RM12-2798 High-Efficiency Rooftop Unit Replacement

Hawaii and Guam Energy Improvement Technology Demonstration Project

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NREL Technical Monitor: Steve Gorin

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List of Abbreviations and Acronyms

AFDD	automated fault detection and diagnostics
AHJ	authority having jurisdiction
AHRI	Air-Conditioning, Heating, & Refrigeration Institute
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Btuh	British thermal units per hour
cfm	cubic feet per minute
CO_2	carbon dioxide
COP	coefficient of performance
CVRMSE	coefficient of variation of the root mean squared error
DAT	discharge air temperature
DCV	demand-controlled ventilation
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DX	direct expansion
ECM	electronically commutated motor
EER	energy efficiency ratio
FEMP	Federal Energy Management Program
ft^2	square feet
fpm	flow per minute
HVAC	heating, ventilation, and air conditioning
IEER	integrated energy efficiency ratio
JBPHH	Joint Base Pearl Harbor-Hickam
kW	kilowatt

kWh	kilowatt-hour
MWh	megawatt-hours
NAVFAC	Naval Facilities Engineering Command
NEMA	National Electrical Manufacturers Association
NREL	National Renewable Energy Laboratory
OA	outdoor air
O&M	operation and maintenance
PAC	Pacific (NAVFAC PAC)
PI	proportional-integral
RH	relative humidity
ROI	return on investment
RTU	packaged air conditioning rooftop unit
SEER	seasonal energy efficiency ratio
SHGC	solar heat gain coefficient
SZVAV	single-zone variable-air volume
TAB	(HVAC) testing, adjusting, and balancing
TMY3	typical meteorological year 3
TWT	Transformative Wave Technologies
UFC	Unified Facilities Criteria
UFGS	Unified Facilities Guide Specifications
W	Watt
WC	water column

Executive Summary

As part of its overall strategy to meet its energy goals, NAVFAC partnered with 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 benefits 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 hangars, 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). Most RTUs are located on a roof but can also be located on concrete pads next to the building they serve. In Hawaii, RTUs provide only space cooling and outdoor air (OA) for ventilation, as no heating is needed. RTUs are popular for three reasons: (1) minimal engineering design and specifications; (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.

DOE issued the High-Performance Rooftop Unit Challenge in January 2011 to:[1]

> catalyze the market introduction of cost-effective, energy-saving RTUs that would significantly outperform any models that were currently available. RTUs built according to this specification are expected to reduce energy use by as much as 50% compared to the current ASHRAE 90.1 Standard, depending on location and facility type.

In May 2012,[2] the Daikin Applied Rebel[3] was the first commercially available RTU to meet the DOE RTU challenge specification. The Rebel met the comprehensive RTU challenge requirements with: an integrated energy efficiency ratio (IEER) exceeding18.0, a variable-speed supply fan, direct digital controls, and automated fault detection and diagnostics (AFDD). This field demonstration evaluated the energy savings and thermal comfort benefits of the Rebel compared to a code-minimum RTU. The baseline RTU met the ASHRAE 90.1-2010 minimum performance requirements per the United Facilities Guide Specification (UFGS) 23 81 00 00 20. Both the Rebel and baseline RTUs served a small office located on JBPHH.

The field demonstration was designed to provide a true apples-to-apples comparison between the Rebel RTU and baseline RTU. Based on an extensive investigation of existing RTUs at JBPHH, NAVFAC and NREL chose to replace two 10-ton, 15-year-old RTUs serving a 5,000-ft^2 office.

[1] "DOE Facilitates Market-Driven Solutions to Develop and Deploy New High-Efficiency Commercial Air Conditioners." U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, February 3, 2011.
[2] "Energy Department Announces First Product to Meet the Commercial Rooftop Air Conditioner Challenge." U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, May 24, 2012.
[3] "Rebel Overview." Daikin Applied, 2014. http://www.daikinapplied.com/rooftop-rebel.php.

The RTU serving the southern half of the space was replaced with a Rebel; the RTU serving the northern half of the space with the baseline. Table ES-1 compares their rated performances and highlights the high-efficiency components of the Rebel.

Table ES-1. Daikin Applied Rebel and Baseline RTU Rated Performance

	Baseline RTU[1]	Daikin Applied Rebel Model DPS010A
Energy Efficiency Ratio (EER)[2]/IEER[3]	11.3/11.8	12.5/19.4
Net Rated Cooling	10 tons	10 tons
Supply Fan	Constant-speed/belt-driven/ National Electrical Manufacturers Association (NEMA) standard efficiency motor	Variable-speed/direct drive/electronically commutated motor (ECM)
Compressors	2 constant speed scrolls on 2 separate direct expansion (DX) circuits	1 variable-speed scroll and 1 constant-speed scroll on a single DX circuit
OA Damper	Fixed parallel blade; No edge/jamb seals	Actuator/linkage-driven opposing blade damper; Low-leakage damper with edge/jamb seals
Cabinet Casing	Single-wall with no insulation	Double-wall with foam insulation

Notes: (1) Per UFGS-23 81 00.00 20, the baseline is a code-minimum RTU meeting ASHRAE Standard 90.1-2010 prescriptive performance requirements of 11.2 EER and 11.4 IEER based on Table 6.8.1A for air conditioners ≥65,000 British thermal units per hour (Btuh) (5.4 tons) and <135,000 Btuh (11.3 tons). The baseline RTU has basic thermostatic control – fan (G), cooling stage 1 (Y1), cooling stage 2 (Y2). (2) EER rated conditions are at an ambient dry-bulb of 95°F and a mixed-air dry-bulb of 80°F and wet-bulb of 67°F per the Air-Conditioning, Heating, & Refrigeration Institute (AHRI) Standard 340/360-2007. (3) IEER rating incorporates the part load performance of an RTU per AHRI Standard 340/360-2007.

NREL stipulated a true apples-to-apples RTU comparison must meet two requirements: (1) both RTUs provide the same amount of cooling to achieve the same duty cycle and (2) both RTUs maintain their respective temperature sensors to ±1°F of a 76°F set point. While operating the RTUs simultaneously during the first month of the demonstration period (October 2013), the monitored data clearly showed that the first parameter was not achievable. Even though the RTUs were conditioning different sides of an open office space, the Rebel RTU was providing more than 70% of the cooling and, consequently, was consuming more energy.

The Rebel provided more cooling because of its single-zone variable-air volume (SZVAV) control logic. The Rebel ramps the supply fan from 40%–100% based on the space temperature versus set point error. The Rebel then modulates the compressors to maintain a user-specified discharge air temperature (DAT). The Rebel would essentially stay on for most of the occupied hours, nimbly adjusting its compressor capacity to maintain more gradual temperature changes within its ±1°F deadband. In contrast, the baseline maintained a constant supply airflow and could only control its cooling to either 50% (first stage) or 100% (second stage) capacity.

Therefore, NREL shifted tactics. For the remainder of the demonstration period, from November 2013 through January 2014, NREL alternated baseline and Rebel operation weekly. The demonstration data were then used to develop calibrated models of both RTUs. The baseline model was calibrated against 36 days of baseline-only operation. The Rebel model was calibrated against 35 days of Rebel-only operation. Oahu's weather year-round is consistent such that this limited dataset was sufficient to capture the performance of both RTUs across the year.

Each calibrated model was then simulated across an entire year using Honolulu typical meteorological year (TMY3) weather data. The baseline model was simulated as if two baseline RTUs were conditioning the entire office space. Similarly, the Rebel model was simulated with the entire office space being conditioned by two Rebel RTUs. Both baseline and Rebel models incorporated identical building envelope, infiltration, and internal loads.

The Rebel RTU model provided ventilation that met ASHRAE 62.1-2010 requirements according to its testing, adjusting, and balancing (TAB) report. The demand-controlled ventilation (DCV) capability of the Rebel was not modeled because it is not common on NAVFAC facilities. The Unified Field Criteria (UFC) 3-410-01stipulates DCV must receive approval from the authority having jurisdiction (AHJ) because of NAVFAC's concern about the carbon dioxide sensors maintaining calibration over time.

The baseline RTU was found to have an extremely leaky OA damper based on its TAB report. Even a fixed 5% OA damper position resulted in a ventilation rate over three times the ASHRAE 62.1-2010 minimum requirement. NREL found typical RTU OA dampers ranging from 5%–20% fixed positions based on site visits to more than 30 RTUs throughout JBPHH. Therefore, NREL compared the Rebel model versus the baseline model with (1) a fixed 5% OA damper, (2) a fixed 20% OA damper, and (3) a ventilation rate exactly meeting the ASHRAE 62.1-2010 minimum requirements.

Table ES-2 compares a single 10-ton Rebel RTU to a single 10-ton baseline RTU with a fixed 5% OA damper configuration. Accounting for the power measurement and model uncertainties, the annual energy savings of 3,862 kilowatt-hours (kWh) has a ±27% uncertainty (±1,042 kWh) based on a 95% confidence interval. Compared to a 10-ton baseline RTU with a fixed 20% OA damper, the Rebel saved 4,552 kWh (37%). Compared to a 10-ton baseline RTU exactly providing ASHRAE 62.1 ventilation rates, the Rebel saved 3,034 kWh (29%).

In summary, a 10-ton Rebel RTU serving a small office at JBPHH will save 34%–37% compared to a code-minimum, baseline RTU with a typical OA damper set to a 5%–20% position. If the baseline RTU is specified with a low leakage damper at least meeting leakage class 2 per Air Movement and Control Association Standard 511, the Rebel saves 29% for a small office at JBPHH. These savings are based on operating the RTUs only during NAVFAC Pacific approved HVAC times (see footnote [a] in Table ES-2).

Table ES-2. Model Energy Usage of One 10-Ton Rebel Versus One 10-Ton Baseline Serving an Office Space in JBPHH

	Baseline RTU 10-Ton Fixed 5% OA Damper[a]	Rebel RTU 10-Ton[a,b]	Savings
Supply Fan	2,607 kWh	1,268 kWh	1,339 kWh (51%)
Compressors & Condenser Fan(s)	8,855 kWh	6,332 kWh	2,523 kWh (28%)
Total RTU	11,462 kWh	7,600 kWh	3,862 kWh[c] (34%)

[a] Models controlled the baseline and Rebel RTUs to operate only during NAVFAC Pacific approved hours of 0600–1530 for summer weekdays (May 1-October 31) and 0800–1530 for winter weekdays (November 1-April 30). This yields 1,950 operational hours annually. RTUs are turned-off outside these hours.
[b] Rebel provided the minimum ventilation rate per ASHRAE 62.1-2010; DCV capability was not enabled.
[c] ±27% total uncertainty (±1,042 kWh) based on a 95% confidence interval

In 2018, the Rebel model was rerun with a lower fan pressure drop. When the demonstration was completed in 2014, Daikin Applied only provided a downward discharge configuration. To integrate with the existing ductwork, the installation at the small office used a roof curb to transition the airflow from downward to horizontal, resulting in an additional inch of static pressure. The Rebel now has a horizontal discharge option. Table ES-3 shows the fan savings increased to 71% over the baseline. Across the three baseline damper configurations, the energy savings ranged from 33-42%.

Table ES-3. Updated Model Energy Usage Account for the Rebel Having a Lower Pressure Drop

	Baseline RTU 10-Ton Fixed 5% OA Damper[a]	Rebel RTU 10-Ton[a,b]	Savings
Supply Fan	2,607 kWh	767 kWh	1,840 kWh (71%)
Compressors & Condenser Fan(s)	8,855 kWh	6,332 kWh	2,523 kWh (28%)
Total RTU	11,462 kWh	7,099 kWh	4,363 kWh[c] (38%)

In addition to energy savings, the Rebel improves thermal comfort compared to the baseline RTU. The variable speed fan and variable capacity cooling maintain a smoother, more constant space temperature throughout the day. The Rebel also maintains a drier space—lower relative humidity (RH) and dew point. By controlling to a constant DAT, the Rebel achieves a consistently lower discharge air dew point. The modeling results showed that during operational hours, the Rebel maintained a 53% annual average space RH compared to the 61% annual average space RH for the baseline RTU with a 5% fixed OA damper.

Based on the energy savings from Table ES-2 and the additional cost of the Rebel, NREL estimates a total discounted operational savings of $18,000 over a 15-year operational life, with a simple payback occurring in the ninth year of operation. Just using the RTU-only cost difference between the Rebel versus the baseline – excluding the Rebel's larger incremental costs for the cabinet coating, condenser coil coating, extended 5-year parts and compressor warranties, and roof curb – the same energy savings yields a simple payback in the fifth year of operation. No utility incentives are included in these paybacks.

During site inspections, NREL found most office buildings not abiding by the NAVFAC Pacific mandated operating hours. Building occupants are over-riding thermostats, enabling cooling from typically 0600 to 1800. Therefore, NREL re-calculated the 10-ton Rebel's annual energy savings to be 7,426 kWh based on weekday operation of 0600 to 1800. The baseline had a fixed 5% damper position. This yielded a simple payback in the fifth year including all incremental costs. When excluding these incremental costs, the simple payback was in the third year.

For next steps, NREL recommends NAVFAC expand the sample size of measured energy savings for high-efficiency RTUs, leveraging the DOE-sponsored field demonstrations that will be completed in spring 2015. If NAVFAC begins to invest in high-efficiency RTUs, NAVFAC service technicians should receive formal training to provide the same level of service they currently provide for typical RTUs. Local distributors of high-efficiency RTUs can provide on-site training. Some manufacturers of high-efficiency RTUs provide multiday, formalized training at their facilities. These trainings will be crucial for NAVFAC to ensure proper control of the advanced features of these high-efficiency RTUs, as well as utilizing the enhanced troubleshooting capabilities of the AFDD features.

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1 Introduction

To meet its energy goals, the Naval Facilities Engineering Command (NAVFAC) partnered with the 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 goal is to demonstrate and measure the energy savings and return on investment (ROI) of the system while monitoring any ancillary impacts to related standards of service and operation and maintenance (O&M) practices.

The standards of service may include acceptable temperature and relative humidity (RH) ranges, power quality, allowable setbacks, noise criteria, air quality parameters, light levels, and other related factors. In short, demonstrations at U.S. Department of Defense (DOD) facilities simultaneously evaluate the benefits and compatibility of the technology with the DOD mission, and with its design, construction, and O&M practices.

The consistent year-round demand for cooling and dehumidification in Hawaii and Guam provide ideal locations for realizing significant energy savings from high-efficiency heating, ventilation, and air conditioning (HVAC) systems. Many of NAVFAC's small- to medium-size facilities are conditioned by packaged roof top units (RTUs). These facilities include offices, warehouses, gymnasiums, commissaries, exchange stores, and hangars.

The term *packaged RTU* refers to a pre-engineered unitary system that houses all the components of an HVAC system. For Hawaii and Guam, RTUs need to provide cooling and ventilation only. Therefore, the DOD has a significant amount of conditioned square footage that can leverage high-efficiency RTUs to reduce energy usage while improving thermal comfort.

The performance range from code-minimum to the highest efficiency RTUs was not that significant until the past couple years. To help incentivize manufacturers to build higher performance RTUs, DOE issued the High-Performance Rooftop Unit Challenge in January 2011 to:[4]

> catalyze the market introduction of cost-effective, energy-saving RTUs that would significantly outperform any models that were currently available. RTUs built according to the specification are expected to reduce energy use by as much as 50% compared to the current ASHRAE 90.1 Standard, depending on location and facility type.

To achieve the DOE RTU Challenge status, RTUs that range from 10 to 20 tons must meet a comprehensive specification codeveloped by DOE national labs, including NREL, and private sector building owners with large building portfolios (i.e., Target, Walmart).[5] The primary specification requirements include a minimum integrated energy efficiency ratio (IEER) of 18.0,

[4] "DOE Facilitates Market-Driven Solutions to Develop and Deploy New High-Efficiency Commercial Air Conditioners." U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, February 3, 2011. http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=16696.

[5] "Install units produced by the High-Performance Rooftop Unit Challenge that meet the high-performance rooftop unit specification." U.S. Department of Energy, Office of Renewable Energy & Energy Efficiency, undated.

a variable- or multispeed supply fan, direct digital controls, and automated fault detection and diagnostics (AFDD).

In May 2012,[6] the Daikin Applied Rebel[7] was the first commercially available RTU to meet the DOE High Performance Rooftop Unit Challenge. The following field demonstration compared the performance of the Daikin Applied Rebel against a code-minimum, baseline RTU serving a small office building on NAVFAC Pacific (PAC).

[6] "Energy Department Announces First Product to Meet the Commercial Rooftop Air Conditioner Challenge." U.S. Department of Energy, Office of Renewable Energy & Energy Efficiency, May 24, 2012. http://apps1.eere.energy.gov/news/progress_alerts.cfm/news_id=20367.

[7] "Rebel Overview." Daikin Applied, 2014. www.go.Rebel.com/rebel.

2 Demonstration Objectives

The demonstration objectives were to evaluate the energy savings, ROI, and thermal comfort impact of the Daikin Applied Rebel against a code-minimum, baseline RTU.

2.1 Rooftop Unit and Rated Performance Definition

To better understand the basic function of an RTU, Figure 1 shows the components and airstreams. An RTU uses a supply fan to draw in return air from the conditioned space along with a controlled amount of outdoor air (OA) needed to ventilate the space. The mixed air is then cooled as it passes through a direct expansion (DX) evaporator coil. For the humid Hawaiian climate, the DX coil also dehumidifies by condensing moisture out of the mixed air stream. For maintaining space comfort in Hawaii and Guam, dehumidifying the air (latent cooling) is as important as sensible cooling. Sometimes, RTUs include exhaust fans that push some of the return air outside, although neither of the RTUs in this demonstration included exhaust fans.

