daily\ Energy\ Use = 1{,}752 + (-132 \cdot mode) + (97 \cdot Day\_Hours) + (-17 \cdot DR) + (356 * avgOAT) + (89 * avgHR)$

where: mode = mode of operation that day [–1 = non-ESM or +1 = ESM]

DR = demand response sequence initiated that day [–1 = DR initiated or +1 = no DR]

Day_Hours = hours of operation per day [–1 = 16 hours or +1 = 20 hours]

avgOAT = coded daily average ambient dry bulb temperature [–1 = min to +1 = max]

avgHR = coded daily average ambient humidity ratio [–1 = min to +1 = max]

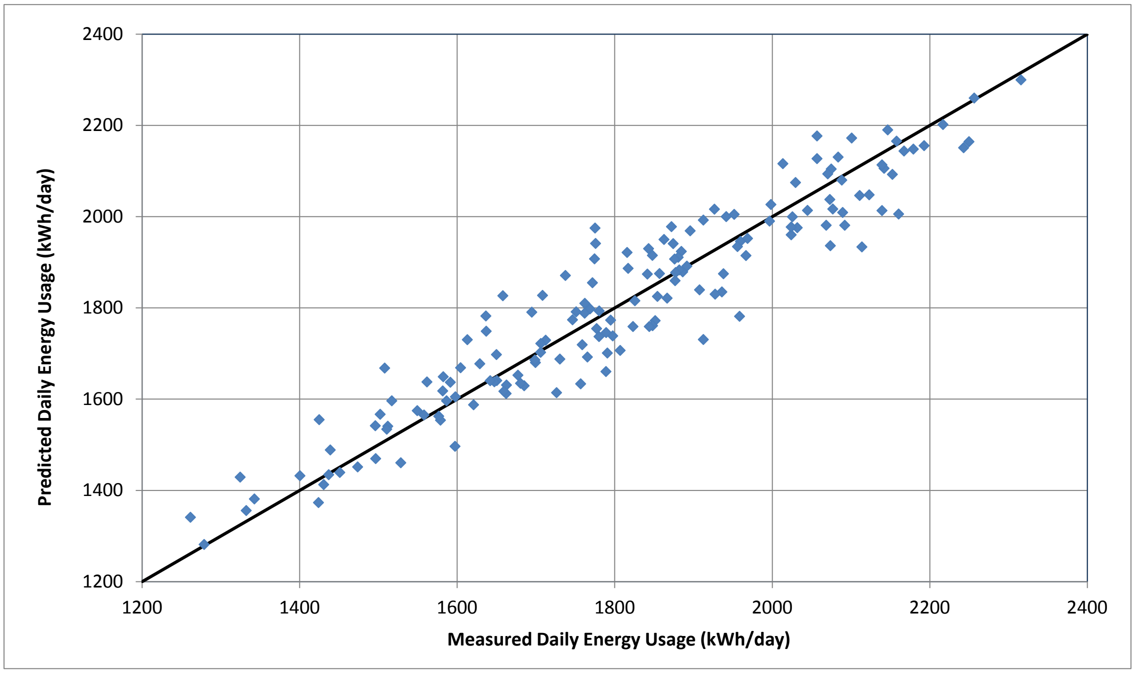

Figure B-1. BXtra 1235H predicted versus measured daily energy usage

C27 Linear Regression

Table B-2 and Equation 3 summarize the final linear regression model for building C27. Figure B-2 shows the measured versus predicted daily energy usage. Like the 1235H BXtra regression model, building C27 found the avgOAT and avgHR predictors to be statistically significant. Yet building C27 did not include the DR predictor because the DR sequence implemented on building C27 worked for only a few days of the demonstration period. The remaining days, the sequence was overridden because the space temperature sensor indicated that the space had become too warm during the demand event, causing the RTU to go into standard cooling operation. A major influence of RTU operation was the improper location of the space temperature sensor (immediately next to an exit door). Consequently, the influence of infiltration on the temperature sensor was exaggerated. The minOAT predictor was significant for this reason. NREL found that on warmer mornings, the space sensor initiated cooling much earlier compared to a cooler morning.

Table B-2. Building C27 Final Linear Regression Model Parameters

Adjusted R-Squared	**0.730**	
Intercept	105.8 coefficient	0.0000 p-value
mode	–2.9 coefficient	0.0009 p-value
Friday	2.5 coefficient	0.0130 p-value
avgOAT	8.6 coefficient	0.0015 p-value
avgHR	9.3 coefficient	0.0001 p-value
minOAT	14.7 coefficient	0.0000 p-value

(3) $Building\ C27\ Daily\ Energy\ Use = 105.8 + (-2.9 \cdot mode) + (2.5 \cdot Friday) + (8.6 \cdot avgOAT) + (9.3 \cdot avgHR) + (14.7 \cdot minOAT)$

where: mode = mode of operation that day [–1 = non-ESM or +1 = ESM]

Friday = whether day is Friday [–1 = Friday or +1 = not Friday]

avgOAT = coded daily average ambient dry bulb temperature [–1 = min to +1 = max]

avgHR = coded daily average ambient humidity ratio [–1 = min to +1 = max]

minOAT = coded daily minimum ambient dry bulb temperature [–1 = min to +1 = max]

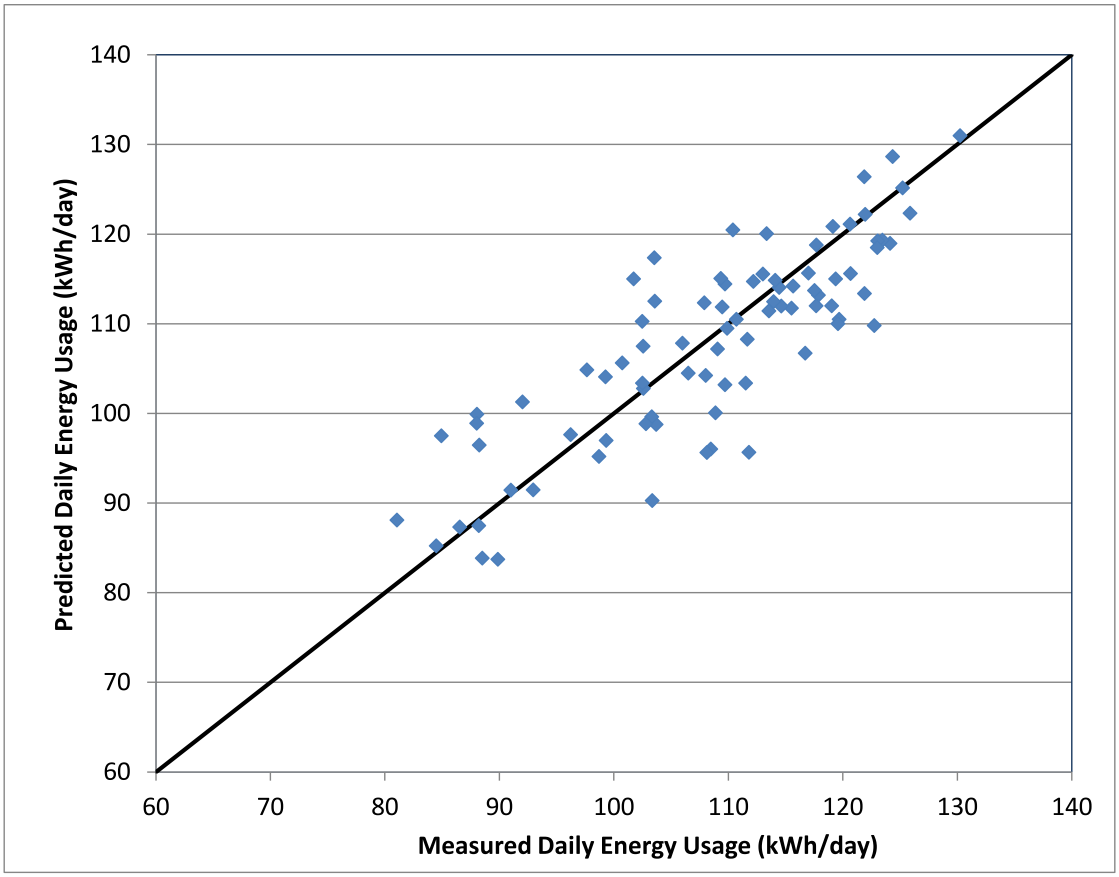

Figure B-2. Building C27 predicted versus measured daily energy usage

The 0.730 adjusted R-squared indicates that the final predictors explain most of the variance in the sample dataset. By including the "Friday" predictor, the model does account for some occupant behavior. Most of the remaining unexplained variance is due to occupant behavior impacting the other HVAC systems that serve the building. Two mini-splits serve two conference rooms adjacent to the space being served by the RTU apart from this demonstration. The mini-splits are controlled by separate thermostats and are turned on during conference room usage. Two other RTUs serve a separate wing of building C27 and may slightly influence the daily energy usage.

A13 Linear Regression

Table B-3 and Equation 4 provide building A13's final linear regression model. Compared to the BXtra and building C27, the only two predictors are mode of operation and daily average ambient dry bulb temperature. NREL was surprised that the HR predictor was not significant when reducing the regression models. When comparing against building C27 demonstration period, building A13 has a significantly smaller sample set and misses several extremely humid days in late July when the daily average HR reached 121 gr/lb. Consequently, the building A13 demonstration period was not long and consistent enough to flesh out other predictors such as HR and Friday operation. Yet an adjusted R-squared of 0.707 provides a reasonable explanation of the variance in the sample data. Figure B-1 plots the predicted versus measured energy usage.

Table B-3. Building A13 Final Linear Regression Model Parameters

Adjusted R-Squared	0.707	
Intercept	163.1 coefficient	0.0000 p-value
mode	–3.5 coefficient	0.0382 p-value
avgOAT	42.6 coefficient	0.0000 p-value

(4) $\boldsymbol{Building\ A13\ Daily\ Energy\ Use = 163.1 + (-3.5 \cdot mode) + (42.6 \cdot avgOAT)}$

where: mode = mode of operation that day [–1 = non-ESM or +1 = ESM]

avgOAT = coded daily average ambient dry bulb temperature [–1 = min to +1 = max]

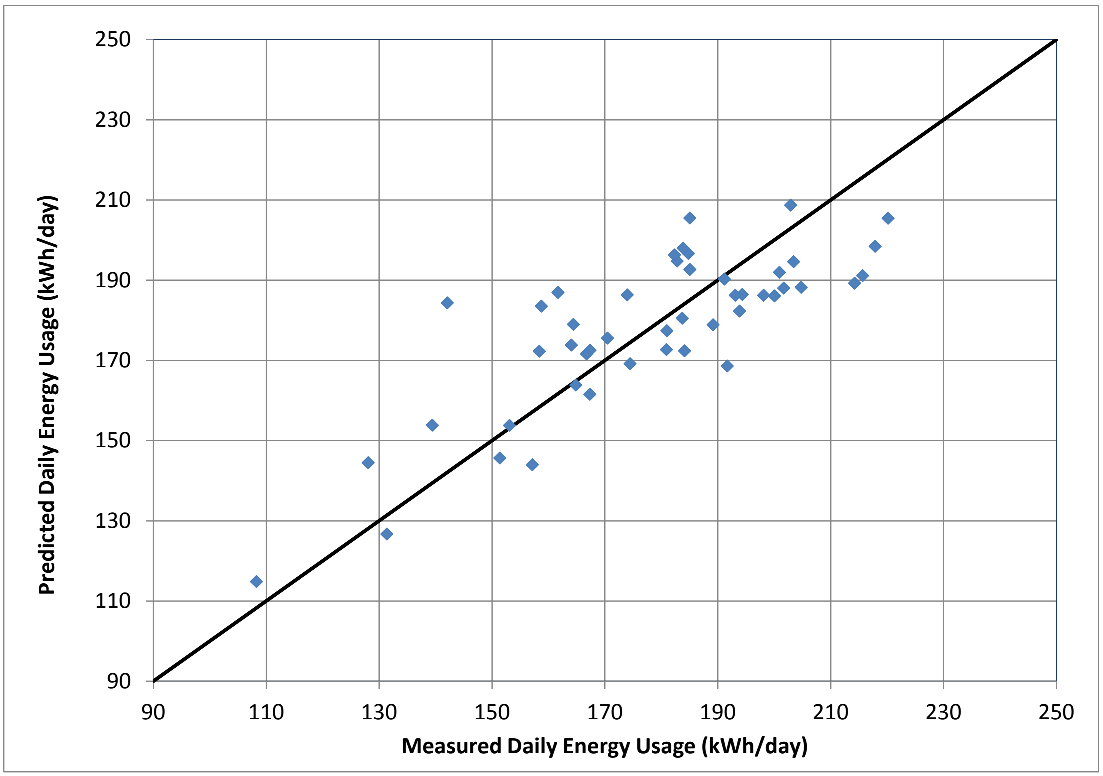

Figure B-3. Building A13 predicted versus measured to evaluate goodness of fit of the regression model

Appendix C: CATALYST Advanced Rooftop Control Retrofit Field Demonstration List

TWT Utility and Private Customer Demonstration Projects

PARTIAL

Customers

- Banner Bank
- Bartell Drugs
- BJ's Wholesale Club
- Cal Tech
- Cinemark Theaters
- Cleveland Clinic
- Commonworth Development – Federal Way Commons Mall
- General Growth Properties – Alderwood Mall
- Goodwill Industries
- Haggen Top Foods
- IKEA
- Kaiser Permanente
- Kemper Development – Bellevue Square Mall
- Los Angeles Unified School District
- Macerich – Lakewood Mall
- Minnetronix
- MOR Furniture
- Planet Fitness
- Restaurant Depot
- Rio Grande County Jail
- Simon Property Group – Seattle Premium Outlets
- Staples
- St. Louis University
- Whole Foods

Utilities and Members of the Energy Efficiency Community

- Alliant Energy – Iowa
- Bonneville Power Administration (BPA)
- Massachusetts Technology Assessment Committee (MTAC)
- Pacific Northwest National Laboratory (PNNL)
- Portland Energy Conservation, Inc. (PECI)
- San Diego Gas & Electric (SDG&E) - California
- Southern California Edison (SCE) – California
- Cape Light and Power (Massachusetts)
- Seattle City Light
- Puget Sound Energy
- Snohomish PUD
- Nextant
- Platte River Valley Authority
- Minnesota Center for Energy and Environment
- National Grid
- NSTAR
- Los Angeles Department of Water and Power

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www.twavetech.com

Appendix D: NAVFAC Routine Rooftop Unit Maintenance Procedures

NAVFAC provided its quarterly "Job Plan and Task Report," which is shown in Figure D-1.

Job Plan and Task Report

JPNum	Description
FY2A-2M	HVAC-AIR CONDITIONING "PACKAGE" UNIT (SELF CONTAINED TYPE)

No Material

Craft **Qty**

Job Task	Description	Duration
10	Notify Building Custodial of PM or Work to be performed.	0
20	CHECK WITH OPERATING PERSONNEL FOR ANY KNOWN DEFICIENCIES	0
30	Lock Out/Tag Out as Applicable, and Practice ORM.	0
40	VISUALLY INSPECT FOR REFRIGERANT, WATER AND OIL LEAKS.	0
50	CHECK SIGHT GLASS AND OPERATING PRESSURES IF GAGE PORTS AND SIGHT GLASS ARE ALREADY IN PLACE.	0
60	CHECK TENSION, CONDITION and ALIGNMENT OF BELTS; ADJUST OR REPLACE AS NECESSARY. (WHERE APPLICABLE)	0
70	CHECK AUTOMATIC CONTROL SAFETY DEVICES AND OPERATING AMPERE AND VOLTAGE. CHECK THERMOSTATE OPERATION.	0
80	REPLACE DISPOSABLE FILTERS AND / OR WASH FILTERS.	0
90	LUBRICATE EQUIPMENT WITH PROPER LUBRICANT. (WHERE APPLICABLE)	0
100	BLOW DRAINS (MANDATORY)	0
110	FOR DISCREPANCIES NOT REQUIRING IMMEDIATE ATTENTION, REPORT IT ON DEIS REPORT FORM NO. NAVFAC-9-11014/89 (REV. 06-96)	0
120	ENSURE NAVFAC HI BAR CODE STICKERS ARE ATTACHED TO EQUIPMENT OR STRUCTURE, REPLACE IF MISSING, AND PROVIDE UPDATED EQUIPMENT SHEET TO CODE WHPP5J(P&E OFFICE)	0

Figure D-1. NAVFAC quarterly RTU maintenance procedure

Appendix E: Testing, Adjusting, and Balancing Results

The TAB was completed on February 16, 2013 for all 11 RTUs on all three buildings. Other than the tables showing the TAB results, this appendix focuses on TAB measurement error. Table E-1 shows the measured ventilation rates at two fan speeds: 40% and 90%. Unfortunately, measuring OA flow rates directly at the RTU OA intake has significant sensor and environmental uncertainties.