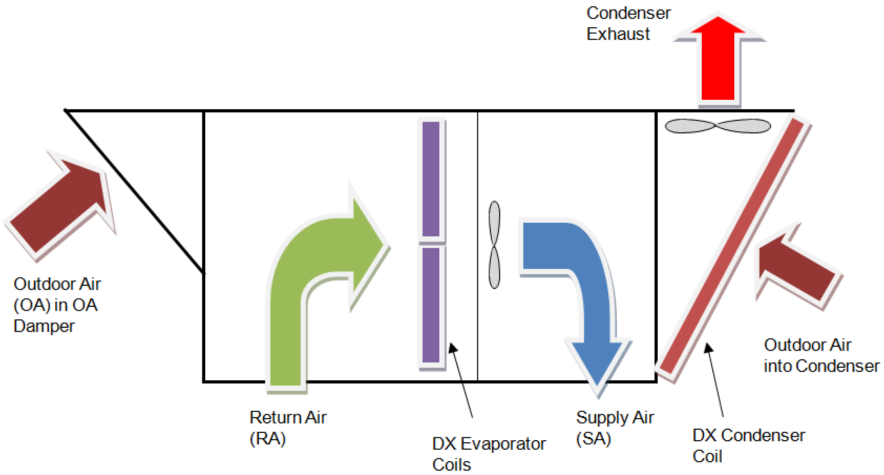


Figure 1. RTU schematic showing basic component operation

(Credit: Eric Kozubal, NREL)

The refrigerant in the evaporator coil is pumped by the compressor to the condenser coil. Here, the DX cycle rejects the heat by blowing OA across the condenser coil. RTUs with 10 tons of cooling operate with two compressors that can be “staged”, operating one or two at a time.

RTU-rated performance is based on the applicable American National Standards Institute (ANSI)/Air-Conditioning, Heating, & Refrigeration Institute (AHRI) standards. For RTUs lower than 65,000 British thermal units per hour (Btuh) (5.4 tons), ANSI/AHRI 210/240-2008 defines an energy efficiency ratio (EER) to characterize peak operational performance and a seasonal energy efficiency ratio (SEER) to represent cooling season average performance. Larger RTUs adhere to ANSI/AHRI 340/360-2007, which also uses EER to define peak performance but defines a separate IEER to represent cooling season average performance. Compared to EER, the seasonal performance ratings, SEER and IEER, provide a better indication of annual energy usage. Consequently, the DOE RTU challenge mandated a minimum 18.0 IEER rating, rather than stipulating an EER rating because annual energy savings was the goal.

2.2 High-Efficiency Rooftop Unit Technology Description

The Daikin Applied Rebel exceeds the 18.0 IEER by packaging multiple advanced technologies and control capabilities. These include a variable-speed direct-drive supply fan, variable-speed condenser fans, and a variable-speed first-stage compressor (second-stage compressor is constant speed). A sophisticated programmable logic controller (PLC) controls all the components and includes AFDD along with open protocol communication (BACnet IP, BACnet MSTP, and LonMark).

As Hawaii does not need heating, the Rebel unit demonstrated did not have gas heating. Yet, because of an ordering mix-up, the Rebel delivered was a heat pump RTU. The heat pump operational mode was never utilized during the demonstration. The marketing schematic developed by Daikin Applied, shown in Figure 2, highlights these advanced components and control features of the Rebel.

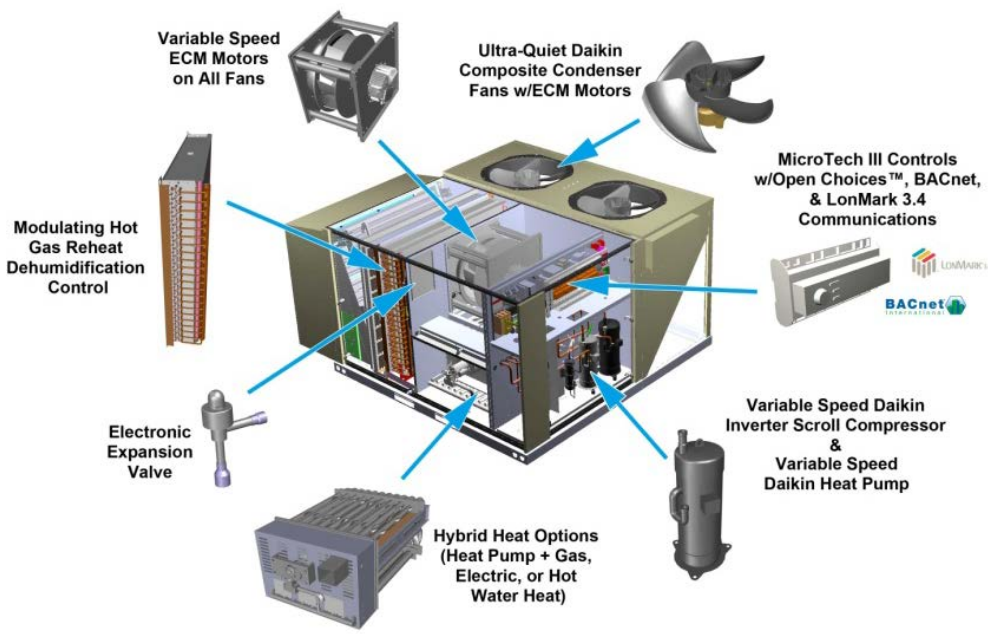


Figure 2. Technologies incorporated into the Daikin Applied Rebel RTU

Source: Daikin Applied

The Daikin Applied Rebel achieves improved energy and thermal comfort performance over a code-minimum, baseline RTU by incorporating the following technologies:

Direct-drive, variable-speed supply fan. RTUs are typically configured with a constant-speed supply fan that moves more air than necessary for most of the year. These constant flow rates are sized to meet the worst-case design condition. These worst-case design conditions typically represent fewer than 100 hours of the year. The Rebel uses a variable-speed electronically commutated motor (ECM) to directly drive the supply fan, eliminating the need for a fan belt. The Rebel supply fan can be controlled in three ways:

- Duct static pressure control for standard variable air volume (VAV) applications,
- Constant air volume (CAV) and
- Single-zone variable-air volume (SZVAV).

NREL configured the Rebel for SZVAV control, which changes the fan speed based on the space temperature relative to the temperature set point. See Appendix C for a detailed summary of the supply fan proportional-integral [PI] control sequence. Consequently, the supply fan will move only enough air as necessary, based on the space demands.

Variable refrigerant flow. Daikin Applied packaged its variable-refrigerant flow technology into the Rebel's DX system. The lead compressor is an inverter-driven scroll. Rebels larger than 5 tons have a second-stage, constant-speed compressor. Both variable- and fixed-speed compressors are part of the same DX circuit. By ramping the variable-speed lead compressor, the Rebel provides the proper amount of cooling to meet the space's needs whether at part load or extreme design conditions. Comparatively, code minimum RTUs achieve cooling load control based on the number of separate compressor stages. The Rebel also leverages electronic expansion valves to achieve improved refrigerant flow control (i.e., tight superheat) compared to standard thermostatic expansion valves.

In addition to greater control of space temperature and RH, the variable-refrigerant flow technology improves the refrigeration cycle efficiency because the full-load heat transfer surface area on the evaporator and condenser coils is available for low-load conditions. The improved part-load efficiency is reflected in the 10-ton Rebel's 19.4 Btuh/W[8] IEER. For context, a 10-ton code-minimum RTU is 11.4 IEER, according to ASHRAE 90.1-2010.

Variable-speed condenser fans. The Rebel's two condenser fans are variable speed, which are controlled to maintain the refrigerant saturated condensing temperature (discharge pressure) a specified delta-T above ambient dry-bulb. For this demonstration, the condenser fan speeds were controlled to maintain a 10°F delta-T. Compared to constant-speed condenser fans, the Rebel can achieve improved refrigerant discharge pressure and subcooling control to enhance performance at part-load conditions.

Low-leakage OA damper. Standard RTU OA dampers are notoriously leaky and typically not certified under Air Movement and Control Association Standard 511. The Rebel has vinyl gasket, motorized blade dampers that maintain low leakage.

[8] Based on AHRI Certified Reference Number 5056846.

Demand-controlled ventilation (DCV). RTUs are typically configured with an OA flow rate based on the expected maximum number of occupants. Yet most spaces typically experience occupancy rates well below this number throughout most of the year. The Rebel has DCV capability in which, based on the return air carbon dioxide (CO_2) concentration, the OA damper will open beyond a set minimum OA flow rate to meet the ventilation needs of the space. However, Unified Facilities Criteria (UFC) 3-410-01 Section 401.1 (dated July 1, 2013) states "Use of CO_2 sensors for ventilation control is prohibited unless approved by AHJ" Based on this requirement, NREL did not demonstrate the Rebel enabled with DCV.

Dual enthalpy economizing. In many U.S. climates, during cooling demands, the OA temperature and RH may be low enough to use in lieu of—or in conjunction with—compressor-based cooling. The Rebel's advanced controller has the ability to leverage multiple economizer control sequences, including fixed dry-bulb, dual dry-bulb, and dual enthalpy. However, Hawaii has such a humid climate that none of the economizing features of the Rebel were initiated for the demonstration.

2.3 Summary of Performance Objectives

NREL developed a list of performance objectives to evaluate the Daikin Applied against the baseline RTU. Table 1 defines each performance objective, the data required, and how success was defined.

Table 1. Performance Objectives Defining How the Daikin Applied Rebel RTU Was Compared Against the Code-Minimum, Baseline RTU

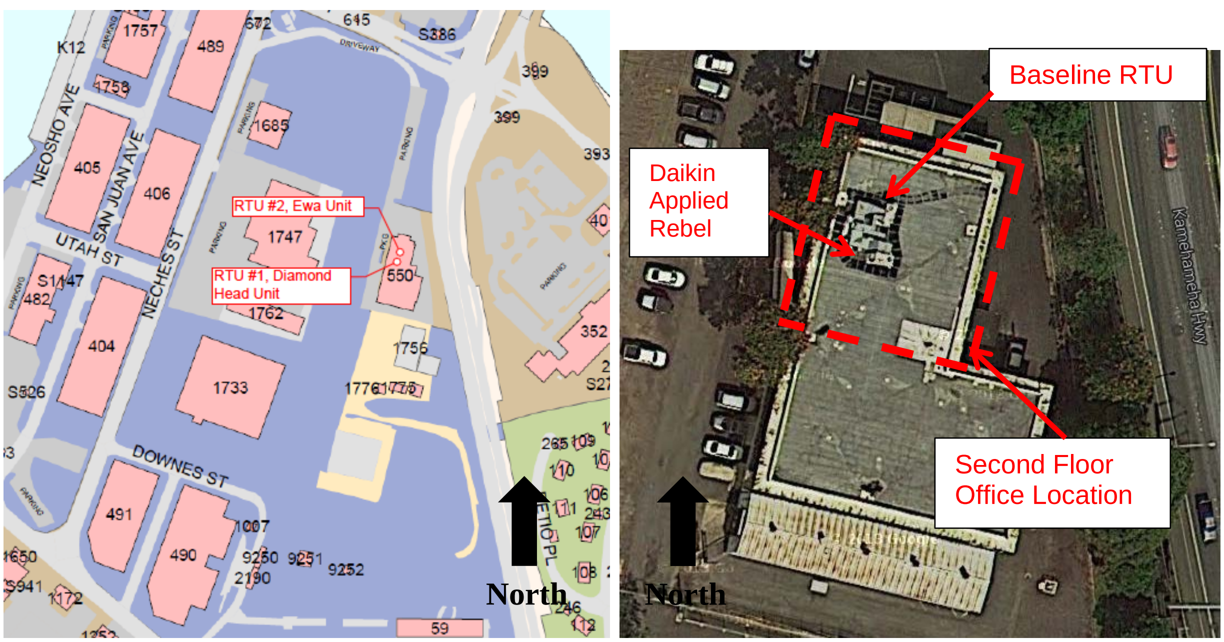
Performance Objective	Metric	Data Requirements	Success Criteria
1. Annual energy savings	Annual kilowatt-hour savings	Calibrated energy models of the baseline and Rebel RTUs, based on measured performance data	Rebel reduces energy usage by at least 30% compared to the Baseline RTU
2. Interior thermal comfort improvement	Space temperature and RH during occupied hours	Measurements of space temperature and RH; calibrated energy models of the baseline and Rebel RTUs, based on measured performance data	Rebel maintains a narrower temperature band and lower annual average RH by at least 5%
3. Proper ventilation rates and reduced OA damper leakage	Leakage flow rates while OA damper is closed; Proper ventilation flow rates maintained during occupied hours per ASHRAE Standard 62.1-2010	Testing, adjusting, and balancing (TAB) OA flow rates measured at different OA damper positions and fan speeds	Rebel reduces OA damper leakage by 30% compared to the baseline RTU; Rebel maintains proper ventilation rates during occupied hours

3 Demonstration Design

The performance benefits of the Daikin Applied Rebel were compared against a code-minimum baseline RTU that the Navy would typically purchase adhering to Unified Facilities Guide Specifications (UFGS) and UFC requirements. After evaluating potential demonstration sites across Joint Base Pearl Harbor-Hickam (JBPHH) and NAVFAC PAC, NAVFAC and NREL determined building 550 NAVFAC PAC Public Works was an ideal configuration with two identically sized RTUs serving a typical small office space. The following section summarizes building 550 characteristics and thermal loads, the baseline RTU, thermostat set point schedules, and the calibrated energy models.

3.1 Demonstration Site Description

Building 550, NAVFAC PAC Public Works, is a two-story building built in 1946, which is broken up into four separate facilities. Figure 3 shows how the Rebel and baseline RTUs serve one of these facilities, a 4,976-ft^2 office space on the second floor. Figure 3 shows the location of building 550 inside NAVFAC PAC and details the location of the second-floor office space on the northern side of the building. Based on NAVFAC's property record (iNFAD) report, building 550 has a total of 26,313 ft^2. Therefore, the second-floor office space comprises 19% of the total floor area. Figure 4 shows the roof of building 550 with the two 17-year-old (built in 1996) 10-ton Trane RTUs that were replaced. Figure 5 shows the Daikin Applied Rebel and baseline RTU on the roof of building 550.



(a) (b)

Figure 3. (a) Location of building 550 in NAVFAC PAC (Rebel = RTU #1; Baseline = RTU #2) (b) Google map satellite image of building 550

Source: (a) JBPHH Building Site Map provide by NAVFAC (b) Google Earth

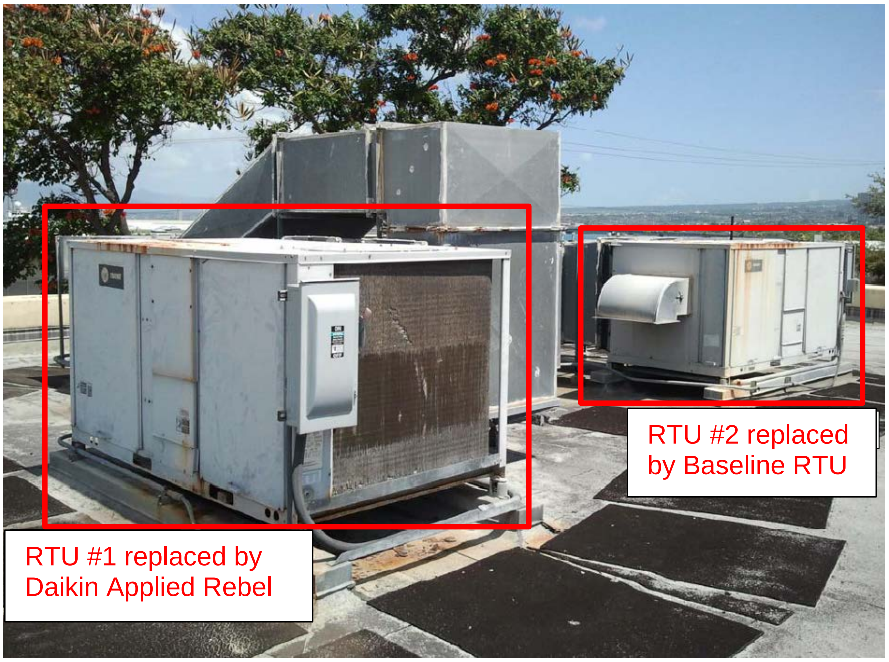


Figure 4. Roof of building 550 showing the existing two Trane TCH120 RTUs

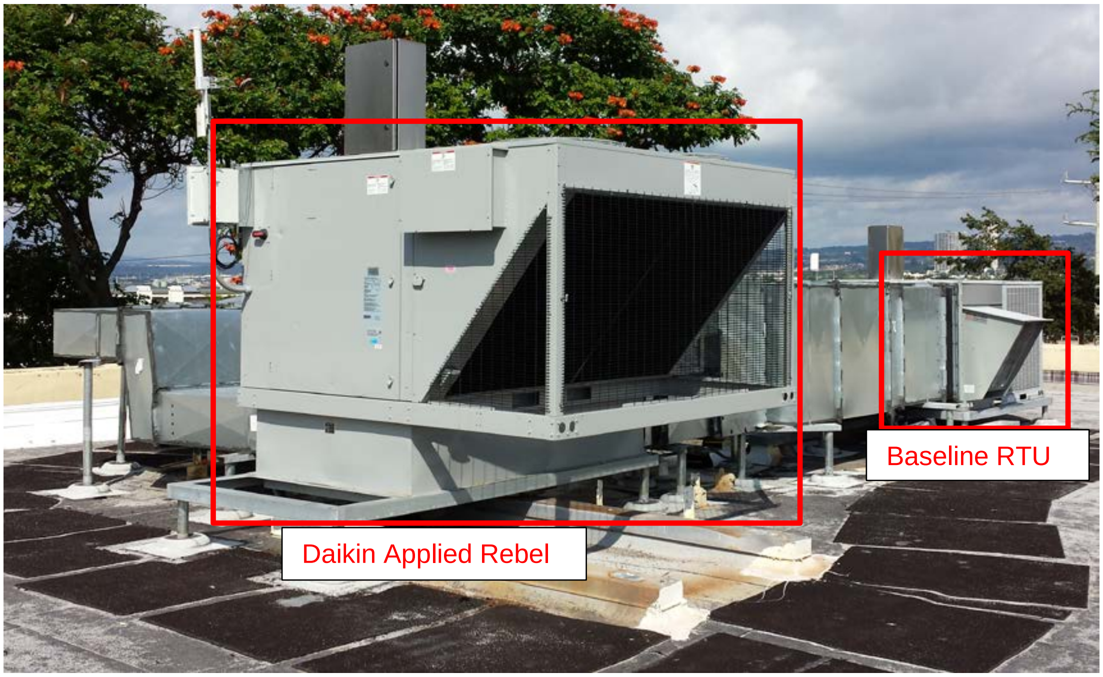


Figure 5. Roof of building 550, which shows the Daikin Applied Rebel and baseline RTU

3.2 Baseline Rooftop Unit Description

The Daikin Applied Rebel was compared against a baseline code-minimum RTU meeting UFC 3-410-01[9] Heating, Ventilating, and Air Conditioning Systems (dated July 1, 2013) and UFGS-23 81 00.00 20[10] Unitary Air Conditioning Equipment. Per Part 2 of UFGS 23 81 00.00 20 (shown in Figure 6), RTUs must exceed the minimum performance requirements of ASHRAE Standard 90.1-2010, ENERGY STAR®, and the Federal Energy Management Program (FEMP). Therefore, these three references were evaluated to confirm the baseline RTU met the most stringent requirements.