- **Sensor uncertainty.** The TAB balancer used a pitot tube array that has a manufacturer-specified measurement range of 50–2,500 fpm; uncertainty is the larger of 7 fpm or 3% of reading. Based on the final TAB report, the OA inlet velocities were 0–600 fpm at the 90% fan speed and 0–220 fpm at the 40% fan speed. Consequently, some of the velocity measurements for the 90% fan speed and most of the velocity measurements for the 40% fan speed were slower than the 50 fpm threshold measurement of the pitot tube array.
- **Environmental uncertainty.** The TAB measured the OA intake velocity measurements outside the RTU cabinet and consequently was extremely susceptible to the wind. Even a 1 mph wind equates to 88 fpm, which exceeded most of the air velocity measures at the 40% fan speed. Typical TAB balancers will try to shield from the wind but will never block all impacts.

Table E-1. TAB Measured Ventilation Rates Measured Including Error Band Based on the Sensor and Environmental Uncertainties Measure Air Velocity at OA Inlet Hoods with Pitot Tubes

Building	Area Served by the RTUs	90% Fan Speeds (Stage 1+2 DX @ 6% Damper Position)			40% Fan Speeds (Fan Only @ 12% Damper Position)		
		+50% Error Band[a]	Actual TAB Reading[a]	–50% Error Band[a]	+150% Error Band[a]	Actual TAB Reading[a]	–150% Error Band[a]
1235H BXtra	69,576 ft^2	11,019 cfm	7,346 cfm	3,673 cfm	9,678 cfm	3,871 cfm	0 cfm
C27	2,706 ft^2	264 cfm	176 cfm	88 cfm	133 cfm	53 cfm	0 cfm
A13	7,834 ft^2	1,277 cfm	851 cfm	426 cfm	838 cfm	335 cfm	0 cfm

[a] As shown in Unit 01, OA flow rate was 1,316 cfm at 40% capacity, which reduced to 613 cfm at 90% capacity. Realistically the slower fan speed at 40% capacity should have reduced the OA flow rate significantly. Furthermore, for Units 01–04, the OA damper blades were fixed shut, which should have reduced the OA flow rate to a reasonable leakage rate of ~200–300 cfm. Consequently, OA flow rates documented in the TAB procedure have a significant error.

Based on the significant uncertainty with measuring ventilation flow rates, NREL assigned an error band around the actual TAB measurement shown in Table E-2 E-1. The 40% fan speed received three times the error caused by sensor and environmental uncertainties at its much small air velocities. NREL created the ± 50% uncertainty at the 90% fan speed and ± 150% uncertainty at the 40% fan speed (see Table E-1). NREL did not conduct a rigorous uncertainty analysis to develop these error bands and could find no documentation by the National Environmental Balancing Bureau, the Air Movement and Control Association International, Inc., or the

Associated Air Balance Council to help quantify typical error bands. Each building was evaluated separately in Section 0. Tables E-2 thru E-4 provide the results of the TAB report.

Table E-2. BXtra Supply Fan Flow Rates, Supply Fan Power, and OA Flow Rates at 100%, 90%, and 40% VFD Speeds

Eq_ID[a]	Calculated Performance at 100% Fan Speed Based on TAB[b]				TAB Report CATALYST Ventilation Mode (90% Capacity; Both Compressor Stages On)						TAB Report CATALYST Ventilation Mode (40% Capacity; Fan Only)					
	SA	Total Static	Power[c]	η_{tot}	SA	Total Static	Power[c]	OA Flow[d]	OA Damper	OA Frac	SA	Total Static	Power[c]	OA Flow[d]	OA Damper Position	OA Frac
Unit 01	9,672 cfm	1.95 in. w.c.	8.2 kW	27%	8,705 cfm	1.58 in. w.c.	6.0 kW	613 cfm	Fixed Closed	7%	3,513 cfm	0.28 in. w.c.	1.0 kW	1,316 cfm	–	37%
Unit 02	10,834 cfm	1.96 in. w.c.	7.0 kW	36%	9,751 cfm	1.59 in. w.c.	5.1 kW	1,477 cfm	Fixed Closed	15%	3,630 cfm	0.29 in. w.c.	0.7 kW	508 cfm	–	14%
Unit 03	9,259 cfm	2.07 in. w.c.	7.0 kW	32%	8,333 cfm	1.68 in. w.c.	5.1 kW	868 cfm	Fixed Closed	10%	3,637 cfm	0.28 in. w.c.	0.8 kW	504 cfm	–	14%
Unit 04	9,443 cfm	2.00 in. w.c.	6.0 kW	37%	8,499 cfm	1.62 in. w.c.	4.4 kW	562 cfm	Fixed Closed	7%	3,818 cfm	0.29 in. w.c.	0.7 kW	562 cfm	–	15%
Unit 05	5,626 cfm	1.60 in. w.c.	1.9 kW	55%	5,063 cfm	1.30 in. w.c.	1.4 kW	2,406 cfm	6%	48%	1,646 cfm	0.21 in. w.c.	0.1 kW	790 cfm	12%	48%
Unit 06	4,124 cfm	1.93 in. w.c.	1.9 kW	49%	3,712 cfm	1.56 in. w.c.	1.4 kW	168 cfm	6%	5%	1,251 cfm	0.24 in. w.c.	0.1 kW	60 cfm	12%	5%
Unit 07	3,518 cfm	0.81 in. w.c.	1.2 kW	28%	3,166 cfm	0.66 in. w.c.	0.9 kW	1,132 cfm	No Response	36%	810 cfm	0.11 in. w.c.	0.1 kW	??	No Response	??
Unit 08	3,310 cfm	1.81 in. w.c.	2.6 kW	27%	2,979 cfm	1.47 in. w.c.	1.9 kW	120 cfm	6%	4%	1,182 cfm	0.22 in. w.c.	0.3 kW	131 cfm	12%	11%
Unit 09	5,187 cfm	0.59 in. w.c.	1.6 kW	23%	4,668 cfm	0.48 in. w.c.	1.2 kW	NA	–	–	1,766 cfm	0.10 in. w.c.	0.1 kW	NA	–	–
Total	60,973 cfm	1.82 in. w.c.	37.5 kW	35%	54,876 cfm	–	27.3 kW	7,346 cfm	–	13%	21,253 cfm	–	3.9 kW	3,871 cfm	–	18%

[a] RTU IDs based on numbering system previously established at the BXtra. All RTUs were numbered with spray paint on the roof, most likely during their installation.

[b] SA flow at 100% fan speed calculated based on the 90% speed SA flow rate assuming the maximum flow is 10% faster. Resultant fan power and total static based on fan laws using 90% fan speed TAB data.

[c] Power calculated as a function of average volts-amps across all three phases multiplied by the motor rated power factor. Note: actual power factor not measured by TAB balancer, which increases the uncertainty of the power calculation.

[d] OA flow rate measured by the TAB balancer at the damper entrance instead of being calculated based on the difference between the SA and RA duct traverses. Consequently, OA flow rates have a significant sensor error at low air velocities and environmental error caused by wind during the TAB measurements. For example, as shown in Unit 01, OA flow rate was 1,316 cfm at 40% capacity, which decreased to 613 cfm at 90% capacity. Realistically, the slower fan speed at 40% capacity should have reduced the OA flow rate significantly. Furthermore, for Units 01–04, the OA damper blades were fixed shut which should have reduced the OA flow rate to a reasonable leakage rate of ~200–300 cfm. Consequently, OA flow rates documented in the TAB procedure have a significant error.