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PART 2   PRODUCTS

**************************************************************************
            NOTE:  Equipment having a higher efficiency than
            required by ASHRAE 90.1 - SI ASHRAE 90.1 - IP or CID
            A-A-50502 shall be specified if shown to be
            life-cycle cost effective.  Minimum efficiencies
            shall be according to Energy Star (
            http://www.energystar.gov/index.cfm?fuseaction=find_a_product.
            ) and FEMP
            (https://www1.eere.energy.gov/informationcenter/)
            recommendations.  The Energy Policy Act of 2005
            requires new buildings to use 30 percent less energy
            than the ASHRAE 90.1 - SI ASHRAE 90.1 - IP level.
            Efficient cooling equipment and components
            contribute to the following LEED credits: EA
            Prerequisite 2; EA1.
**************************************************************************
```

Figure 6. Unitary air-conditioning equipment (RTUs) efficiency requirements per UFGS 23 81 00.00 20, last edited November 2009

3.2.1 ENERGY STAR/Federal Energy Management Program Rooftop Unit Performance Requirements

FEMP requirements[11] state "Federal purchases of light commercial heating and cooling equipment must be ENERGY STAR qualified." The ENERGY STAR website reveals RTUs lower than 65,000 Btuh (approximately 5 tons) must meet a minimum 11.0 EER and 14.5 SEER.[12] Because this demonstration was for a 10-ton RTU, the FEMP/ENERGY STAR requirements did not apply.

3.2.2 ASHRAE 90.1-2010 Rooftop Unit Performance Requirements

Based on ASHRAE Standard 90.1-2010, Table 6.8.1A stipulates for nominal tonnages ≥ 65,000 Btuh and < 135,000 Btuh, RTUs must exceed 11.2 EER and 11.4 IEER. Consequently, NREL specified a baseline RTU that just exceeds the ASHRAE Standard 90.1-2010 requirements to represent the baseline, code-minimum RTU (Table 2). Beyond the EER and IEER performance requirements, the baseline represents a typical RTU installed today at JBPHH with a constant-

[9] National Institute of Building Sciences, Whole Building Design Guide, Unified Facilities Criteria 3-410-01: www.wbdg.org/ccb/browse_cat.php?c=4.

[10] National Institute of Building Sciences, Whole Building Design Guide, Unified Facilities Guide Specifications 23 81 00.00 20: www.wbdg.org/ccb/browse_cat.php?c=3.

[11] "Covered Product Category: Light Commercial Heating and Cooling." U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, April 24, 2014. http://energy.gov/eere/femp/covered-product-category-light-commercial-heating-and-cooling.

[12] "Air-Source Heat Pumps and Central Air Conditioners Key Product Criteria." ENERGY STAR, April 24, 2014. www.energystar.gov/index.cfm?c=airsrc_heat.pr_crit_as_heat_pumps.

speed fan and standard thermostatic control. Although the OA damper can modulate, for this demonstration it was controlled to be fixed at a specified position.

Table 2. Performance and Component Comparison Between the Baseline RTU and the Daikin Applied Rebel

	Baseline RTU 1	**Daikin Applied Rebel Model DPS010A**
EER 2 (note ASHRAE 90.1-2010 = 11.2 EER)	11.3	12.5
IEER 3 (note ASHRAE 90.1-2010 = 11.4 IEER)	11.8	19.4
Gross Cooling Capacity at EER-rated conditions [Btuh]	124,700 Btuh	122,000 Btuh
Gross Cooling Capacity at EER-rated conditions (tons)	10.4 tons	10.2 tons
Supply Fan	Constant speed/belt driven/National Electrical Manufacturers Association (NEMA) standard efficiency motor	Variable-speed/direct-drive/ECM
Refrigeration Circuit(s)	Two DX circuits with thermostatic expansion valves/constant speed scroll compressors	Single DX circuit served by one variable-speed scroll compressor and one constant speed scroll compressor with electronic expansion valves
Condenser Fan(s)	Two fans at constant speed with NEMA standard efficiency motors	Two fans at variable speed
OA Damper	Gear-driven parallel blade damper with direct coupled actuator No edge or jamb seals: ASHRAE 90.1-2010 code-min leakage Not certified to Air Movement and Control Association Standard 511	Actuator/linkage-driven opposing blade damper Low-leakage damper with edge and jamb seals
Humidity Control	Hot gas reheat coil	Modulating hot gas reheat coil
Cabinet Casing	Single-wall with no insulation	Double-wall with foam insulation

Notes: (1) Per UFGS-23 81 00.00 20, the baseline is a code-minimum RTU meeting ASHRAE Standard 90.1-2010 prescriptive performance requirements of 11.2 EER and 11.4 IEER, based on Table 6.8.1A for air conditioners ≥ 65,000 Btuh (5.4 tons) and < 135,000 Btuh (11.3 tons). RTU has a constant-speed supply fan, fixed outdoor-air damper, and basic thermostatic control. (2) EER-rated conditions are at an ambient dry-bulb of 95°F and a mixed air dry-bulb of 80°F/wet-bulb of 67°F per AHRI Standard 340/360-2007. (3) IEER rating represents the part-load performance of an RTU per AHRI Standard 340/360-2007.

3.3 Monitoring Plan

A Web-based building management system called the eIQ[13] was installed on site and enabled cellular control and monitoring of both RTUs. The baseline RTU was fitted with an advanced RTU control system called the CATALYST.[14] The CATALYST changes the supply fan to variable speed, controls the OA damper, and sequences the compressors. Through the eIQ, the CATALYST system was controlled remotely based on the defined baseline operation. The CATALYST also provided RTU operation and airside and power monitoring points, which are summarized in Table F-1 in Appendix F. Through BACnet, the eIQ also controlled the Rebel and monitored its internal points, which are summarized in Table F-2 in Appendix F. Figure 7 provides the power and airside measurements for both RTUs.

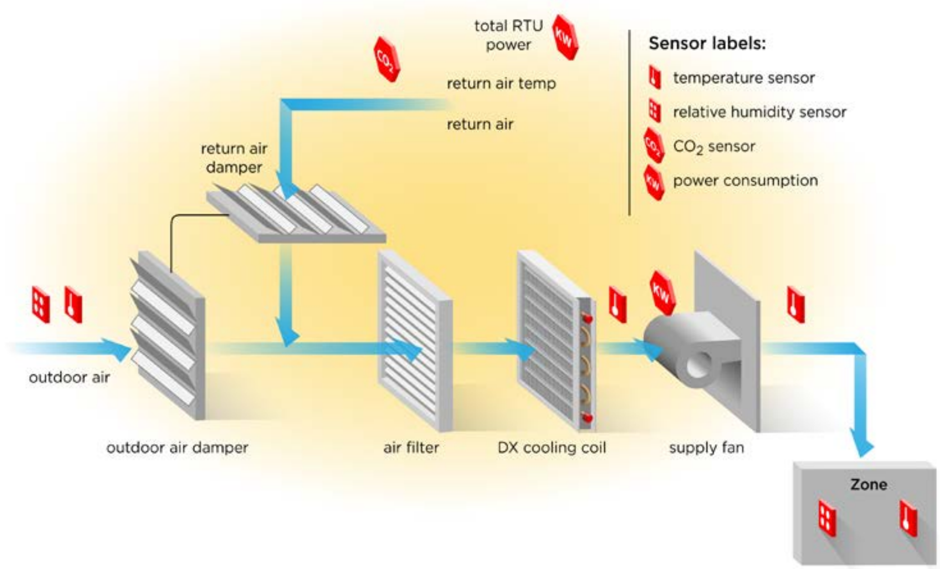


Figure 7. Airside monitoring

Credit: Al Hicks, NREL

Beyond the airside and total power monitoring, NREL monitored the refrigerant side in detail to implement a methodology that would calculate total DX cooling capacity and coefficient of performance (COP) in real time. Figure 8 and equations 1–3 provide a summary of the methodology for a simple DX circuit. By measuring the refrigerant temperature and pressure at points 1, 2, and 3 on the DX circuit and assuming the compressor jacket heat loss, the DX COP can be calculated in real time. Then, by measuring the compressor power, the real time cooling capacity can be calculated. When the DX circuit has achieved steady state, typically 2 minutes after the compressor starts, the ClimaCheck methodology provides performance accuracy to ±5%

[13] "eIQ Platform." Transformative Wave Technologies, undated. https://transformativewave.com/technology-solutions/eiq-platform.
[14] "Catalyst." Transformative Wave Technologies, 2013. https://transformativewave.com/technology-solutions/catalyst.

and capacity accuracy to ±7%.[15] Appendix A summarizes the ClimaCheck methodology in more detail.

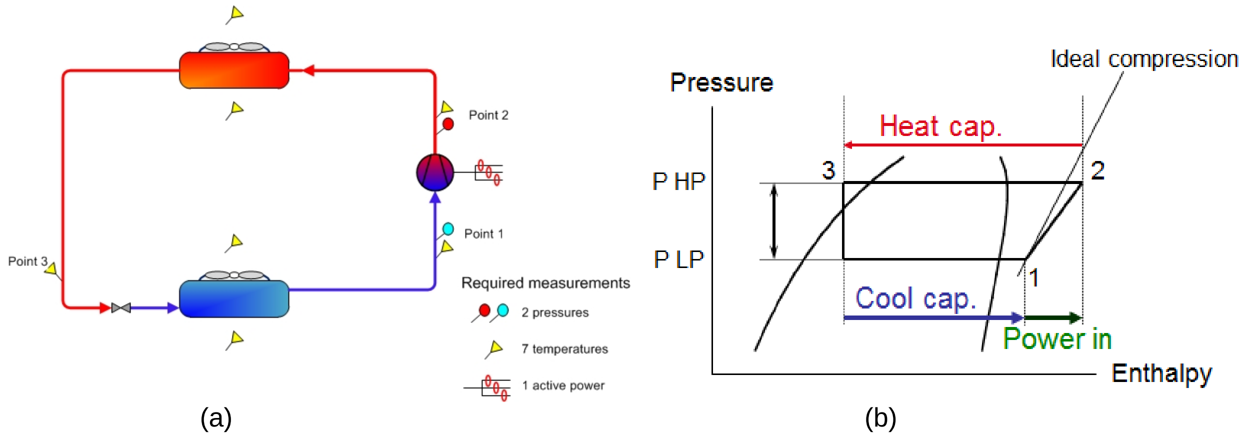


Figure 8. ClimaCheck methodology to measure temperatures, pressure, and power of the DX circuit to calculate real-time cooling capacity and COP

$$\boldsymbol{COPcool = \frac{h_1 - h_3}{h_2 - h_1} * (1 - comp\_heat\_loss)} \quad (1)$$

$$\boldsymbol{Refrigerant\ Massflow = \frac{comp\_power * (1 - comp\_heat\_loss)}{h1 - h2}} \quad (2)$$

$$\boldsymbol{Real\,Time\ Cooling\ Capacity = COPcool * comp\_power} \quad (3)$$

where
h1 is the superheated refrigerant enthalpy entering the compressor
h2 is the superheated refrigerant enthalpy leaving the compressor
h3 is the subcooled refrigerant enthalpy entering the thermostatic expansion valve
comp_power is the power of the DX compressor
comp_heat_loss is the percentage of the compressor power loss to the ambient environment (power not delivered to the refrigerant).

[15] Berglof, K. *Performance Inspections with Innovative Analyzing Equipment Results in Significant Energy Savings in Air-Conditioning and Refrigeration Systems.* Accessed January 10, 2013: www.eeswest.com/wp-content/themes/xero/pdf/pr-berglof-performance-inspections-iir-prag-2011(v2).pdf.

3.4 Maintaining Internal Sensible and Latent Loads

Soon after both RTUs were installed, building 550's occupants in the second-floor office space were moved to another office location. Fortunately, NREL had monitored the space temperature, space RH, and power consumption of the original Trane TCH120 RTUs from December 2012 through May 2013 prior to installing the new RTUs. Based on these monitored data and on interviews with the original occupants of the second-floor space, NREL installed heat lamps and humidifiers on timers to represent typical office space sensible and latent internal loads. NAVFAC personnel were also scheduled to turn on/off the overhead lights. Table 3 provides a summary of the artificial loads. Appendix E reviews the sensible and latent loads maintained in the space during the demonstration period in more detail.

Table 3. Artificial Internal Sensible and Latent Loads Established to Represent a Typical Office Space

	Load and Schedule	Schedule/Notes
Overhead Lights	1 W/ft^2	NAVFAC personnel would turn lights on at 0700 and off at 1700
Occupancy	34 occ [146 ft^2/occ] Sensible = 8,500 Btuh (250 Btuh/occ) Latent = 4.2 gal/day (200 Btuh/occ)	Timers would control to 0700–1700 Sensible represented by heat lamps Latent represented by humidifiers
Plug Loads	0.4 W/ft^2	Timers would control to 0700–1700 Sensible represented by heat lamps Office plug loads are not a latent load

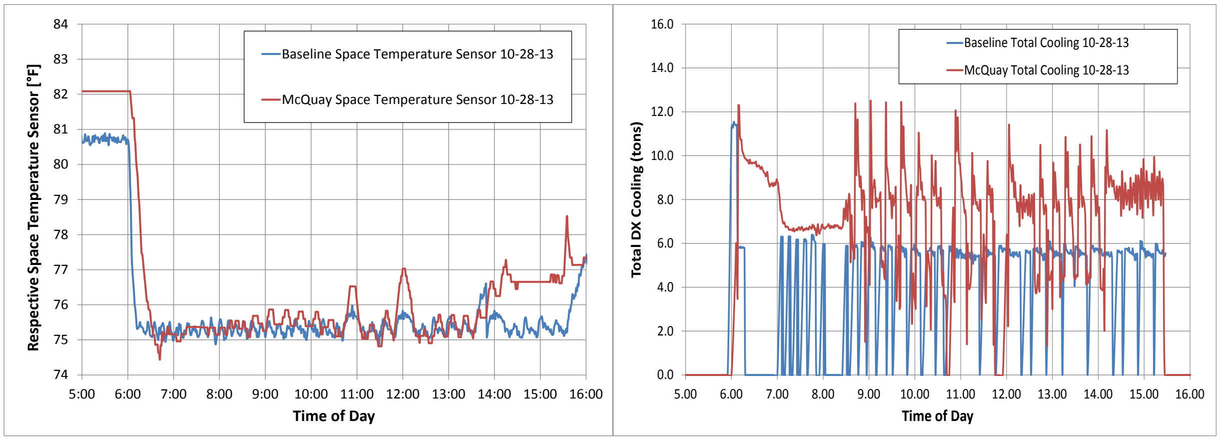
4 Technical Performance Analysis and Assessment

The demonstration was initiated as planned, with simultaneous operation of the baseline and Rebel RTUs cooling to the same 76°F set point. However, the monitored data clearly showed the Rebel and baseline RTUs interact with the space very differently. The Rebel's set point deadbands and control logic differ from the baseline in a way that caused the Rebel to provide more than 70% of the cooling and, consequently, use more energy.

The Rebel has a 2°F (±1°F) control deadband *about* the set point. The baseline's control deadband was +0.5° to +1°F *above* the set point for first stage and +1° to +1.5°F *above* the set point for second stage. Therefore, given the same temperature set point of 76°F, the Rebel would maintain a slightly cooler temperature range of 75°–77°F compared to the baseline range of 76.5°–77.5°F.

In the hope of balancing out the loading, NREL compensated for the deadband control difference by setting the baseline RTU set point to 74.5°F, while the Rebel continued to control to a 76°F set point. Figure 9(a) shows how offsetting the baseline set point resulted in both RTUs maintaining their respective sections of the office space within ±1°F. These set points are recommended for use after the demonstration period.

However, the Rebel RTU still provided most of the cooling because its control logic maintains the compressor on for almost the entire cooling period shown in Figure 9(b). Comparatively, the baseline cycles its compressors. Table 4 provides a daily summary between the RTUs. While the Rebel maintained a higher daily average EER, it provided more than twice the cooling and consumed significantly more energy than the baseline unit. This is fine for long-term conditioning of the space, but it did not meet the needs of the demonstration, as NREL needed the RTUs evenly loaded to provide a true comparison.



(a) (b)

Figure 9. Rebel and baseline RTU simultaneous operation on October 28, 2013: (a) space temperature measured by each RTU's temperature sensor (b) total DX cooling by each RTU

Table 4. Performance Comparison Between Baseline and Rebel RTUs on October 28, 2013

	Baseline RTU	Rebel RTU
Total Cooling Delivered[a]	34 ton-h	69 ton-h
DX Energy[b]	30 kWh	52 kWh
Supply Fan Energy	18 kWh	6 kWh
Daily Average EER[c]	8.6	14.1[d]

[a] Calculated based on the ClimaCheck methodology.
[b] Includes compressors, condenser fans, and controller.
[c] Includes supply fan energy.
[d] Discharge air temperature (DAT) set point to 55°F (daily average EER equals 17–19 with a 60°F DAT set point).

Therefore, NREL modified its demonstration plan to run the units independently, alternating weeks between the Rebel and the baseline RTU operations, starting in November 2013. Because the space was unoccupied during the demonstration period, NREL was not concerned about leaving half the space unconditioned. The focus of the demonstration period was collecting calibration data for baseline and Rebel energy models. The performance data collected are described in Section 4.1.

Table 5 provides a summary of the demonstration data utilized for both model calibrations. The total number of days shown in Table 5 does not include the demonstration period days in October 2013 when both RTUs were being run simultaneously. Although NREL could not use days of simultaneous day operation for calibrating the models (could only use alternating operational days), the performance data were still useful in developing DX performance models of the baseline and Rebel RTUs, which are summarized in Section 4.1.