Table E-3. BXtra MA and Leaving Air Conditions with Both Compressor Stages Operational During 90% Capacity TAB

Eq_ID[a]	TAB Report[e] CATALYST Ventilation Mode (90% Capacity; Both Compressor Stages)														
	SA	Total Static	Power[b]	OA Flow[c]	OA Damper Position	OA Frac	MA Dry bulb	MA Wet-Bulb	MA Dew Point	SA Dry bulb	SA Wet-Bulb	SA Dew Point	Delta T Dry bulb	Delta T Dew Point	SA RH
Unit 01	8,705 cfm	1.58 in. w.c.	6.0 kW	613 cfm	Fixed Closed	7%	76.0°F	65.6°F	59.9°F	58.0°F	54.3°F	51.5°F	18.0°F	8.4°F	79%
Unit 02	9,751 cfm	1.59 in. w.c.	5.1 kW	1,477 cfm	Fixed Closed	15%	69.0°F–note d	61.8°F	57.5°F	49.0°F	46.5°F	44.1°F	20.0°F	13.4°F	83%
Unit 03	8,333 cfm	1.68 in. w.c.	5.1 kW	868 cfm	Fixed Closed	10%	68.0°F–note d	63.6°F	61.2°F	50.0°F	47.1°F	44.4°F	18.0°F	16.8°F	81%
Unit 04	8,499 cfm	1.62 in. w.c.	4.4 kW	562 cfm	Fixed Closed	7%	69.0°F–note d	61.8°F	57.5°F	54.0°F	51.5°F	49.5°F	15.0°F	8.0°F	85%
Unit 05	5,063 cfm	1.30 in. w.c.	1.4 kW	2,406 cfm	6%	48%	75.0°F	68.5°F	65.4°F	55.0°F	52.8°F	51.1°F	20.0°F	14.3°F	87%
Unit 06	3,712 cfm	1.56 in. w.c.	1.4 kW	168 cfm	6%	5%	77.0°F	68.5°F	64.4°F	54.0°F	50.7°F	47.9°F	23.0°F	16.4°F	80%
Unit 07	3,166 cfm	0.66 in. w.c.	0.9 kW	1,132 cfm	No Response	36%	72.0°F	65.8°F	62.6°F	53.0°F	49.6°F	46.6°F	19.0°F	15.9°F	79%
Unit 08	2,979 cfm	1.47 in. w.c.	1.9 kW	120 cfm	6%	4%	74.0°F	63.5°F	57.3°F	55.0°F	52.3°F	50.2°F	19.0°F	7.2°F	84%
Unit 09	4,668 cfm	0.48 in. w.c.	1.2 kW	No OA Damper	–	–	72.0°F	62.4°F	56.6°F	58.0°F	53.7°F	50.4°F	14.0°F	6.2°F	76%
Total	54,876 cfm	–	27.3 kW	7,346 cfm	–	13%	–	–	–	–	–	–	–	–	–

[a] RTU IDs based on numbering system previously established at the BXtra. All RTUs were numbered with spray paint on the roof, most likely during their installation.
[b] Power calculated as a function of average volts-amps across all three phases multiplied by the motor rated power factor. Note power factor not measured by TAB balancer, which increases the uncertainty of the power calculation.
[c] OA flow rate measured by the TAB balancer at the damper entrance instead of being calculated based on the difference between the SA and RA duct traverses. Consequently, OA flow rates have a significant error because of wind during the TAB measurements. For example, as shown in Unit 01, OA flow rate was 1,316 cfm at 40% capacity, which decreased to 613 cfm at 90% capacity. Realistically, the slower fan speed at 40% capacity should have reduced the OA flow rate significantly. Furthermore, for Units 01–04, the OA damper blades were fixed shut, which should have reduced the OA flow rate to a reasonable leakage rate of ~200–300 cfm. Consequently, OA flow rates documented in the TAB procedure have a significant error.
[d] MA temperatures were lower than expected because significant SA was entrained into the RA for Units 02–04. This entrainment also resulted in the inability to infer the space RH based on the RA RH. Entrainment also reduces the efficiency of the DX circuits by driving down the suction pressure and reducing the sensible cooling capacity. Note that Unit 01 has reasonable mix air temperature because it has sufficient ductwork that prevents SA entrainment into the RA.
[e] Dry bulb temperature drop across the evaporator coil ranging from 15°F to 23°F indicates that both DX stages are working adequately for all 9 RTUs.

Table E-4. Buildings A13 and C27 Supply Fan Flow Rates, Supply Fan Power, and OA Flow Rates at 100%, 90%, and 40% VFD Speeds

Eq_ID[a]	Calculated Performance at 100% Fan Speed Based on TAB[b]				TAB Report CATALYST Ventilation Mode (90% Capacity; Both Compressor Stages)						TAB Report CATALYST Ventilation Mode (40% Capacity; Fan Only)					
	SA	Total Static	Power[c]	η_{tot}	SA	Total Static	Power[c]	OA Flow[d]	OA Damper	OA Frac	SA	Total Static	Power[c]	OA Flow[d]	OA damper	OA Frac
A13 Unit 02	6,726 cfm	1.31 in. w.c.	2.2 kW	47%	6,053 cfm	1.06 in. w.c.	1.6 kW	851 cfm	Hand set to ~50%- motorized damper not installed yet	14%	2,633 cfm	0.21 in. w.c.	0.2 kW	335 cfm	Hand set to ~50%- motorized damper not installed yet	13%
C27 Unit 01	4,257 cfm	1.60 in. w.c.	?	?	3,831 cfm	1.30 in. w.c.	?	176 cfm	Hand set to ~0%- motorized damper not installed yet	5%	1,571 cfm	0.27 in. w.c.	0.2 kW	53 cfm	Hand set to ~0%- motorized damper not installed yet	3%

[a] RTU IDs based on the numbering system previously established at the BXtra. All RTUs were numbered with spray paint on the roof, most likely during their installation.

[b] SA flow at 100% fan speed calculated based on the 90% speed SA flow rate assuming the maximum flow is 10% faster. Resultant fan power and total static based on fan laws using 90% fan speed TAB data.

[c] Power calculated as a function of average volts-amps across all three phases multiplied by the motor rated power factor. Note power factor not measured by TAB balancer, which increases the uncertainty of the power calculation.

[d] OA flow rate measured by the TAB balancer at the damper entrance instead of being calculated based on the difference between the SA and RA duct traverses. Consequently, OA flow rates have a significant sensor error at low air velocities and environmental error caused by wind during the TAB measurements. For example, as shown in Unit 01, OA flow rate was 1,316 cfm at 40% capacity, which decreased to 613 cfm at 90% capacity. Realistically, the slower fan speed at 40% capacity should have reduced the OA flow rate significantly. Furthermore, for Units 01–04, the OA damper blades were fixed shut which should have reduced the OA flow rate to a reasonable leakage rate of ~200–300 cfm. Consequently, OA flow rates documented in the TAB procedure have a significant error.

Table E-5. Buildings A13 and C27 MA and Leaving Air Conditions with Both Compressor Stages Operational During 90% Capacity TAB

Eq_ID[a]	TAB Report[d] CATALYST Ventilation Mode (90% Capacity; Both Compressor Stages)														
	SA	Total Static	Power[b]	OA Flow[c]	OA Damper	OA Frac	MA Dry bulb	MA Wet-Bulb	MA Dew Point	SA Dry bulb	SA Wet-Bulb	SA Dew Point	Delta T Dry bulb	Delta T Dew Point	SA RH
A13 Unit 02	6,053 cfm	1.06 in. w.c.	1.6 kW	851 cfm	Hand set to ~50%- motorized damper not installed yet	14%	Stage 2 Compressors not running at time of the TAB								
C27 Unit 01	3,831 cfm	1.30 in. w.c.	?	176 cfm	Hand set to ~0%- motorized damper not installed yet	5%	70.0°F	64.7°F	61.9°F	53.0°F	51.9°F	51.0°F	17.0°F	10.8°F	93%

[a] RTU IDs based on a numbering system previously established at the BXtra. All RTUs were numbered with spray paint on the roof, most likely during their installation.

[b] Power calculated as a function of average volts-amps across all three phases multiplied by the motor rated power factor. Note power factor not measured by TAB balancer, which increases the error band of the power calculation.

[c] OA flow rate measured by the TAB balancer at the damper entrance instead of being calculated based on the difference between the SA and RA duct traverses. Consequently, OA flow rates have a significant error because of wind during the TAB measurements. For example, as shown in Unit 01, OA flow rate was 1,316 cfm at 40% capacity, which decreased to 613 cfm at 90% capacity. Realistically, the slower fan speed at 40% capacity should have reduced the OA flow rate significantly. Furthermore, for Units 01–04, the OA damper blades were fixed shut, which should have reduced the OA flow rate to a reasonable leakage rate of ~200–300 cfm. Consequently, OA flow rates documented in the TAB procedure have a significant error.

[d] Dry bulb temperature drop across C27's evaporator at 17°F indicates that both its DX circuits are operating properly. Unfortunately, stage 2 on building A13 needed maintenance and its operation was not documented during the TAB.

Appendix F: Buildings A13 and C27 Demand Response Results

The demand response sequence for A13 and C27 was slightly different compare to the BXtra. Both RTUs were included into the same sequence despite serving distinct buildings. The methodology is for applying one sequence to RTUs serving multiple buildings.

The demand response sequence defines one RTU as lead and the other as lag. For buildings C27 and A13, the units that were lead and lag alternated depending on the day. During a demand event, the second compressor is turned off in the lead unit for 15 minutes. If only one compressor is running, that compressor will be turned off. If no compressors are running, the system will take no action. At the end of each 15-minute period, one compressor in the lag unit will be turned off for 15 minutes while the lead RTU can turn back on one compressor. This process will continue for the entire demand period. The lead/lag sequence is alternated each day the demand response sequence is required.

The cooling set point temperature is lowered by 2°F before the demand period begins. During the demand event, the space temperature is allowed to float up 2°F above set point. At the end of the demand event, the space temperature is reset to its normal set point temperature. The monthly peak demand savings comparing the standard day, October 25, versus the demand response day, October 24, is provided in Table F-1.

Table F-1. C27 and A13 Monthly Demand Savings

Maximum Peak on Standard Day 1:30pm-3:30pm October 25, 2013 (kW)	Maximum Peak on Demand Response Day 1:30pm-3:30pm October 24, 2013 (kW)	Maximum Peak Reduction (kW)	Maximum Peak Reduction (Watt/ft^2)
36.5	15.4	21.1	2.0

TWT had problems implementing the demand response sequence at C27 and A13. The sequence did not activate for the first few months of operation. A control technician reinitiated the control sequence and it operated successfully for 2 days. On the second day, A13 stopped responding to control signals from the ARC controller due to a maintenance issue unrelated to the CATALYST. When the A13 RTU was repaired, NREL decided to eliminate the C27-A13 DR sequence to focus on the energy savings.

For the 2 days the sequence worked, the maximum peak demand from 1:30 pm to 3:30 pm was reduced by 21.1 kW. The power profiles for October 24 and 25 are provided in Figure F-1. Compared to the demand response sequence implemented on the BXtra, this sequence did not perform well. Small office buildings such as A13 and C27 have minimal thermal inertia and do not have the HVAC operational diversity to accommodate this sequence. Consequently, these types of buildings cannot be “charged” like a thermal battery such that the space can ride through a demand response event while maintaining thermal comfort. While there is some W/ft^2 demand response capability; however, the demand response sequence needs to be reworked.

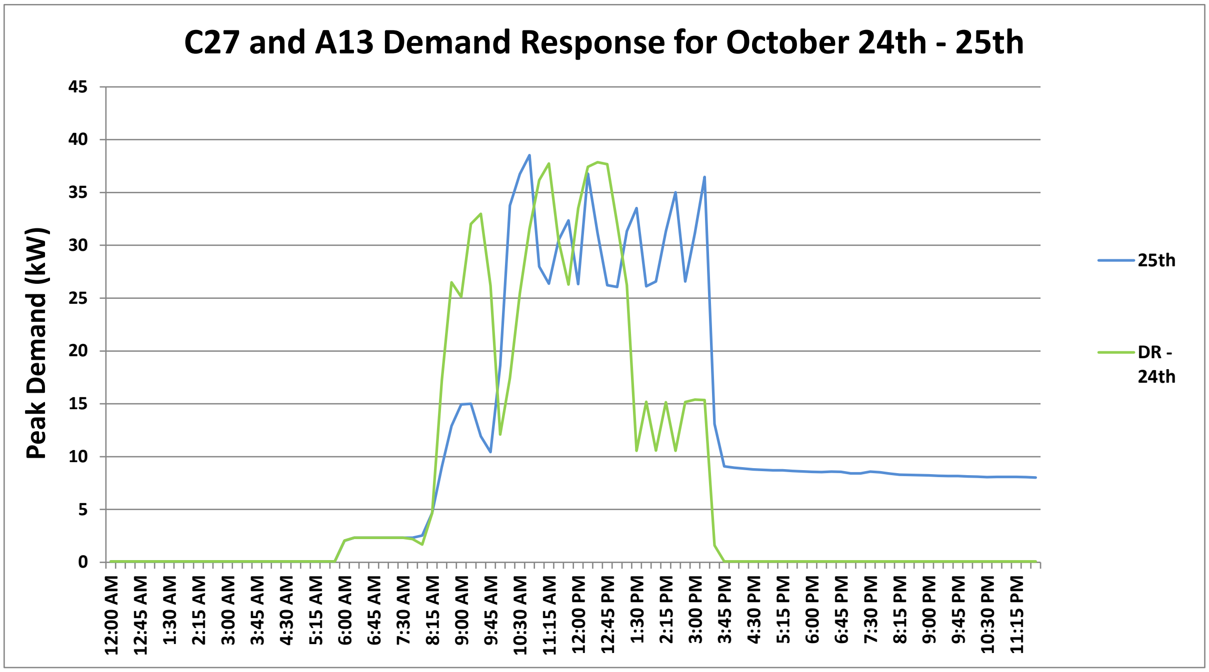

Figure F-1. C27 and A13 demand response for October

Appendix G: Economizing Performance Objective

OA economizers are not typically applied to HVAC systems in this climate zone. Yet these are a standard feature of ARC retrofit systems. Five units on the BXtra, C27, and A13 were retrofitted with electronic damper actuators and a differential dry bulb with dew point lockout economizer sequence. The percent of time that each unit operated in OA economizer mode from February 1 through October 31 was calculated. Although there was slight variation from one unit to the next, the overall time in economizer mode was minimal (Table G-1).

Table G-1. Percent of Time in OA Economizer Mode

Month	BXtra 05	BXtra 06	BXtra 07	BXtra 08	BXtra 09	C27	A13
	Percent of Time in Economizer Mode	Percent of Time in Economizer Mode	Percent of Time in Economizer Mode	Percent of Time in Economizer Mode	Percent of Time in Economizer Mode	Percent of Time in Economizer Mode	Percent of Time in Economizer Mode
February	0.00%	0.00%	0.03%	0.00%	0.00%	0.51%	3.28%
March	0.02%	0.05%	0.02%	0.00%	0.00%	0.21%	1.53%
April	0.01%	19.57%	0.04%	0.11%	0.00%	0.28%	0.18%
May	0.00%	25.11%	0.00%	0.00%	0.00%	0.31%	0.25%
June	0.00%	40.32%	0.00%	0.02%	0.00%	0.06%	0.06%
July	0.00%	25.56%	0.00%	0.00%	0.00%	0.00%	0.01%
August	2.99%	30.09%	0.00%	0.00%	0.00%	0.00%	0.00%
September	0.0%	24.8%	0.0%	0.0%	0.0%	0.0%	0.0%

The average time in OA economizer mode across all units over the monitored period was 0.2%. In summary, the analysis shows that an OA economizer sequence is not recommended for this climate zone; the performance objective of operating in OA economizer mode for 1,300 hours annually could not be met.

Appendix H: Coil Coating Performance Objective

The HVACArmor DX coating was applied to five of the 11 RTU evaporator and condenser coils shown in Table 1 and Table 2. All units of identical size were the same model and vintage. The units that did not receive the coating were intended to serve as the baseline to which the newly coated units could be compared. To provide a consistent basis of comparison, only data from March 7, 2013 to May 29, 2013 that met the following criteria were included in the analysis:

- OA dry bulb temperature: 70°–80°F
- RA dew point: 60°–65°F
- Minimum 4-minute runtime for steady state condition
- Fan speed @ 100% (non-ESM operation only)
- OA damper @ minimum position.