Table 5. Summary of Performance Data Used to Develop and Calibrate the Baseline and Rebel Energy Models Across Dates November 10, 2013, through January 26, 2014

	Rebel Measured Performance Data Used for Calibration	Baseline Measured Performance Data Used for Calibration
Days of Operation	35 days	36 days
DX Operation Time	262 h	241 h
Supply Fan Operation Time	332 h	342 h

To achieve a true RTU comparison, NREL used the calibrated models of the baseline and Rebel RTUs to simulate each conditioning building 550. The methodology used to calibrate each model is summarized in Section 4.1, Appendix C, and Appendix D. The baseline model was simulated as if two Baseline RTUs were conditioning the entire space. Similarly, the Rebel model was simulated with the entire space being conditioned by two Rebel RTUs. Both models incorporated identical building envelope, infiltration, and internal loads (Appendix E). The internal space loads mirrored the artificial sensible and latent heat gains maintained during the actual demonstration period (Section 3.4). The results from the calibrated models addressed the demonstration objectives of energy savings and thermal comfort described in Sections 4.2 and

4.3, respectively. The TAB results addressed the ventilation demonstration objectives in Section 4.4. Table 6 summarizes the performance objective results.

Table 6. Performance Objective Results

	Performance Objective	Success Criteria	Results
1	Annual Energy Savings	The Rebel reduces energy usage by at least 30% compared to the baseline RTU	The Rebel met the energy savings demonstration objective. The calibrated energy models showed the Rebel saving 34%–37% annual energy compared to a baseline RTU with a typical leaky OA damper fixed at a 5%–20% position.
2	Interior Thermal Comfort	The Rebel maintains a narrower temperature band and lower annual average RH by at least 5%	The temperature band for both RTUs depends on their respective deadbands. Based on its default setting, the Rebel maintains a ±1°F temperature band while the baseline maintains a ±0.5°F temperature band. Yet despite a larger temperature band, the Rebel provides improved thermal comfort because it maintains a more stable space temperature. The modeling results show the Rebel maintains a drier space with the annual average space RH (during operational hours) being 8% lower than that of the baseline RTU model.
3	Ventilation Quality	The Rebel reduces OA damper leakage by 30% compared to the baseline RTU; Rebel and baseline maintain proper ventilation rates during occupied hours	The Rebel and Baseline met the minimum ventilation rates according to ASHRAE 62.1-2010. Compared to the leaky baseline OA damper, the Rebel maintained ~60% reduction in ventilation flow rate while still meeting ASHRAE 62.1 minimum ventilation rates.

4.1 Monitored Performance Data for Model Calibration

The models were calibrated using performance data from November 10, 2013, through January 25, 2014. To achieve a larger cross section of operation, the control parameters were modified during the demonstration period (see Table 7). The Rebel RTU supply fan speed was controlled to modulate at 34%–100%. The Rebel compressors throttled to maintain a DAT set point from 55°–65°F. NREL changed the DAT set point during the demonstration period to capture the impact of different suction pressures on performance.

Table 7. Rebel and Baseline Control Parameters During Demonstration Period

	Rebel	Baseline
Temperature Set Point Schedule	Ranged from 70°–76°F 0600–1530	Ranged from 68°–76°F 0600–1530
Temperature Control Deadband	±1.0°F	1st stage: +0.5 to +1.0 2nd stage: +1.0 to +1.5
Temperature Set Back	100°F	100°F
Humidity Control	None	None
DAT Set Point	Ranged from 55°–65F[a]	N/A
Supply Fan Control	SZVAV[b]	Constant
Supply Flow Rate	1,601–4,069 cfm[c] (controller range 34%–100% fan speed)	3,558 cfm
OA Damper	Position Range = 5%–15%[d] Ventilation Range = 219–342 cfm	Position Range = 0%–20% Ventilation = 574–1,413 cfm[e]

[a] For SZVAV control, the Rebel RTU controls the compressors to maintain a constant DAT regardless of the fan speed.
[b] For SZVAV control, the Rebel RTU controls the supply fan using a PI logic based on the current and previous minute's space temperature compared to set point (see Appendix C).
[c] The Rebel supply fan was allowed to ramp from 34%–100% based on the controller's settings. The TAB report provided the supply flow rates associated with these settings.
[d] Prior to the TAB, the Rebel OA damper was fixed at 15% open; after the TAB, the Rebel OA damper was controlled to open linearly from 5% at 100% fan speed to 15% at 40% fan speed.
[e] The baseline OA damper was measured to have significant leakage. After the TAB report, NREL and its subcontractor, Transformative Wave Technologies (TWT), separately measured the ventilation flow rate at a 0% damper position and verified the baseline RTU was still bringing in almost 600 cfm of OA.

For both RTUs, the temperature set points were lowered below 76°F for some days to ensure sufficient operation in second stage. Figure 10 shows that despite these lower set points, both RTUs operated most of the time near 50% of capacity. Although the baseline does not have a variable-speed compressor, the cooling capacity at both of its stages change slightly based on the mixed-air conditions (entering the evaporator coil) and ambient dry-bulb conditions (entering the condenser coil).

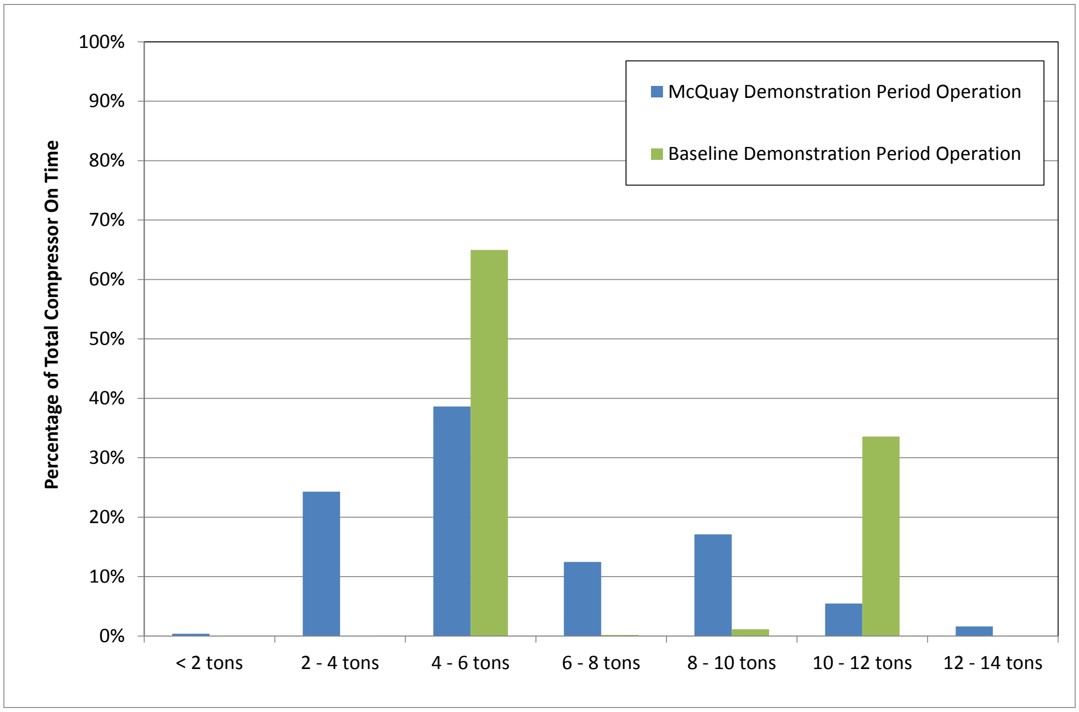


Figure 10. Histogram of monitored baseline and Rebel operational cooling capacities

After gathering a sufficient range of calibration data under various control configurations (most of November 2013), NREL configured the Rebel to achieve its maximum efficiency while meeting NAVFAC's standards of comfort and ventilation. Two Rebel control settings that had a dramatic impact on performance were DAT set point and OA damper position. These maximum efficiency control settings were maintained for the remainder of the demonstration period from November 24, 2013, through January 25, 2014.

DAT set point. The warmer the DAT set point, the more efficient the DX operation. However, the supply fan would then have to work harder (move more air) to meet the space conditioning load. At first, NREL was considering a 65°F DAT set point. Yet, the warmer the supply air, the higher the resulting space moisture conditions, causing discomfort and greater potential for mold growth. To balance DX efficiency with space moisture, NREL specified a constant 60°F DAT set point.

At a 60°F DAT set point, the saturated supply air would have a dew point ranging from 56°–58°F. NREL determined this supply air dew point range was sufficient to maintain a space dew point < 63°F (< 65% RH at a 76°F dry-bulb set point). The only moisture-based requirement in UFC or UFGS is UFC 3-410-01 Section 3-4.3.1 (dated July 1, 2013), which states "78°F (26°C) dry bulb and a maximum of 55°F (12.8°C) dew point." However, this is a *design-based* requirement, namely for sizing HVAC equipment. There are no *operational* moisture (RH or dew point) requirements throughout the UFC, UFGS, Commander Navy Installations Command Common Output Level Standards, or NAVFAC Hawaii energy mandates. NREL proposed—and NAVFAC agreed—to use 65% RH (maximum 63°F dew point at a 76°F dry-bulb set point) as the moisture threshold during occupied hours. A maximum RH of 65% is based on ASHRAE Standard 55-2010 for maintaining thermal comfort and mitigating mold issues.

OA damper position. Based on the TAB report, the Rebel OA damper was configured to maintain the minimum ventilation per ASHRAE 62.1-2010 (the DCV features were not exercised in this demonstration according to UFC 3-410-01 Section 401.1 [dated July 1, 2013]; see Section 2.2). The OA damper position was controlled based on the supply fan speed; 5% open at 100% fan speed to 15% open at 40% fan speed. Section 4.4 reviews the ventilation rates maintained compared to the ASHRAE 62.1-2010 minimum requirement.

Table 8 presents representative Rebel RTU daily performance for five weekdays of the demonstration period. The "Total DX Cooling" is the daily sum of refrigeration-based cooling calculated using the ClimaCheck methodology summarized in Appendix A. Dividing this daily total DX cooling (converted to Btuh) by the daily total electric energy usage (converted to Watt-hour) provides a daily average EER that includes the supply fan energy. Note these daily average EERs should not to be compared against rated EER or IEER conditions because these field measurements were not at proper AHRI rating conditions.

To fully characterize performance, the baseline was operated at a 68°F set point for many hours of the demonstration to realize more second-stage operation. NREL found that the greater percentage of time the baseline RTU operated in first stage cooling, the lower the overall daily EER. The baseline under first-stage operation realizes a lower performance because both fixed-speed condenser fans are operating with only one compressor providing cooling. These additional parasitic power draws drive down the real-time EER. During the demonstration period days with a 76°F set point, the baseline RTU would operate more often under first-stage operation, which would further drive down the daily average EER. Table 9 presents the baseline RTU daily performance for five weekdays of the demonstration period when the set point was 68°F.

The baseline RTU also experiences performance degradation caused by compressor cycling the ClimaCheck methodology does not capture. The ClimaCheck methodology is accurate only when the DX circuit has reached steady-state operation, which is typically 2 minutes after the compressors turns on. When the baseline RTU turned on a compressor, the ClimaCheck method was calculating a cooling rate well beyond the capacity of that DX circuit. For example, when the second-stage compressor turned on, the first minute of operation would report 10 tons of additional cooling, the second minute 7 tons of additional cooling, and from the third minute on, the additional cooling would settle to a realistic 5 tons. When calculating the daily total DX cooling, NREL set the first and second minute cooling rates to that measured in the third minute each time a compressor started. Yet this adjustment of the monitored data does not fully address the performance degradation caused by significant compressor cycling. Therefore, the daily average EER provided in Table 9 may overstate the baseline RTU performance. The true daily average EER may be up to 8% below that shown, based on the uncertainty in the measurement.

The daily average EERs and energy usage from Table 8 and Table 9 should not be used for the true RTU comparison, nor should they be compared to the unit's rated IEER. They are field test measurements, not lab test results at proper AHRI rating conditions. Instead, the monitored data from the demonstration period were used to calibrate a Rebel RTU model and baseline RTU model. NREL used calibrated whole-building energy models to establish a true RTU performance comparison.

Table 8. Monitored Daily Rebel RTU Performance[a]

Date	Avg. OAT (°F)	Total DX Cooling[b] (ton-h)	Compressor + Cond. Fan Energy[c] (kWh)	Supply Fan Energy[d] (kWh)	Total Energy[e] (kWh)	Daily Average EER[f]
12/9/13	81.2	54	30.6	3.6	36.0	17.9
12/10/13	80.1	52	31.6	4.0	37.0	16.7
12/11/13	78.4	47	25.7	3.4	30.9	18.1
12/12/13	78.5	38	23.2	3.2	27.1	17.0
12/13/13	77.5	40	20.9	3.1	25.5	19.0

[a] For December 2013, the Rebel RTU was controlled to a 76°F set point, 60°F DAT set point, modulating OA damper to maintain ASHRAE 62.1 minimum ventilation based on fan speed, and variable-supply flow rate of 1,601–4,069 cfm.
[b] Daily DX cooling capacity calculated using the ClimaCheck methodology with ±7% uncertainty.
[c] Compressor and condenser fan energy measured at a ±3% accuracy (separately submetered).
[d] Supply fan energy with uncertainty of 5%; based on subtraction of compressor, condenser fan, and controller energy from total RTU energy (supply fan power was not separately submetered).
[e] Total RTU energy (including controller) with ±3% uncertainty (separately submetered).
[f] Daily averaged performance based on total daily cooling provided (ton-hours) and total RTU energy (including supply fan energy) with ±5% uncertainty; not to be compared against rated EER or IEER conditions as these field measurements were not at proper AHRI rating conditions.

Table 9. Monitoring Daily Baseline RTU Performance[a]

Date	Avg. OAT (°F)	Total DX Cooling[b] (ton-h)	Compressor + Cond. Fan Energy[c] (kWh)	Supply Fan Energy[d] (kWh)	Total Energy (kWh)	Daily Average EER[f,g]
12/2/13	75.0	70	56.0	10.5	66.7	12.5
12/3/13	75.7	69	55.9	10.5	66.7	12.4
12/4/13	76.5	67	54.9	10.5	66.2	12.2
12/5/13	75.6	65	53.9	10.5	64.9	12.0
12/6/13	76.8	66	54.2	10.5	64.7	12.2

[a] For December 2013, the baseline RTU was controlled to a 68°F set point, 20% fixed OA damper, and 3,558 cfm supply flow rate.
[b] Daily cooling capacity calculated using the ClimaCheck method with ±7% uncertainty.
[c] Compressor and condenser fan energy measured at a ±3% accuracy (separately submetered).
[d] Supply fan energy with uncertainty of 5%; based on subtraction of compressor, condenser fan, and controller from total RTU energy (supply fan power was not separately submetered).
[e] Total RTU energy (including controller) with ±3% uncertainty (separately submetered).
[f] Daily averaged performance based on daily cooling provided (ton-hours) and total RTU energy (including supply fan energy) with ±5% uncertainty; not to be compared against rated EER or IEER conditions as these field measurements were not at proper AHRI rating conditions.
[g] Baseline daily average EER ranged from 8.5–10.5 with more typical compressor staging where 80% of DX operation time was under first stage and 20% operation time under second stage. When the set point was reduced to 68°F, the greater percentage of second-stage operation improved daily average EER to 10.5–12.5.

The following two subsections describe how the RTUs were modeled using the EnergyPlus[16] whole-building energy simulation program. Two models were constructed with identical building characteristics (geometry, envelope, and internal loads). These building parameters were based on measurements taken on site; structural drawings; and the artificial occupant, plug, and lighting loads (Section 3.4). Because the space was unoccupied for the demonstration period and the internal loads were artificial, the randomness induced by human behavior was nearly eliminated. The RTUs conditioning the space constituted the only difference between the two models.

4.1.1 Rebel Rooftop Unit Modeling Process

The Rebel RTU modeling was a three-part process:

1. The monitored demonstration data were used to develop mathematical models to characterize the Rebel supply fan and DX system.
2. The Rebel RTU model was integrated into a whole-building simulation of building 550. Two unknown envelope parameters— infiltration rate and window properties (solar heat gain coefficient [SHGC] and U-value)—were adjusted within appropriate bounds to calibrate the whole-building simulation against the measured data. NREL conducted a rigorous uncertainty analysis comparing the measured versus modeled daily energy to quantify the 95% confidence bounds of the model (Appendix H). There were 35 days in the Rebel calibration period. NREL also stipulated the model must maintain the occupied average space temperature to ±1°F and dew point to ±3°F of the measured space conditions. Based on these specifications, NREL was assured the model represented the measured Rebel RTU energy usage and resultant space conditions (sensible and latent).
3. The calibrated model was simulated for an entire year using typical meteorological year 3 (TMY3) weather data. The resultant annual energy usage was compared to the calibrated baseline model also simulated using TMY3 weather.

Steps 1 and 2 are described below. Step 3’s annual energy results are summarized in Section 4.2.

Step 1. Rebel Supply Fan and DX System Models

The Rebel RTU’s PI supply fan control logic was integrated into the model. For each minute, the Rebel RTU calculates a projected error (difference between space temperature and set point) based on the current and previous minute’s error. The supply fan speed changes based on the projected error and a gain term. Appendix C explains the supply fan control logic in detail. Appendix C also summarizes the relationship between fan speed, supply air flow rate, total static pressure drop, and supply fan power. The Rebel DX system was controlled to maintain a constant 60°F DAT.

Once the compressor and supply fan control logic was integrated into the EnergyPlus model, NREL used the monitored data to develop a regression model of DX (compressors and condenser fans) power. Equation 4 shows this regression model. At each time step (1 minute) in the EnergyPlus model, these predictors are known. The calculated DX power for each time step is then used to calculate energy usage.

[16] https://energyplus.net/

$$DX_{Power} = -0.752 + (-0.051 \cdot T_{DA}) + (0.077 \cdot T_{OA}) + (6.067 \cdot Cap_{Frac}) + (-0.772 \cdot Comp1or2) \quad (4)$$

where
DX_{Power} is the combined power draw of the compressors and condenser fan (kW)
T_{DA} is the DAT (°C)
T_{OA} is the ambient dry-bulb temperature (°C)
Cap_Frac is the capacity fraction based on the ClimaCheck calculated real-time cooling normalized to the RTU's AHRI nominal capacity (117,907 Btuh; 9.8 tons)
$Comp1or2$ signifies whether operating in first or second stage (+1 = stg 1; -1 = stg 2).

NREL included the predictor *Comp1or2* because the monitored data showed a step-wise change in performance when the second-stage compressor initiated. For example, the ClimaCheck methodology would show the real-time DX efficiency operating around 18 EER (not including the supply fan energy) with only the first-stage compressor operating. When the second-stage compressor turned on, the real-time DX efficiency would immediately drop to around 15 EER (not including the supply fan energy). Including the *Comp1or2* predictor in equation 4 captures this step-wise change.

Based on the monitored data, NREL found the second-stage compressor would initiate when the capacity fraction exceeded 0.6. Therefore, during the modeling process, only the first stage was operating until the capacity fraction exceeded 0.6. Figure 11 shows the Rebel DX power regression equation provides a ±10% uncertainty at a 68% confidence based on the coefficient of variation of the root mean squared error (CVRMSE).

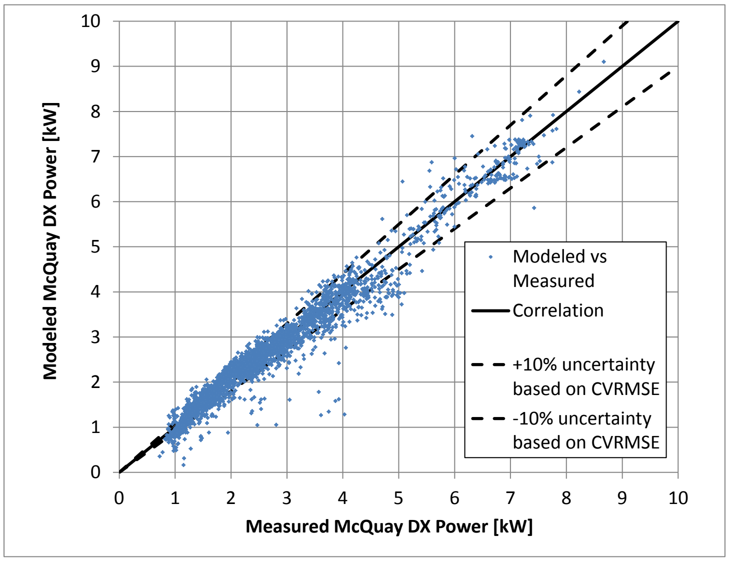


Figure 11. Rebel DX power regression modeled versus measured, including uncertainty based on CVRMSE

Table 10 summarizes the parameters of this regression model. Appendix C summarizes this regression model in greater detail. Figure 12 uses equation 4 to compare the Rebel's DX performance, not including the supply fan power, across a range of predictor values. The step-wise change in performance is apparent when the second stage compressors turn on at capacity fractions that exceed 0.6.

Table 10. Rebel RTU DX Power Regression Model Parameters

Adjusted R-squared	0.96
Standard error/CVRMSE	0.28 kW/10%
Total RTU operational hours	262 h (245 h first stage; 17 h second stage)
Regressed DX power range (includes condenser fan)	First-stage operation: 0.7–5.2 kW Second-stage operation: 3.7–8.7 kW
Regressed T_{DA} range	55°–68°F
Regressed T_{OAc}	61°–87°F
Regressed Cap_Frac	0.1–1.3

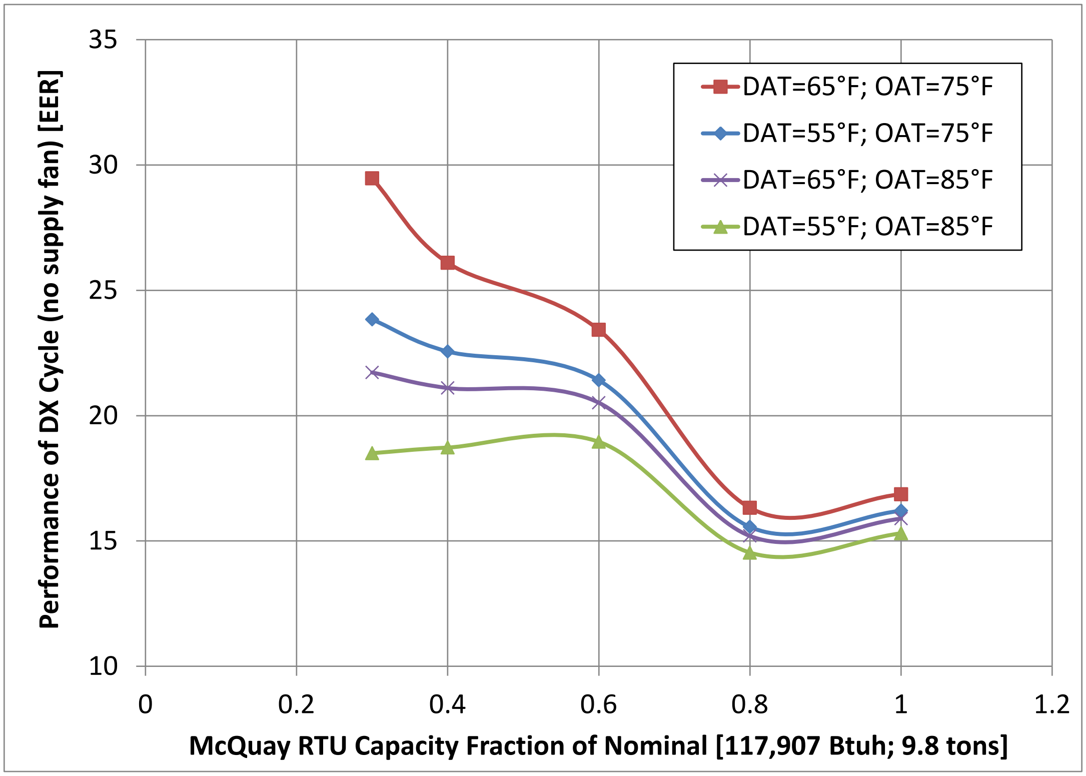


Figure 12. Using DX power regression model to calculate DX cycle performance (EER) for a range of DAT, OAT, and capacity fractions

Step 2. Rebel Rooftop Unit and Building 550 Model Calibration

With the supply fan logic, compressor logic, and DX power regression model implemented, the EnergyPlus model was calibrated against 35 days of monitored data between November 24, 2013 and January 25, 2014. These were days when only the Rebel RTU was operating, and the control parameters were adjusted to maximize efficiency while meeting thermal comfort requirements. These control parameters included a 76°F set point, 60°F DAT set point, and OA damper modulating from 15% open at 40% fan speed to 5% open at 100% fan speed. The ventilation flow rate at this supply fan and OA damper control met the ASHRAE 62.1 minimum ventilation requirements. The model was simulated using a 1-minute time step and the measured National Oceanic and Atmospheric Administration Honolulu International Airport weather data.

For calibration, NREL adjusted two "knobs" to ensure the model aligned with the monitored data. These were two model inputs that characterized building 550's envelope; infiltration rate and double-pane window properties (SHGC and U-value). Appropriate upper and lower bands were established for both inputs. NREL found an infiltration of 0.10 cfm/ft^2 of wall area at 0.05 in. water column (WC) pressure (equivalent to 0.34 air changes per hour), glazing SHGC of 0.50, and glazing U-value of 0.5 resulted in the best fit to the measured daily energy usage.

Figure 13b shows the comparison for the daily RTU energy calibration (including supply fan, compressors, and condenser fans). Using the uncertainty analysis in Appendix H, the uncertainty of the Rebel EnergyPlus model was based on the CVRMSE. The CVRMSE was calculated to be ±17% at a 68% confidence. These confidence bands are plotted in Figure 13b. Appendix H goes into further detail regarding the propagation of modeling error in the final annual energy savings prediction. Figure 13a shows the daily RTU energy usage versus the daily average ambient dry-bulb temperature. The plots trend well together and provide confidence that the Rebel RTU model captured the impact of weather on energy usage. Appendix C summarizes all the Rebel calibration results.

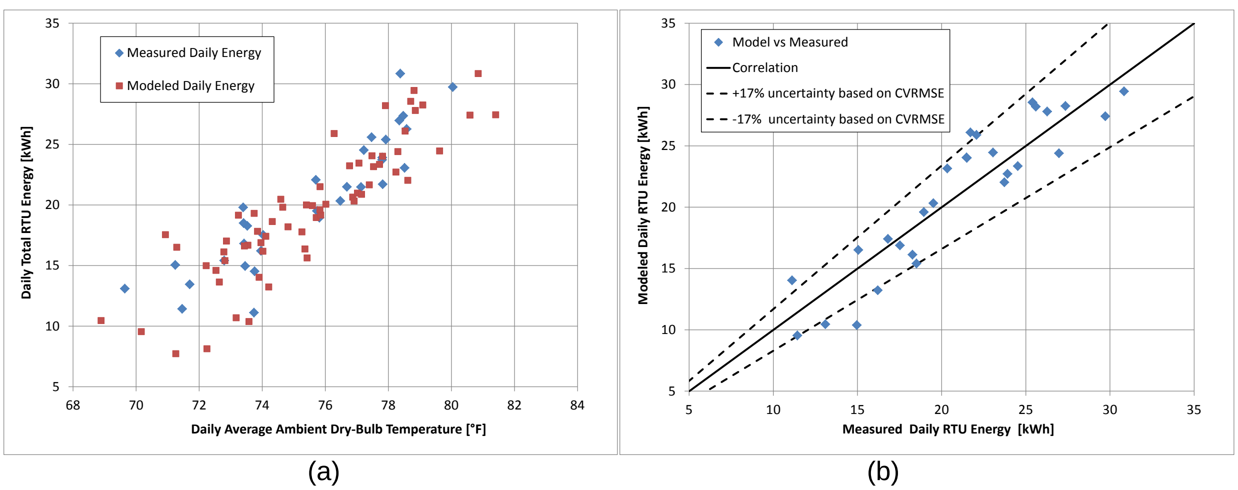


Figure 13. Rebel RTU model versus measured daily RTU energy usage

4.1.2 Baseline Rooftop Unit Modeling Process

The baseline RTU modeling was a three-part process:

1. The monitored data were used to develop mathematical models characterizing the baseline's supply fan and DX system.
2. The baseline RTU model was integrated into a whole-building simulation of building 550. The infiltration and window properties established during the Rebel RTU model calibration were maintained for the baseline RTU model. The baseline RTU model was calibrated based on the same set of specifications:
   a. Measured versus modeled daily energy usage
   b. Model must maintain the occupied average space temperature to ±1°F and dew point to ±3°F of the measured space conditions.
3. The calibrated model simulated two baseline RTUs that served the entire office space in building 550 using TMY3 normalized weather data.

The following subsection summarizes step 1 and step 2. Section 4.2 reviews the annual energy results from step 3.

The baseline RTU was modeled by determining for each time step whether first- or second-stage compressors were operating based on the space temperature versus set point error. Depending on the stage of operation, the mixed-air wet-bulb temperature, ambient dry-bulb temperature, and two sets of regression equations were used to calculate the cooling capacity and associated DX (compressor(s) and condenser fans) power. Based on the baseline RTU sequence, both condenser fans operated whether in stage 1 or 2 cooling operation. The baseline RTU OA damper was modeled at 20% open based on how it was configured during the days used in the calibration period. The supply fan was modeled with a constant 3,558 cfm based on the TAB report.

Step 1. Regression Models

The baseline RTU was characterized with two sets of regression equations. Equations 5 and 6 capture the variations in the first- and second-stage DX system power draw, respectively, based on the mixed-air wet-bulb and ambient dry-bulb temperatures. NREL found the ambient dry-bulb temperature had the most significant impact on compressor power because it directly impacts discharge pressure (saturated condensing temperature) and refrigerant subcooling. To a lesser extent, the mixed-air wet-bulb impacted the compressor power because it influences the suction pressure (saturated suction temperature).

$$Stage\ 1\ DX\ Power\ 15{,}058 + (-919\ \cdot T_{WB}) + \left(16\ \cdot {T_{WB}}^2\right) + (-283\ \cdot T_{OA}) + \left(1.4\ \cdot {T_{OA}}^2\right) + (16\ \cdot\ T_{WB}\ \cdot T_{OA}) \quad (5)$$

$$Stage\ 2\ DX\ Power\ 17{,}559 + (-487 \cdot T_{WB}) + \left(-6\ \cdot {T_{WB}}^2\right) + (-634\ \cdot T_{OA}) + \left(3.1\ \cdot {T_{OA}}^2\right) + (34\ \cdot\ T_{WB}\ \cdot T_{OA}) \quad (6)$$

where

DX Power includes the compressors and condenser fans power (W),
T_{WB} is the mixed-air wet-bulb temperature entering the evaporator coil (°C), and
T_{OA} is the ambient dry-bulb temperature (°C).

The DX system power includes the compressors and condenser fans power draw. Although the mixed-air wet-bulb was not measured directly during the demonstration period, NREL used the return air temperature/RH conditions, ambient temperature/RH conditions, and OA fraction based on the TAB report to calculate the mixed-air wet-bulb temperature. Figure 14 shows the regression model for both stages of cooling with both having a 2% uncertainty at a 68% confidence interval based on the models' CVRMSE.

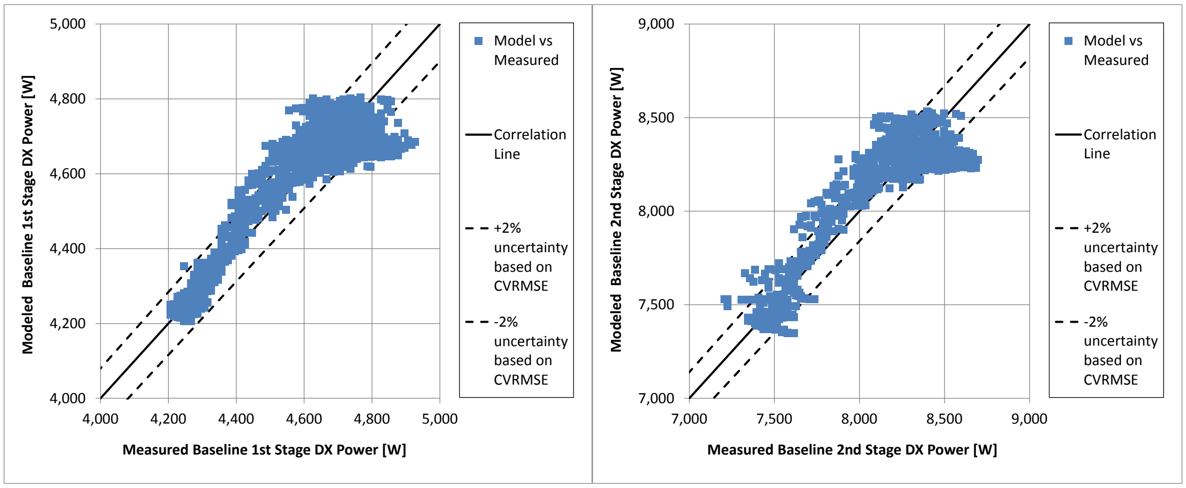


Figure 14. Baseline RTU DX power regression (including compressors and condenser fans)

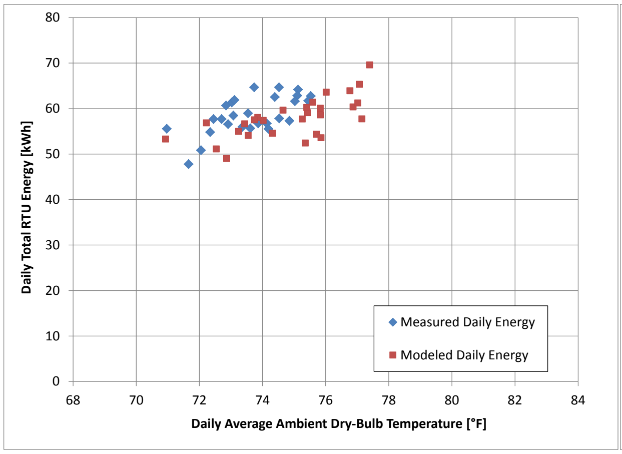
Table 11 shows some additional regression parameters. A second set of regressions was conducted that related the cooling capacity under first- and second-stage operation to the mixed-air wet-bulb temperature and ambient dry-bulb temperature (see Appendix D).