A methodology was developed to compare the real-time coefficient of performance of RTUs with and without HVACArmor DX. Although the overall uncertainty of the calculated coefficient of performance is significant by compounding multiple measurement uncertainties, NREL considered the exercise likely to at least identify a performance trend. The results were inconsistent such that no trend could be established. In addition to the significant uncertainty, the other variables that impact RTU coefficient of performance such as refrigerant charge, poor oil distribution, condenser fan motor health, and thermostatic expansion valve operational impacts had too large an impact on coefficient of performance. Most of these variables cannot be measured with any level of confidence.

To properly evaluate whether coil coatings impact RTU performance, a more detailed evaluation of the refrigeration cycle would need to be used to evaluate a sample of more than 30 similarly sized RTUs. NREL recommends using a field monitoring product such as the ClimaCheck (www.climacheck.com) that can measure both the real-time cooling and compressor only power draw to a much greater accuracy than the methodology NREL used for this demonstration. The ClimaCheck could monitor the sample set pre- and post-coil coating such that each RTU's performance would be compared to itself. The combination of the larger sample set, improved measurement accuracy, and pre/post measurement should provide the level of detail needed to determine whether coil coatings impact RTU performance.

Appendix I: Summary of Advanced Rooftop Control Savings in Other U.S. Climates

A multiyear research study was conducted by Pacific Northwest National Laboratory (PNNL), with funding from DOE's Building Technologies Office and Bonneville Power Administration (BPA) to monitor the performance of 66 RTUs across eight locations (Wang et al. 2013). The objective was to determine the magnitude of energy savings achievable by retrofitting packaged RTUs with ARC systems. The evaluated RTUs were located in Cleveland, Ohio, (ASHRAE climate zone 5A); Oaks, Pennsylvania, (ASHRAE climate zone 4A), Valencia, California, (ASHRAE climate zone 3B), and Seattle, Washington, (under which all Washington sites fall) (ASHRAE climate zone 4C). The building types included retail, office, food sales, and healthcare. Seventeen of the RTUs tested were heat pumps and the rest were traditional packaged units with gas heat.

The CATALYST ARC system evaluated in this Navy demonstration was the same used in the PNNL study. All the energy efficiency features evaluated were the same except for the specific type of economizer control. The PNNL demonstration evaluated differential dry-bulb control with a dry-bulb lock out. This demonstration evaluated differential dry-bulb control with a dew-point lock out.

The PNNL study focused solely on energy savings and did not measure the impacts on thermal comfort or demand response. PNNL did apply some FDD software tools to the various sequences of operation to ensure the OA economizer, DCV, and variable-speed fan settings were operating correctly.

Major findings from the PNNL report are highlighted below:

- The ARC reduced the normalized annual RTU energy consumption by 22%– 90%, with an average of 57% reduction for all the RTUs.
- Fan energy savings made a dominant contribution to the total RTU electricity savings; the heating and cooling energy savings varied by unit and were relatively smaller. The fan energy savings were 26%–94%, with an average of 74%.
- Normalized annual electricity savings per hour of fan/unit operation ranged from 0.47 kWh/h (kWh per hour of fan/unit operation) to 7.21 –kWh/h, with an average of 2.39 kWh/h.
- Three utility rates were used to calculate a simple payback period: $0.05/kWh, $0.10/kWh and $0.15/kWh, resulting in average payback of 6, 3, and 2 years, respectively. This payback included the ARC system and labor for installation.

Compared to the Navy demonstration in Hawaii, the PNNL demonstration showed a much higher average energy savings across the 66 RTUs, because the OA economizer and DCV features saved significantly more energy in the demonstration climate zones. Also compared to typical Hawaii operation, the RTUs in these other climate zones all spent less time in first- and second-stage cooling or heating modes and more time in ventilation mode, which increased the fan savings in the PNNL study.

In summary, ASHRAE climate zone 1A will always have the lowest energy savings of all U.S. climate zones. The normalized energy savings from the PNNL report are provided in Table I-1. NREL modified the PNNL energy savings to match the metric used in this demonstration. These energy savings are averaged across the four climate zones in the PNNL report. As shown, the normalized energy savings changed dramatically based on the RTU system size.

Table I-1. Normalized RTU ARC Electrical Energy Savings from PNNL Report

RTU Size Range	Energy Savings
< 10 tons	103 kWh/ton per 1,000 h
10–15 tons	150 kWh/ton per 1,000 h
> 15 tons	282 kWh/ton per 1,000 h

Before the field demonstration began, PNNL conducted a thorough simulation study of ARC system energy savings across 16 climate zones in the continental United States (Wang 2011). Four building types were modeled: small office, standalone retail, strip mall, and supermarket. The annual energy savings from the PNNL energy simulation results are provided in Figure I-1.

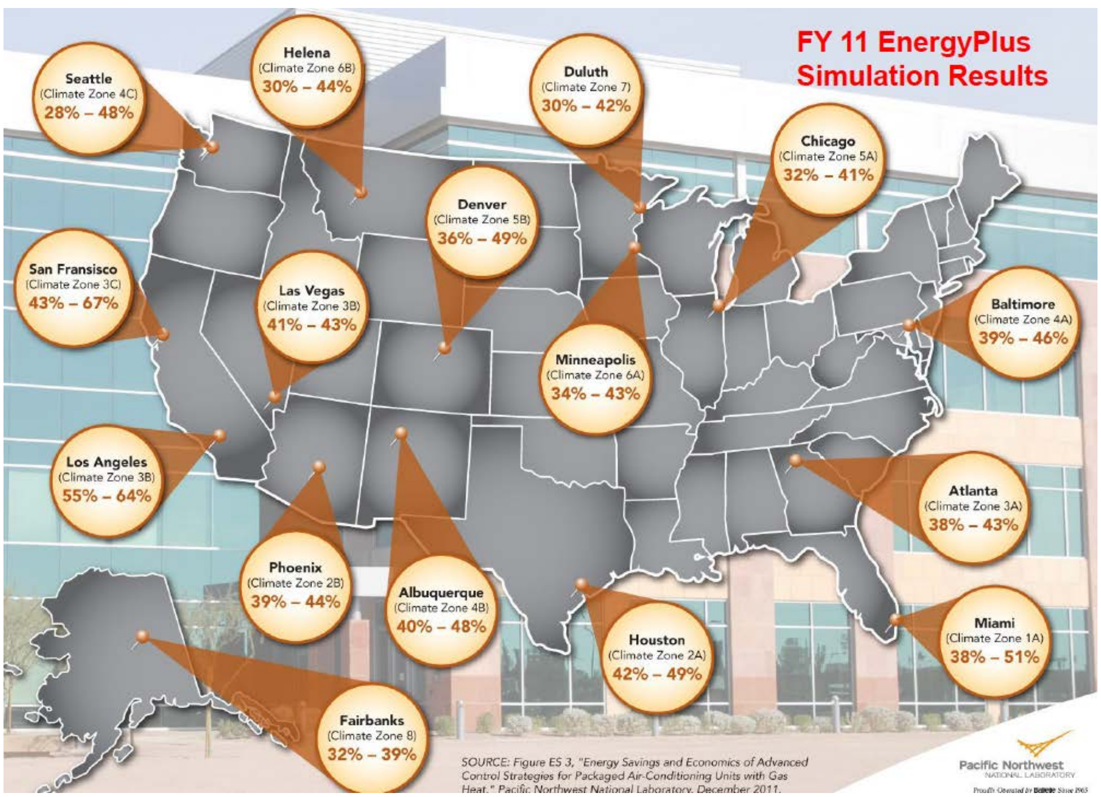

Figure I-1. ARC energy savings based on detailed energy modeling study across 16 climates and four building types

Source: Wang et al. 2011

Appendix J: Practical Lessons Learned for Future NAVFAC Advanced Rooftop Control Installations

The following practical lessons learned are offered for follow-on ARC retrofit installations on all building types. Most were the result of insight gleaned during the demonstration. Some are specific to NAVFAC, predominantly based on COLS and NAFVAC Hawaii strict temperature set point and HVAC operating time requirements.