Table 11. Baseline RTU DX Power Regression Parameters (including Compressors and Condenser Fans)

	First-Stage DX	Second-Stage DX
Adjusted R-squared	0.86	0.83
Standard error / CVRMSE	0.08 kW / 2%	0.16 kW / 2%
Regressed DX power range (includes cond. fans)	4.2–5.0 kW	7.1–8.7 kW
Regressed operational hours	173 h	68 h
Regressed T_{WB} range	62°–68°F	62°–69°F
Regressed T_{OA} range	62°–86°F	63°–87°F

Step 2. Baseline Rooftop Unit and Building 550 Model Calibration

Figure 15 shows the calibration of the model versus monitored daily DX energy usage. Compared to the Rebel model, the baseline model showed a better calibration with respect to the measured daily energy usage with a ±7% uncertainty at a 68% confidence interval based on the CVRMSE. Additional calibration results are presented in Appendix D.



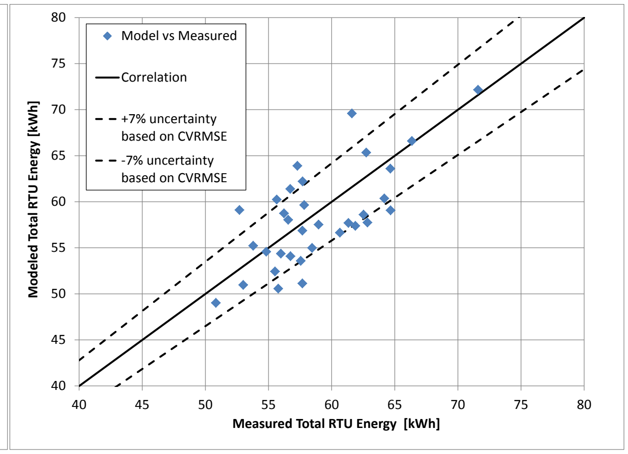


Figure 15. Baseline RTU model versus measured daily DX energy usage

4.1.3 Supply Fan Models

Table 12 provides a performance comparison between the Rebel and baseline RTU supply fans. The Rebel's ECM direct drive supply fan achieves a much higher static efficiency compared to the baseline. NREL found the baseline static efficiency was lower than the expected range of 40%–50%. Regardless, the power draw was consistent with expectations and used as the baseline fan power for the model.

Table 12. Supply Fan Comparison

	Rebel	Baseline
Fan Type	Variable-speed Direct-drive ECM	Belt driven Constant-speed NEMA std eff
Flow Rate During Demonstration	1,600–3,575 cfm	3,558 cfm
Pressure Drop at Peak Flow Rate	1.96 in. WC	0.91 in. WC
Power Draw at Peak Flow Rate	1.3 kW	1.1 kW

The Rebel total static pressure drop was significant because the Rebel had to be transitioned from vertical discharge to horizontal discharge. Most standard RTUs can be provided in either configuration. The Rebel was designed for vertical discharge only, but is adaptable to horizontal discharge through a custom roof curb. The supply air duct leaving the roof curb under the Rebel was a small, cross-sectional area of 1.9 ft^2 compared to 4.5 ft^2 horizontal discharge ductwork on the baseline. The Rebel air speeds at 1,880 feet per minute (fpm), compared to 870 fpm for the baseline, resulted in a significant supply fan static pressure drop. The 1.3-kW Rebel supply fan power was implemented in the model at the TAB measured 3,575 cfm. To capture the fan power changes at variable supply fan speeds, the fan power was correlated to variable supply air flow rates established from the TAB report. See Appendix C and Appendix D for more detailed summaries of the supply parameters for the Rebel and baseline supply fans, respectively.

4.2 Model Results

The two calibrated models were then simulated for a year's operation using Honolulu TMY3 weather data. TMY3 weather data eliminate weather abnormalities and provide an annual RTU energy use that would be expected averaged over 30 years of operation. Table 13 provides the control parameters for each RTU model. For the most part, the models mirrored the controls implemented during the December 2013 through January 2014 timeframe of the demonstration period.

Table 13. Rebel and Baseline Control Parameters

	Rebel	Baseline
Temperature Set Point Schedule	76°F 0600–1530 weekdays (Summer May 1-October 31) 0800–1530 Weekdays (Winter November 1-April 30)	74.5°F 0600–1530 Weekdays (Summer May 1-October 31) 0800–1530 Weekdays (Winter November 1–April 30)
Temperature Control Deadband	±1.0°F	First stage: +0.5 to +1 Second stage: +1 to +1.5
Temperature Setback	100°F	100°F
Humidity Control	None	None
DAT Set Point	60°F[a]	N/A
Supply Fan Control	SZVAV[b]	Constant speed
Min–Max Flow Rate	1,601–3,575 cfm	3,558 cfm
OA Damper	Minimum position (Closed all other times) 0800–1530 weekdays (Summer May 1-October 31) 1000–1530 weekdays (Winter November 1-April 30) Ventilation range = 219-342 cfm Meets ASHRAE 62.1[c]	Fixed 5% open Ventilation[d] = 672 cfm Meets ASHRAE 62.1

[a] Rebel controls the compressors to maintain a constant DAT at any fan speed.
[b] Rebel controls the supply fan based on its SZVAV logic, which ramps the fan using a PI control based on the current and previous minute's space temperature compared to set point (see Appendix C).
[c] Rebel model simulated OA flow rates based on correlation between OA flow rate and supply air flow rate established using the TAB report. OA flow rates meets minimum ventilation rate according to ASHRAE Standard 62.1 non-DCV requirements.
[d] Baseline model simulated constant OA flow rate of 672 cfm, based on the TAB report.

The major control change to the baseline RTU model was maintaining the OA damper fixed at 5% compared to the 20% position during the demonstration. As summarized in Section 4.4, the excessive leakage of the OA damper even at a 5% damper position resulted in approximately three times the ventilation required per ASHRAE 62.1-2010. The baseline temperature set point was maintained lower than the Rebel because of their respective deadbands. This offset ensured both models maintained the average office space temperature within ±1°F of each other; to be considered a true RTU comparison, both models needed to maintain nearly the same bulk space temperature during occupied hours.

The calculated energy consumptions of the two Rebel RTUs were averaged together. Similarly, the two baseline RTU's energy consumptions were averaged together. Table 14 then compares these averages to show the energy savings of one 10-ton Rebel RTU versus one 10-ton baseline RTU serving a small office space. The Rebel provides 34% energy savings compared to the baseline RTU at a fixed 5% OA damper position. Despite a much larger total static pressure drop, the Rebel supply fan still provided a 51% energy savings compared to the baseline supply fan.

The annualized EER was calculated based on the annual cooling provided by each RTU (in British thermal units) divided by the annual energy usage (in Watt-hour). As mentioned previously, the EER numbers below should not be compared to the unit's rated IEER because they are modeled results averaged across a year's operation (not lab test results at proper AHRI-rating conditions). The Rebel 15.6 annualized EER is slightly below the daily EER range measured during the demonstration period as shown in Table 8. The daily range shown in Table 8 represents cooler days in the winter while the slightly hotter summer months drive down the annualized EER. The baseline 10.1 annualized EER was lower than the EER range measured during the demonstration period because the annualized EER is influenced by summer operation and the fact the baseline RTU operated significantly more in first-stage operation where its real-time EER is lower because two condenser fans were operating.

Appendix H summarizes the uncertainty analysis of the predicted annual energy savings. Based on the measured power, sampling, and model uncertainties, NREL calculates the 3,682 kWh annual energy savings presented in Table 14 has a ±27% uncertainty at a 95% confidence interval. This energy savings was then used in Section 5 to conduct the ROI analysis.

Table 14. Modeled Annual Energy Consumption and Savings Between One 10-Ton Rebel RTU Versus One 10-Ton Baseline RTU Serving the Building 550 Small Office Space

	1 Baseline RTU 5% OA Damper	**1 Rebel RTU**	**Savings**
Supply Fan	2,607 kWh	1,268 kWh	1,339 kWh (51%)
Compressors + Condenser Fans	8,855 kWh	6,332 kWh	2,523 kWh (28%)
Total RTU	11,462 kWh	7,600 kWh	3,862 kWh[a] (34%)
Total Cooling	9,616 ton-h	9,879 ton-h	
Annualized EER[b] (do not use as rated IEER)	10.1 EER	15.6 EER	

[a] Propagation of uncertainty yields ±27% of the annual energy savings, based on a 95% confidence interval (see Appendix H)

[b] Not to be compared against rated EER or IEER conditions as these model results are annualized and not at proper AHRI rating conditions.

Figure 16 shows a histogram of the annual capacity operation for the Rebel and baseline RTUs. The baseline RTU spent more than 90% of its DX operational hours in first stage. Because the Rebel was able to vary its capacity, it spent most of its time lower than 4 tons. The reason both the baseline and Rebel RTUs operate at a lower capacity is most likely because they are oversized. Based on site visits of different RTU installations at JBPHH, the typical range is 250–400 ft^2/ton. Building 550 at 20 tons serving 5,000 ft^2 is on the small side of 250 ft^2/ton. These RTUs serving spaces in the 300–400 ft^2/ton range would operate more hours at a larger capacity.

Figure 17 compares the daily energy usage versus the daily average ambient dry-bulb for both RTUs.

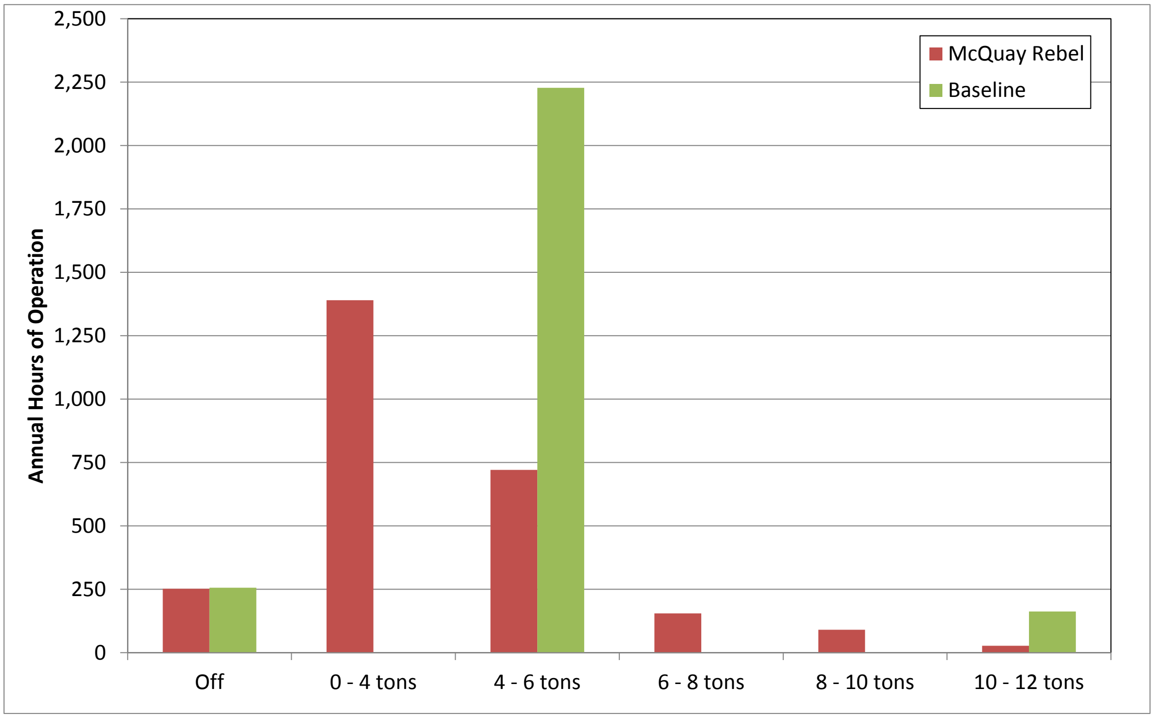


Figure 16. Baseline and Rebel annual operating hours at different capacity bins

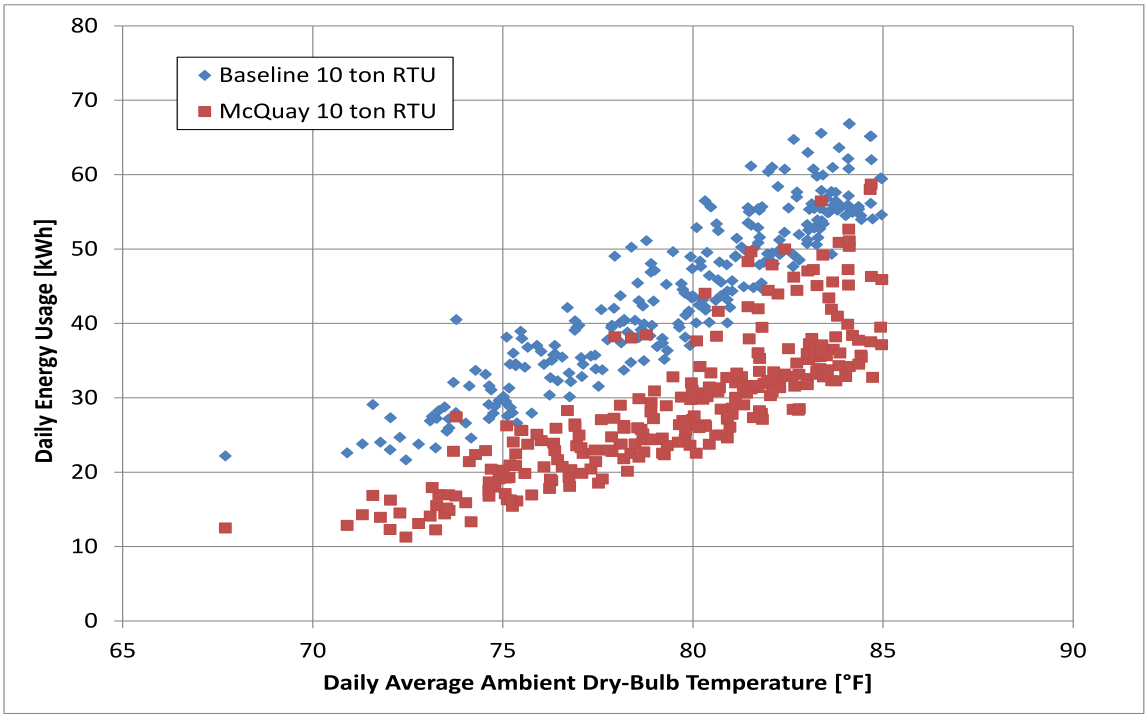


Figure 17. Baseline and Rebel daily energy usage versus daily average dry-bulb temperature

Based on JBPHH site visits, NREL found that typical RTU OA dampers were fixed at some arbitrary 5%–20% opening. These OA dampers were also of typical construction—not low leakage. To provide a better cross-section of savings beyond the 5% damper position shown in Table 14, NREL compared the Rebel energy usage versus two additional OA damper configurations. One configuration represented a low leakage damper installed on a baseline unit, which provides just the correct amount of ventilation to meet ASHRAE 62.1-2010. This configuration isolates the energy savings of the Rebel from its variable-speed supply fan and variable refrigerant flow technologies—eliminating the energy savings of the Rebel's low-leakage OA damper. Based on correspondence with the local HVAC distributors on Oahu, code-minimum RTUs can be specified with low-leakage dampers. The second configuration represented OA dampers set to a larger 20% opening. Table 15 shows the energy savings ranges from 29%–37%, depending on the OA damper configuration of the baseline RTU. Considering that the typical OA damper at JBPHH is not low leakage and the fixed positions fluctuate from 5%–20%, the annual energy savings should be within the 34%–37% range.

In 2018, the Rebel model was rerun with a lower fan pressure drop. When the demonstration was completed in 2014, Daikin Applied only provided a downward discharge configuration. To integrate with the existing ductwork, the installation at the small office used a roof curb to transition the airflow from downward to horizontal, resulting in an additional inch of static pressure. The Rebel now has a horizontal discharge option. In Table 15 below, the number in brackets shows the Rebel energy savings with the lower fan pressure drop. Across the three baseline damper configurations, the energy savings ranged from 33-42%.

Table 15. Modeled Rebel Savings Over the Baseline RTU Maintaining Different Ventilation Flow Rates

	1 Baseline RTU	1 Rebel RTU	Savings
Baseline with low-leakage OA damper meeting ASHRAE 62.1 minimum ventilation rate	10,634 kWh	7,600 kWh [7,099 kWh[b]]	3,034 kWh[a] (29%) [3,535 kWh[b]] (33%)
Baseline with standard OA damper fixed at 5% open	11,462 kWh	7,600 kWh [7,099 kWh]	3,862 kWh[a] (34%) [4,363 kWh[b]] (38%)
Baseline with standard OA damper fixed at 20% open	12,151 kWh	7,600 kWh [7,099 kWh]	4,552 kWh[a] (37%) [5,052 kWh[b]] (42%)

[a] Propagation of uncertainty yields ±27% of the annual energy savings based on a 95% confidence interval (see Appendix H).

During the site inspections of 30 RTUs throughout JBPHH, NREL found that most office buildings were not abiding by the NAVFAC Pacific operating hours limits for HVAC equipment. Table 13 above shows these allowed hours. Outside these hours, the RTUs were supposed to be completely off, not even maintaining a set-back temperature set point. While NREL found a large range in the times the thermostats were set to enable cooling, the general trend was from 0600 to 1800, or 12 hours a day. Since most of these thermostats had 7-day programmable capability, these operating hours were just during the weekdays – the thermostats were correctly set to prevent weekend operation.

To account for the longer hours of operation, NREL ran the Rebel and baseline energy models from 0600 to 1800 on weekdays. NREL chose the baseline with a standard OA damper fixed at 5% open. The annual energy savings was 7,426 kWh, nearly double that shown in Table 15. NREL found that the percentage energy savings increased to 48% because of the larger number of hours in the early morning and late afternoon that the Rebel was able to operate in its improved part load operation of the supply fan and DX circuit. Essentially, the longer the operating hours of the facility, the larger the percentage energy savings for high-efficiency RTUs that enable improved part-load performance.

4.3 Interior Thermal Comfort

The modeling results also show the Rebel will provide slightly more cooling over a year compared to a baseline RTU because it will provide more latent cooling. The Rebel maintains a lower space dew point because it can maintain a constant DAT. At a 60°F DAT set point, the Rebel is providing supply air at a 57°F dew point or lower. The baseline RTU supply air dew point changes based on the cooling stage and the cycle rate. Under consistent first-stage cooling (over 10 consecutive minutes), the baseline RTU is typically maintaining a 65°–68°F supply air temperature, which results in a supply dew point of 60°–63°F. Only under consistent second-stage cooling can the baseline supply air at 55°–60°F yielding a supply dew point of 53°–58°F.

Yet, when the second stage frequently cycles, as was seen during the demonstration period and in the model, the second stage provides negligible latent cooling. While the second-stage compressor is on for 5 minutes, moisture is condensing on the coil and fin surfaces. When the compressor turns off, that moisture re-evaporates into the supply air. Because the baseline RTU typically operates in first-stage cooling and cycles the second stage on for brief periods only, the supply air dew point will be consistently 60°–63°F. As a result, the Rebel's supply of lower dew point air will maintain a drier space, but the additional latent cooling will require more work from the DX system. Therefore, the Rebel provides both energy savings and improved thermal comfort by maintaining a drier space. Section 4.3 further summarizes the difference in thermal comfort between the Rebel and the baseline RTUs.

For the same reasons energy modeling was used to predict annual energy savings, the models were also used to predict interior space conditions throughout the year. The Rebel and baseline RTUs were modeled according to what NREL defined as the typical JBPHH interpretation of the NAVFAC Hawaii *Region Energy Instruction*. This mandate states that thermostats should not be set lower than 78°F. Based on discussions with NAVFAC building energy managers, most JBPHH small office buildings were being set to a 76°F set point. The NAVFAC building energy managers justified this lower set point by stating a thermostat set point at 76°F would ensure the hottest location within the conditioned space would not exceed 78°F. NREL also took into consideration the Common Output Level Standards established by the Commander Navy Installations Command. Although Common Output Level Standards 3 and 4 push the minimum thermostat requirement warmer than 78°F, these levels are not typical. Therefore, NREL established 76°F as the average space temperature to maintain for both RTU models (Table 13).

Regarding set point schedules, NAVFAC Hawaii *Region Energy Instruction* stipulates air conditioning is allowed only from 1000–1500 for winter hours (November 1–April 30) and 0800–1600 for summer hours (May 1–October 31). During the demonstration period, NREL defined a thermostat schedule based on what was determined to be typical from discussions with

NAVFAC building energy managers. This schedule was 1000–1530 for winter hours and 0800–1530 for summer hours. NREL was concerned about the RH within the space when these schedules were implemented while the office space was still occupied by NAVFAC personnel (June to July 2013). The RH was exceeding 65%, which NREL established with NAVFAC as the maximum allowable. NREL found that by starting the RTUs 2 hours prior to the NAVFAC Hawaii *Region Energy Instruction* schedule, the space was sufficiently dehumidified and maintained space RH lower than 65% for the remainder of the day. Therefore, the RTU operation was modeled to occur from 0800–1530 for winter hours (November 1–April 30) and 0600–1530 for summer hours (May 1–October 31), as shown in Table 13Table 13.

Figure 18 plots a histogram of the hourly average space temperature maintained during occupied hours for both models. Despite a few fringe hours during the morning cooldown (temperature bins higher than 77°F), the temperature bins emphasize each respective RTU's deadband control. The baseline RTU shows a tighter temperature range of 75°–76F as the two DX stages are cycled to maintain the space at 0.5°–1.5°F higher than the 74.5°F set point. The Rebel 2°F deadband is shown with most of the hourly averages at 75°–77°F. This histogram of binned hourly averages appears to show that the baseline RTU maintains improved thermal comfort. However, dialing down to 1-minute monitored, not model, data show the Rebel maintaining a more stable space temperature.

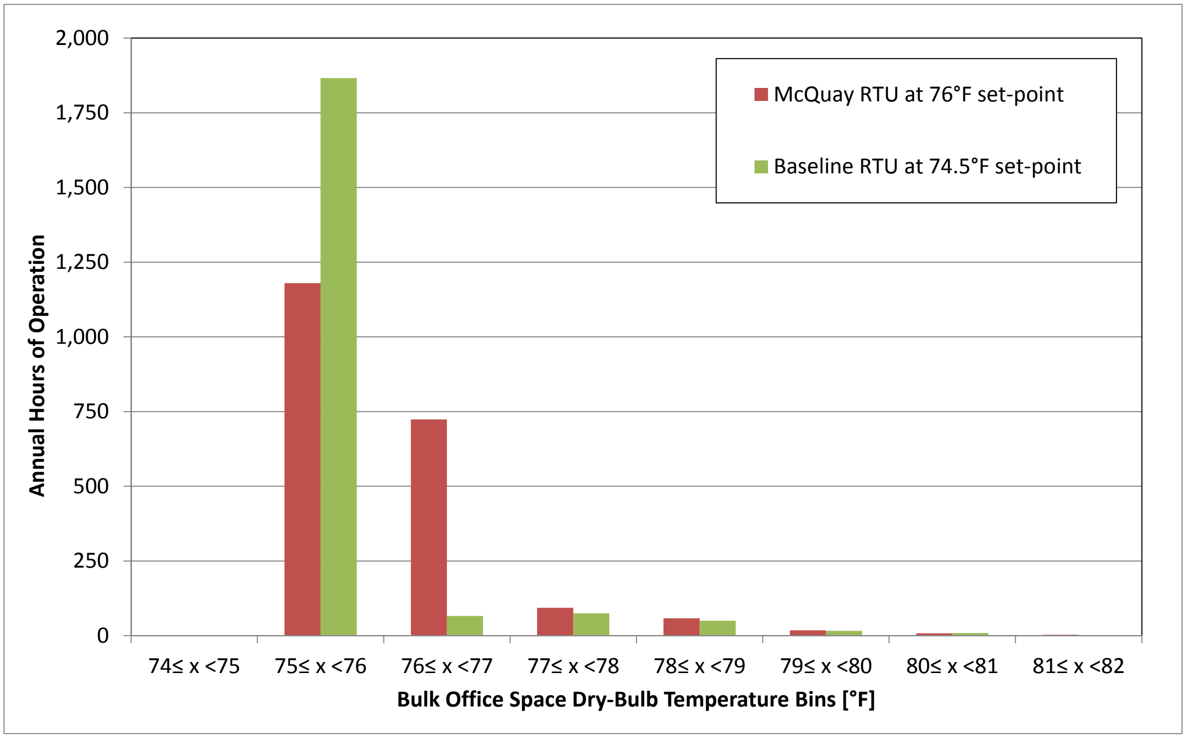


Figure 18. Office space dry-bulb temperature histogram comparing the Rebel model versus the baseline model with a fixed 5% OA damper position

Figure 19 plots the measured space temperature under Rebel-only operation on December 10, 2013 (76°F set point), compared to baseline-only operation on December 4, 2013 (68°F set point). Just focusing on the shape of the temperature profiles (ignoring the set point differences), the Rebel leverages its variable capacity to maintain a smooth temperature profile compared to the baseline, which experiences more dramatic temperature swings because the compressor cycles—at a warmer set point of 74.5°F, the baseline unit experienced a lower cycling frequency but the general trend was the same. Consequently, the smoother temperature control of the Rebel enables it to provide improved thermal comfort despite a larger deadband of 2°F (compared to 1°F deadband for the baseline). Note the Rebel enables users to reduce the deadband control from 2°F to 1°F. NREL recommends the control is kept to a 2°F deadband because it achieves greater energy savings while still providing improved comfort compared to a baseline RTU.

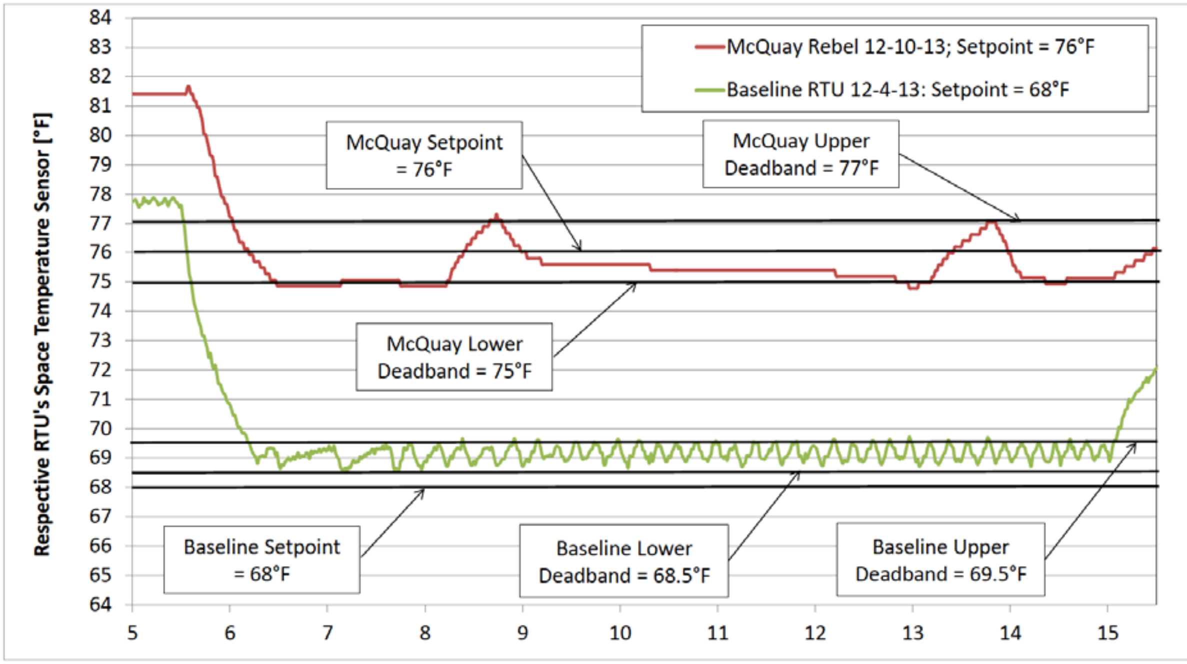


Figure 19. Measured (not modeled) space temperature fluctuation across the day between the Rebel RTU at a 76°F set point and baseline RTU at a 68°F set point

Figure 20 plots the modeling results of the Rebel versus baseline hourly average space RH (operational hours only). This histogram clearly shows the Rebel maintaining a drier space. The annual average space RH during occupied hours was 53% for the Rebel compared to 61% for the baseline. Therefore, the models indicate that by maintaining a constant 60°F DAT, the Rebel was able to maintain a more comfortable space with a lower annual average RH of at least 5% compared to a baseline RTU (see Figure 20).

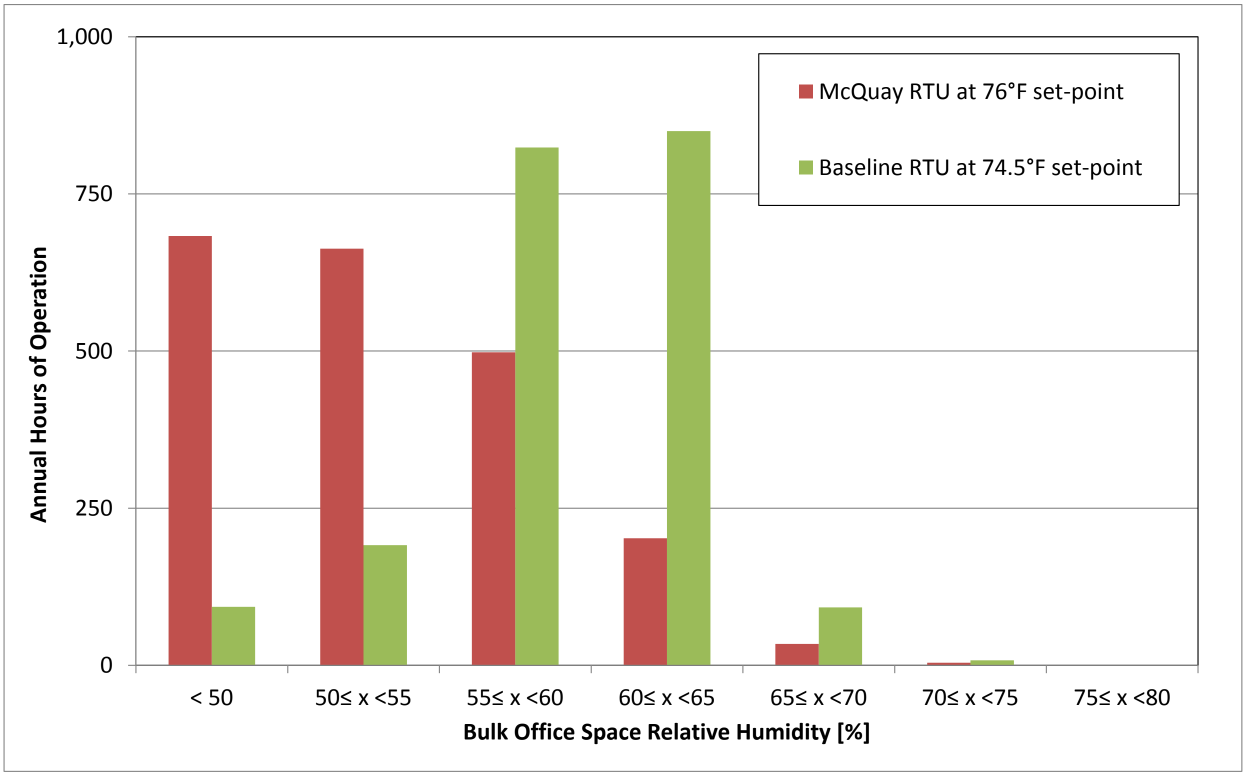


Figure 20. Office space RH histogram comparing the Rebel model versus the baseline model with a 5% OA damper position

For future applications of the Rebel, if a lower moisture condition is desired, the control can be changed to maintain a lower DAT and maintain the same space temperature set point. For example, setting the DAT to 55°F will maintain the supply air dew point lower than 53°F, and the space set point can be left at 76°F. This flexibility enables users to control the Rebel to provide more latent cooling and maintain a drier space—lower RH—if so desired. Note the lower the DAT set point, the lower the overall efficiency of the Rebel, resulting in increased energy usage. To balance space moisture conditions with energy usage, users want to determine the maximum DAT set point that maintains the space under some specified moisture threshold which was 65% RH for this demonstration.

4.4 Ventilation Rates

UFGS 23 05 93 “Testing, Adjusting, and Balancing for HVAC” mandates that ventilation rates must meet ASHRAE standard 62.1-2010 requirements. According to UFC 3-410-01 Section 401.1 (dated July 1, 2013), “Use of CO2 sensors for ventilation control is prohibited unless approved by AHJ.” To provide the most flexibility for applying these demonstration results for future installations (where the AHJ may not grant approval for DCV), NREL operated the Rebel model without DCV capability. Therefore, the annual energy savings provided in Section 4.2 is based on the Rebel meeting ASRHAE 62.1-2010 minimum ventilation requirements.

The building 550 minimum ventilation rates are presented in Table 16. The DCV-based minimum ventilation is provided for reference only, as the Rebel was evaluated without DCV enabled. Compared to other building types, the ASHRAE 62.1 Ventilation Rate Procedure has lower requirements for offices. Table 16 shows the difference between the non-DCV and DCV requirements is approximately 30%.

Table 16. Office Minimum Ventilation Rates per ASHRAE Standard 62.1-2010

Building	Area Served	Occupancy Ventilation Rate	Default Occupant Density	Area Ventilation Rate	Combined Ventilation Rate Inc. Occ. and Area	Min. Required (no DCV)	Min. Required (with DCV)	Delta Between Min. Required
Baseline	2,400 ft^2	5.0 cfm/occ	5 occ/ 1,000 ft^2	0.06 cfm/ft^2	0.09 cfm/ft^2	204 cfm	144 cfm	60 cfm (29%)
Rebel	2,576 ft^2	5.0 cfm/occ	5 occ/ 1,000 ft^2	0.06 cfm/ft^2	0.09 cfm/ft^2	219 cfm	155 cfm	64 cfm (29%)

The ventilation rates of both RTUs were measured during the TAB, and these measurements were input into the energy models. Table 17 shows the baseline RTU far exceeded the ASHRAE 62.1 minimum ventilation rates. NREL was surprised by the significant leakage through the OA damper, even at 0% and 5% positions. To validate these measurements, NREL then directly measured the ventilation flow rate into the damper using a pitot tube grid. At a 5% damper position, NREL measured 487 cfm. At a 0% damper position, NREL again measured 487 cfm. Repeatability in the measurements leads NREL to believe the baseline OA damper was leaking around 500 cfm, even at a 0% OA damper position (approximately 185 fpm face velocity across the OA damper). Consequently, NREL was confident in the TAB results, and therefore, used the Table 17 OA flow rates in baseline models.

Table 17. Baseline RTU Ventilation Flow Rates

OA Damper Position	Ventilation Flow Rate[a]	Meets ASHRAE 62.1
0%	574 cfm	Yes
5%	672 cfm	Yes
20%	1,413 cfm	Yes

[a] Based on TAB measurements.

Table 18 shows the ventilation flow rates calculated at different OA damper and supply fan speed configurations. For the demonstration period and the model, the Rebel was operated from 5% position at 100% fan speed to 15% position at 40% fan speed.

Table 18. Rebel Ventilation Flow Rates

OA Damper Position	Fan Speed	Ventilation Flow Rate[a]	Meets ASHRAE 62.1 Minimum
0%	88%	3 cfm	No
5%	100%	318 cfm	Yes
7%	88%	350 cfm	Yes
11%	63%	288 cfm	Yes
15%	40%	233 cfm	Yes

[a] Based on TAB measurements

The Rebel met the ventilation-based demonstration objectives. At all OA damper and supply fan speed configurations (except for the 0% damper position), the Rebel provided ventilation that exceeded the ASHRAE 62.1 minimum requirement. Additionally, the Rebel maintained an OA flow rate range of 233–318 cfm, which is an approximately 60% reduction from the OA flow rate for the baseline RTU, even at a 0% damper position. Section 4.2 summarizes the annual energy savings impacts of the Rebel maintaining a lower ventilation flow rate while still maintaining the minimum ASHRAE 62.1 requirements (Table 15).

5 Economic Performance Analysis and Assessment

Economic results of the demonstration indicate application of high-efficiency RTUs can yield a positive economic return in Hawaii. In demonstration of the Rebel, the aggregate annual energy savings is estimated at 3.8 MWh/yr for a 10-ton RTU serving a small office building. In comparison to a baseline RTU, minimally compliant with ASHRAE Standard 90.1-2010, NREL estimates a total discounted operational savings of $18,000 over a 15-year operational life, with a simple payback occurring within the ninth year of operation. The economic analysis conducted (results shown in Table 19) was based on a cost different between the Rebel versus the baseline which included the Rebel's larger incremental costs for the cabinet coating, condenser coil coating, extended 5 year parts and compressor warranties, and roof curb. NREL thought it important to add that just comparing the RTUs themselves, excluding these incremental costs, the same energy savings yields a simple payback in the fifth year of operation.

Regional factors, including Hawaii's relatively high electricity pricing and year-round demand for cooling, were key contributors to the cited economic return. Results indicate the Navy would achieve a positive ROI in deployment of this technology in Hawaii assuming a minimum of 15 year economic life. These energy savings and ROI are not directly transferable to other geographic regions (see note b for Table 19). Section 8 states that additional field demonstrations are recommended to quantify savings in other climates that most likely have much lower utility rates.

Table 19 provides a full summary of economic results, in addition to key analysis inputs. Estimates for total discounted operational savings, savings to investment ratio, and simple payback were calculated using the latest version of the National Institute of Standards and Technology-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.[17]