Benefits of Bundling Web-Based BMS with Advanced Rooftop Control Retrofit

Sophisticated controls should be coupled with sufficient monitoring to extract their full value. The ARC retrofit can act as a standalone controller and can provide the annualized energy savings summarized in this report in the first 2 or 3 years after installation. However, HVAC energy-saving measures, especially those that focus on improved control, can lose their initial energy savings over the years. Oversight is necessary to ensure sustained energy savings.

Bundling the Web-based BMS service with the ARC retrofit technology provides the necessary feedback so that:

- Building energy managers can quickly ensure that temperature set points and schedules meet the latest NAVFAC requirements.
- HVAC service technicians can quickly and easily verify proper system operation and leverage automated FDD alarming to be made aware of an issue before the system fails.

The ARC energy savings shown in this report can be boosted through the BMS functionality, which enables NAVFAC to strictly enforce HVAC operational and temperature set point requirements. During the initial site surveys, NREL found nine of the 11 RTUs operating outside the correct temperature and operational schedules. The non-ESM baseline used in the demonstration used the proper set points and schedules. These energy savings are commonly called *soft energy savings*. They are very real but hard to quantify because they are due to improper operation based on human-machine interaction. Finally, the Web-based BMS provides monitored data of past performance that will be crucial for adjusting space temperature set points to meet RH requirements and other crucial adjustments.

Benefits of Testing, Adjusting, and Balancing Conducted by an Advanced Rooftop Control Retrofit Installer

For this demonstration, NREL enforced a parsed down version of UFGS 23 05 93 “Testing, Adjusting, and Balancing for HVAC.” This modified specification still required a third-party TAB-certified contractor to balance the supply and OA flows. Although TWT’s standard CATALYST installation includes no TAB activity, TWT complied.

Taking a step back, a comprehensive TAB for RTU ventilation rates is typically conducted on new construction projects when design drawings are available. RTU replacements or retrofits on existing buildings typically do not have engineered drawings and therefore no TAB is conducted.

When asked about standard procedure regarding balancing RTU OA dampers, a NAVFAC HVAC technician responded:

> I assume if an installation is being performed via a contract with a TAB requirement, then the damper would be adjusted to design specs. If we do an installation, we just use our judgment and leave the damper about 20% to 50% open depending on the actual damper size and tonnage of the unit. If the unit is undersized we tend to keep the OA at a ver*y* minimum position. If the occupants are complaining we would open the damper further.

This comment matches NREL's observations of OA damper positions during site visits. Before the CATALYST was installed, the six RTUs that had OA dampers seemed to be arbitrarily set to a 5%–20% open fixed position.

Examining the benefits of the TAB activity and deliverables, NREL recommends an even further streamlined TAB procedure for future ARC retrofit installations:

1. **SA TAB.** The SA shall be balanced according to NEBB TAB Procedural Standards 2005. The fan sheave, VFD, and ARC sequence shall be adjusted to ensure SA flow equals or exceeds (1) 300 cfm per nominal ton under first-stage cooling; (2) 350 cfm per nominal ton under second-stage cooling; and (3) 150 cfm per nominal ton during "fan only" operation. For cooling stages and fan only operation, the final TAB report will show the measured airflow, each phase amp draw and voltage upstream of the VFD, and make-model of the TAB instruments used, including last calibration dates.
2. **OA TAB.** NREL does not recommend balancing the ventilation flow rate at the OA damper because of the significant uncertainty caused by measurement inaccuracy at air speeds lower than 50 fpm and impacts of wind. The uncertainties will realistically exceed 100% of the measured ventilation flow rate (see Appendix E). Instead, the OA flow rates should be calculated based on the measured SA flow rate minus the measured RA flow rate. The overall uncertainty of the SA and RA flow rates are significantly reduced because these air speeds exceed 50 fpm.
3. **Third-party, TAB-certified contractor.** NREL recommends not using a third-party, TAB certified contractor to conduct the TAB activity. Instead, NREL recommends that the ARC contractor, whether TAB certified or not, conduct the TAB activity during the installation. One of the main reasons the ARC retrofit is cost effective is its fast and low-cost installation, typically taking 1 day per RTU. By using a third-party TAB contractor, the entire ARC installation activity becomes more complicated and expensive with minimal additional energy cost savings to offset the cost. Although a third-party TAB contractor enforces some level of independent oversight, balancing the SA properly is in the best interest of the ARC installer. An improperly balanced airflow rate will cause the coils to ice and require a call to the installer. It is in the installer's best interest to conduct the SA TAB properly. Yet NAVFAC will need to use the TAB measured ventilation airflow rates to ensure that the OA damper configuration at different fan speeds meets ASHRAE 62.1 ventilation rates.
4. **DX Coil Performance Documentation.** The TAB should include documenting the temperature deltas across the DX coils under first and second stage operation. To be

assured of proper DX performance, the temperature delta should be 5-10°F under first stage cooling and 15-20°F under second stage cooling. Temperature deltas outside these ranges would indicate potential DX maintenance issues. The temperature reading measured downstream of the DX coil should be made after the supply fan to ensure that the air is properly mixed. Measuring the air immediately after the DX coil and before the supply fan may provide inaccurate readings since the air can be stratified for split-face coil arrangements.

5. **Sight Inspection of Existing Ductwork and Gravity Dampers.** Rather than conducting a detailed TAB to evaluate duct leakage, there is a greater cost benefit of conducting a visual inspection. Any unsealed seams or holes should be properly sealed. Also any gravity dampers that are provided on the RTU for return air relief should be sealed if the building is determined to not have sufficient positive pressure. Return air relief dampers are notoriously leakage and being located near the suction of the supply fan can cause unintentional OA intake.
6. **Building pressurization.** The ventilation flow rates at the different fan speeds should be compared against any exhaust streams from the single zone. Most buildings have bathroom exhaust and some buildings will have additional exhausts such as commissaries with kitchen hoods. NAVFAC should ensure that the RTUs are properly balanced against any exhaust fans and ensure proper building pressurization.

Space Temperature Sensor and Location

With aggressively warm temperature set point and HVAC operational requirements through NAVFAC Hawaii energy instructions and NAVFAC COLS requirements (see Appendix A), the ARC retrofit should include replacing the old thermostat with an accurate temperature sensor located near the center of the conditioned zone. Compared to a typical thermostat, the temperature sensor will transmit the actual space temperature to the ARC rather than simply cooling commands. Knowing the space temperature allows the ARC to make more detailed decisions about RTU operation.

For future control flexibility, NREL recommends that the space sensor includes tenant set point adjustment and tenant override. To ensure that NAVFAC Hawaii and NAVFAC COLS operational and set point requirements are met, NREL recommends that the ARC sequence ignore the tenant set point adjustment and tenant override. This way, only NAVFAC-designated personnel, such as the building energy managers, have BMS Web access to adjust those schedules and set points. Yet, depending on the application, NAVFAC may decide to allow the tenants some override privileges. For example, during the demonstration, NREL enabled late day and weekend RTU operation for NAVFAC's contracts department in building A13 at the end of the fiscal year. Rather than having the building energy manager make all these specialty changes, allowing the tenants some level of control for non-typical building operation may be easier. In short, including the space sensor tenant adjustment and override provides enough flexibility to find the correct control balance, including future flexibility if the building function changes. The NAVFAC AHJ should stipulate whether the tenant override control is included.

The model series of temperature sensor, including transmitter, must have NIST-traceable accuracy to ± 2.0°F within the range of 60°–100°F. Although this is not required, NREL recommends that the space temperature sensor is ordered with a three-point factory calibration at

60°F, 75°F, and 90°F reference temperatures. Sensor manufacturers typically charge only $25 to $50 for a three-point factory calibration, which ensures that the sensor meets or exceeds the manufacturer's stated accuracy. If a factory calibration is not ordered, the temperature sensor once installed should be compared to a calibrated hand-held temperature sensor during the commissioning process. If the temperature sensor is not accurate, then it should be replaced.

Space temperature sensor location is important. Building C27's space temperature sensor was improperly located next to an exit door and was causing the RTU to provide too much cooling (see Section 4.2.2). The space temperature sensor should be located on an interior wall or column near the center of the conditioned space. The sensor should be 4–5 feet off the finished floor for a standard 8-foot ceiling. In the case of high ceilings, such as a retail space or warehouse, the space temperature sensor can be located above 5 feet but not more than 10 feet off the finished floor surface. The sensor should be at least 4 feet from any doors if along the same wall or 20 feet if along a wall perpendicular to the door. If the thermostat does not meet these requirements, the space temperature sensor will need to change locations and new control wire will need to be pulled from the RTU.

Space Relative Humidity Sensor (Recommended in Hawaii; Required in Guam)

This demonstration showed that RTU humidity control was not necessary for non-refrigerated spaces in Hawaii; however, NREL recommends that the space temperature sensor include a humidity sensor. NAVFAC Hawaii and NAVFAC COLS requirements are extremely aggressive about allowable RTU operation and warm temperature set points. NREL found that these aggressive requirements result in space RH > 65% during occupied and unoccupied times, which causes occupant discomfort and potential mold growth (see Appendix A).

For non-refrigerated Hawaii buildings, the space humidity sensor can be monitored through the Web-based BMS and provide feedback to NAVFAC about whether the temperature set points and schedules need to be adjusted to ensure the space RH does not exceed 65% during occupied and unoccupied hours. For example, in the case of buildings C27 and A13, a "morning dehumidification" sequence was added to enable the RTUs to operate 2 hours earlier than NAVFAC Hawaii allowed for HVAC hours. The space RH was still maintained at < 65%, which provided acceptable thermal comfort despite warm occupied temperature set points. The RH also stayed below 65% during unoccupied times, which mitigates mold issues.

For all Guam buildings and refrigerated Hawaii buildings such as commissaries, the space RH sensor should be installed to enable a separate dehumidification control sequence when the RH exceeds 65% during either occupied or unoccupied hours. The ARC system should then respond to a dehumidification call enabling both cooling stages plus reheat (hot gas or electric) if available. The humidity sensor series should have a NIST-traceable accuracy of ± 3% RH of 40%–80%.

The RH should never be inferred from an RA humidity sensor, as NREL found these to be influenced by ambient conditions if the ductwork was leaky or entrainment from the SA due to poorly designed air distribution systems.

CO2 Sensor Accuracy and Drift Concerns

If the AHJ will accept the use of CO_2 sensors for determining occupancy-based ventilation rates, there are certain installation and control provisions that can help ensure that the DCV operation maintains proper ventilation. The CO_2 sensor can be factory calibrated and come with a certificate of calibration that is NIST traceable. This will cost an extra $50-100 per sensor but worth ensuring that the sensor being sent from the factory meets their specifications. Then during the commissioning process, the CO_2 sensor in the space or RA duct should be spot checked against a calibrated hand-held CO_2 sensor measuring the space CO_2 concentration. NAVFAC can then be assured that the CO_2 sensor whether in the space or RA duct is within a certain accuracy of the actual space CO_2 concentration. Finally, the AHJ can stipulate a more conservative CO_2 ppm concentration to initiate a call for additional ventilation. Typically, 1,000 ppm is used as the concentration limit. The AHJ may want to specify 700 ppm as the concentration limit. Over the lifetime of the ARC system, the CO_2 sensor should be spot checked by a calibrated hand-held CO_2 sensor to maintain accuracy. The frequency should be based on the CO2 sensor manufacturer's recommendations, which ranges from 5 to 15 years. Sometimes the expected life of the RTU will be shorter than the next time the CO2 sensor will need to be checked. In this case, the CO2 sensor can be expected to maintain sufficient ventilation over the life of the ARC technology.

Equalizing Duty Cycle across Multiple Rooftop Units Serving a Single Space

The monitored data for the BXtra showed that Unit 01 under ESM and non-ESM operation provided most of the cooling. NAVFAC or the ARC retrofit installer (or both) should evaluate the monitored data and determine if the operational sequence and/or temperature sensor locations need to change to balance the duty cycle across the RTUs serving the same space. Having one RTU operate significantly longer than the other RTUs will cause O&M issues for that unit.

Post-Construction Meeting, Including NAVFAC HVAC Technician Training

As a part of NAVFAC construction procedures, the ARC retrofit contractor must have a preconstruction meeting with the appropriate NAVFAC construction manager and engineering technician. NREL recommends that a post-construction meeting occur at some specified time, at least 1 month after the ARC installation and TAB are completed. NAVFAC and the ARC installer can review the performance data and ensure that expectations for RTU operational hours and space conditions are being met. This meeting can close the loop on several items, including whether proper space RH is being achieved, RTU duty cycles are balanced (if multiple RTUs serve the same space), ventilation rates are sufficient (satisfy occupant and CO_2 concentrations), and the space temperature sensor is in the correct location. During this meeting, the ARC installer should provide training about Web-based BMS access and on-site troubleshooting to the applicable NAVFAC HVAC service technicians.

Appendix K: Demonstration Economic Analysis and Cost Details

Cost Information

As referenced in Section 5, cost reductions were assumed for the economic analysis of follow-on deployments of the CATALYST technology relative to demonstration actuals. Specific reductions and rationale follow:

- **Local distributor versus technology provider installation.** For the demonstration, the ARC systems were installed by the technology provider. For non-demonstration acquisition, ARC systems would likely be provided and installed through a local distributor, significantly reducing travel and installation costs.
- **Overprescribed commissioning.** Post-demonstration review of the TAB specifications used for the demonstration indicate they were likely overprescribed and presented a set of requirements and procedures that are not necessary in general acquisition and deployment of this technology. Estimated costs for commissioning follow-on installations were reduced based on engineering judgment. See Appendix J for recommendations regarding the follow-on TAB scope.

eROI Analysis Information

Table K-1 provides a summary of key information regarding the eROI analyses developed for this project.

Table K-1. Key Information Regarding eROI Analyses Performed for This Report

eROI Analyses: Key Information			
Input Type	DD1391 Estimate	Demo Actuals	Follow-On Estimate
Date of Analysis	August 21, 2012	Dec. 14, 2013	Dec. 14, 2013
eROI Version	v.2.914	v2.9.16B	v2.9.16B
Project Overview Tab			
Project Category	Facility En. Impr.	Facility En. Impr.	Facility En. Impr.
Regional Priority Project	No	No	No
Max. Financial Benefits Tab			
Salvage Value	$4,000	$0	$0
Provide Reliable Energy Tab			
MDI Critical Facilities	0	0	0
Regulatory & SH Expect. Tab			
Regulatory Compliance	3	2	2
Public Perception	0	0	0
Quality of Service, Goals	1	1	1
Quality of Service, # People	3	3	4
Develop. Enabling Infrast. Tab			
Question 1, Data Improvement	2	2	2
Question 2, Flex. Energy Inf.	2	1	1
Question 3a, Energy Indep.	2	2	2
Question 3b, % of Installations	25%	25%	25%
Project Risk Tab			
1. Timeline and Cost	± 10%	± 10%	± 25%
2. Energy Reduction	± 25%	± 10%	± 10%
3. a Facility Energy Reliance	± 10%	± 10%	± 10%
3.b Facility Outages	± 10%	± 10%	± 10%
3.c Backup Power	± 10%	± 10%	± 10%
4. Regulatory & Stakeholders	± 10%	± 10%	± 10%
5. Enabling Infrastructure	± 10%	± 10%	± 10%
6. Aggregate Benefits	± 25%	± 10%	± 10%
Impact of Deferring Tab			
Impact of Deferring 1 Year	100% Loss	0% Loss	0% Loss

Building Life Cycle Cost Analysis Information

Table K-2 provides a summary of key information regarding the BLCC analyses developed for this project.

Table K-2. Key Information Regarding BLCC Analyses Performed for This Report

BLCC Analyses: Key Information	
Input Type	**Value**
Report Type:	MilCon
BLCC Version:	5.3
Location:	Hawaii
Discounting Convention:	Mid-Year
Analysis Type:	Constant dollars
Base Date:	October 1, 2013
Beneficial Occupancy:	October 1, 2013
Length of Study:	10 years
Energy Usage Index:	100% throughout economic life
Investment Cost, Cost-Phasing:	0%
Major Repair and Replacement Costs:	
At 7.5 years	$14,000
Energy Escalation Factor:[a]	0%
Real Discount Rate:	3.0%

[a] DOE and state-specific escalation rates were not used because of recent pricing variability.