[17] 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 contributions to energy, as well as its 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 indicates the project's benefits are anticipated to exceed its costs. The higher the eROI value, the more attractive the project.

Table 19. Overall Economic Analysis of Rebel RTU Demonstration

Economic Analysis Results		Key Analysis Inputs	
eROI Value	12.4	Annual energy savings	3.8 MWh/yr
Total Discounted Operational Savings	$18,000	Electricity price[a]	$0.425/kWh
Savings to Investment Ratio	1.4	Investment cost delta[b]	$14,519
Simple Payback	<9 years	Units installed	1
Adjusted Internal Rate of Return	5%	Economic life	15 years

[a] Electricity pricing reflects the average price of FY 2013 and FY 2014 rates at JBPHH.
[b] Investment delta reflects the calculated difference in the purchase price between a code-minimum, baseline RTU versus the high-efficiency RTU including the Rebel's larger incremental cost adds for the cabinet coating, condenser coil coating, extended 5 year parts and compressor warranties, and roof curb. Excluding these incremental costs, the investment cost delta is $9,679.

Based on the uncertainty analysis (Appendix H), the annual energy savings of 3.8 MWh/yr is ±27% based on a 95% confidence interval. Consequently, the economic analysis metrics provided in Table 19 also realize the same uncertainty band.

Beyond the uncertainty bands in the predicted annual energy savings, economic results were reviewed to evaluate performance sensitivities and potential sources of error in the estimates provided. Three key factors are identified and described below:

- **Utility electricity rate volatility**. Significant volatility in JBPHH utility rates from FY 2013 to FY 2014 indicate analysis results may be susceptible to uncertainty in projecting future year utility rate pricing. More specifically, electricity rates jumped from $0.24/kWh in FY 2013 to $0.58/kWh in FY 2014. The expectation, based on discussion 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 this demonstration, as applied to JBPHH.

  A preliminary sensitivity analysis was performed to evaluate the effect of electricity pricing uncertainty on economic yield. Figure 21 shows savings to investment ratio estimates for a 15-year economic life across an electricity pricing range of $0.325–$0.525/kWh. This range encompasses a ±$0.10/kWh sensitivity band around the nominal rate applied to the economic analysis. As indicated by the figure, electricity pricing has a significant impact on estimated economic return.

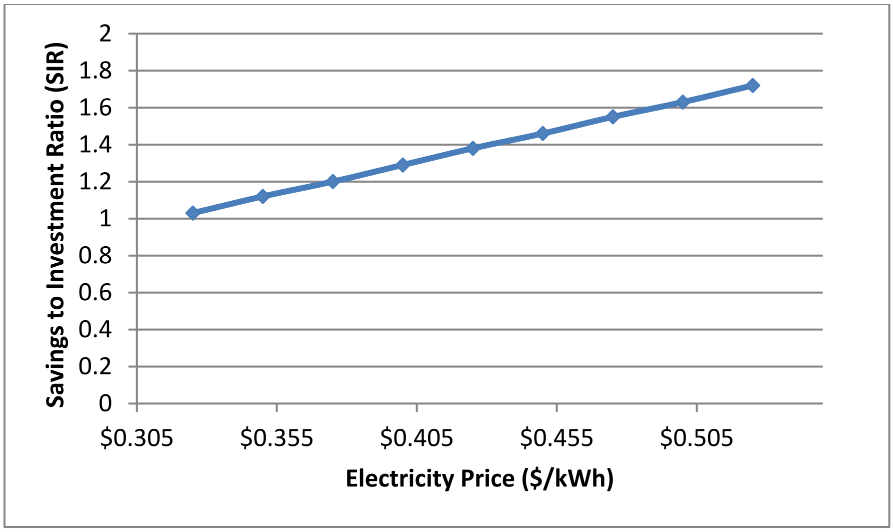


Figure 21. Sensitivity analysis on electricity pricing

- **Results are region-specific**. Electricity pricing, weather patterns, and climate are key input parameters in estimating energy and 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. Energy and cost saving estimates as presented, although promising, are not directly translatable to other geographic regions.
- **Results based on a single sample**. The annual energy savings was calculated by comparing a single high-efficiency RTU to a single, code-minimum, baseline RTU serving one type of building, a small office. Applying the annual energy savings from this field demonstration to a larger population for potential future high-efficiency RTU installations is susceptible to significant sampling uncertainty. In Section 8, NREL recommends additional monitoring of other high-efficiency RTU installations to achieve a larger sample size with which to provide greater confidence in the annual energy saving expectations.

6 Project Management Considerations

Execution of this technology demonstration was programmatically straightforward. Challenges experienced were unique to the constraints of the demonstration. Section 6.2 summarizes how the acquisition using a minor construction contract mechanism resulted in lack of response from several design-build firms b burdensome administrative requirements associated with the demonstration. Further deployment of this technology should not present significant challenges beyond those typical to the installation of RTUs. There are negligible cost differences in the design (Section 6.3) and installation (Section 6.4) activities between high-efficiency and baseline RTUs. Table 20 provides a summary of programmatic elements of this project and a high-level timeline of events.

Table 20. Summary of Programmatic Elements

Programmatic Summary		
Implementation Method	Design-build contractor, minor construction	
Key Contractors	TWT Critchfield Pacific Inc.	
Period of Performance	20 months	
Project Timeline	March 2012–September 2012	Site selection and approval
	October 2012–February 2013	Design build solicitation and award
	March 2013–June 2013	Design
	June 2013–July 2013	Site construction
	August 2013–October 2013	Commissioning and TAB
	October 2013–January 2014	Demonstration

6.1 Site Approval, National Environmental Policy Act, and DD1391

Site selection was based on identification of facilities needing RTU replacement and evaluation of these facilities in providing an effective environment for comparison of the high-efficiency RTU to a baseline RTU. Site approval, the National Environmental Policy Act, and DD1391 activities were required for this demonstration. All of these activities presented minimal administrative burden and were performed over a period of a few months. For the National Environmental Policy Act evaluation, a categorical exclusion was determined.

6.2 Contracts and Procurement

The implementation strategy for this project used a competitively selected design-build contract. As a technology demonstration of a set of two RTUs, acquisition using a minor construction, the design-build contract presented a solicitation challenge. Applicable Division 01, General Requirements, utilized by this project are presented in Table 21.

Table 21. Applicable Division 01, General Requirements

Unified Facilities Guide Specifications	
Division 01—General Requirements	
01 11 00	Summary of Work
01 14 00	Work Restrictions
01 30 00	Administrative Requirements
01 33 00	Submittal Procedures
01 35 26	Governmental Safety Requirements
01 45 00.10 20	Quality Control for Minor Construction
01 57 19.00 20	Temporary Environmental Controls
01 74 19	Construction and Demolition Waste Management
01 78 00	Closeout Submittals

For future acquisitions, we recommend the following:

1. Facility owners should consider defining equipment conditions that determine an RTU's useful lifetime, accounting for economic considerations and applicable climate zones.
2. Facility owners should perform an evaluation of their RTUs, using defined conditions of a useful lifetime, which will enable them to determine whether a funded action constitutes an activity of "repair" or "construction." This is especially important for government agencies to ensure the correct funding mechanism is applied.
3. Projects should be considered for individual facilities (that result in a complete and usable facility) within funding source restrictions. Economy-of-scale benefits are, however, realizable in a large number of multifacility deployments of this technology.
4. Extended warranties should be considered, but economic payback should be considered in evaluation of the net benefits.

6.3 Design

Design requirements of the Rebel RTU were limited and consistent with installations of commercially available RTUs. A roof curb was required for transitioning the Rebel RTU from a vertical discharge to a horizontal discharge unit. This is not a typical requirement in RTU installations. UFGS facility construction and technical design specifications were developed, and are presented in Table 22.

Table 22. UFGS Facility Construction/Technical Design Specifications Used in the Construction Activity

Unified Facilities Guide Specifications	
Division 23—Heating, Ventilating, and Air Conditioning	
23 00 00	Air Supply, Distribution, Ventilation, and Exhaust Systems
23 05 93	Testing, Adjusting, and Balancing for HVAC
23 08 00.00 10	Commissioning of HVAC Systems
23 09 53.00 20	Space Temperature Control Systems
23 82 02.00 10	Unitary Heating and Cooling Equipment
Division 26—Electrical	
26 00 00.00 20	Basic Electrical Materials and Methods
26 20 00	Interior Distribution System

6.4 Installation and Construction *(includes permitting, interconnect agreements, factory acceptance testing, commissioning)*

RTU installation was straightforward and easily executed for the baseline and Rebel RTUs. Except for some additional commissioning work to set up the Rebel's more advanced controller, there was no difference in the construction activity or construction cost between the baseline and Rebel. The additional Rebel controls configuration is no more than 2 hours during the commissioning activity. The additional 2 hours of a commissioning agent were not factored into the economic analysis in Section 5, as this additional cost was minimal relative to the cost of the entire installation; an additional 2 hours of commissioning costs approximately $300, based on $150 per hour.

Both RTUs were installed over the course of a few weeks. Utilization of a crane for removing existing RTUs and installing the new RTUs presented the greatest degree of permitting and site coordination but remained consistent with this type of construction activity.

TAB of the RTUs did present some scheduling challenges. Initial TAB report results were not consistent with ASHRAE 62.1, and a second TAB activity was required. Unfortunately, coordination with the independent TAB provider to execute the second TAB activity took significantly longer than expected; commissioning activities were not completed until October 2013 (3 months postcompletion of RTU installation). These delays, although unfortunate, were related to facility conditions and contractual issues, and were not caused by the technical performance of the installed RTUs.

6.5 Operation and Maintenance

The maintenance activities for the Rebel RTU will be similar to those for a baseline RTU, such as filter changes and blowing drains. Yet, some of the routine maintenance inspections will require interfacing with the advanced controller on the Rebel. The controller settings are numerous and can be overwhelming to an untrained technician. Although Rebel provides significant control, installation, and O&M literature on its website (www.go.Rebel.com/rebel), if NAVFAC begins to adopt high-efficiency RTUs, NREL recommends the NAVFAC HVAC technicians receive formal training to work on them. As a part of the DOE challenge specification, these high-efficiency RTUs incorporate more sophisticated AFDD. The advanced controller on the Rebel can be leveraged for enhanced troubleshooting and deep dive assessment of system components.

6.6 Training

At the completion of the construction activity, NREL, subcontractor TWT, and the local Rebel distributor, Norman S. Wright, held a 3-hour training for NAVFAC HVAC technicians. One hour was spent in the classroom reviewing the capabilities of the Rebel and reviewing the control and O&M literature for the unit. Two hours were spent at the Rebel RTU, reviewing the system layout and interfacing with the controller. In Section 8, NREL recommends NAVFAC HVAC technicians receive formal Rebel training to enable them to provide the same level of maintenance they currently provide on baseline RTUs. NAVFAC HVAC shop's standard routine maintenance procedure is summarized in Appendix I.

7 Commercial Readiness Qualitative Assessment

High-efficiency RTUs that meet the DOE Challenge specification are at technology readiness level 9. In addition to the Rebel, Carrier has a high-efficiency RTU called the WeatherExpert. Table 23 provides a summary. Both Rebel and Carrier distributors in Hawaii have been trained on these two new units. These high-efficiency RTUs currently are higher priced and have a 6-week longer lead time than their standard RTU equivalents.

Table 23. Commercially Available DOE RTU Challenge RTUs

Daikin Applied Rebel (DPS) (www.go.rebel.com/rebel)	**Carrier WeatherExpert (48LC / 50LC)** (www.carrierweatherexpert.com)
3–15 ton capacity	3–23 ton capacity
18.5–20.6 IEER range (>5 ton) 16.9-17.0 SEER range (≤5 ton)	17.8–20.8 IEER range (>5 ton) 17.1–17.5 SEER range (≤5 ton)
Variable-speed lead compressor Fixed-compressor added above 5 tons	Fixed-speed compressors 2 stages ≤5 ton; 3 stages >5 ton
Variable ECM direct-drive supply fan	Variable-speed belt-driven supply fan ECM direct-drive option for ≤5 ton
Variable-speed direct-drive condenser fans	Direct-drive ECM condenser fans
Low-leakage OA damper with dry-bulb or enthalpy economizing and DCV capability	Low-leakage OA damper with dry-bulb or enthalpy economizing and DCV capability
Heat pump, electric heat, gas heating	Electric heat, gas heat
Heat pump COP @ 47°F 3.33–9.2 Heat pump COP @ 17°F 2.5–2.75	N/A

HVAC technicians will require additional training to maintain, repair, and fully benefit from the more sophisticated controls and advanced technology features. The Rebel is a much more sophisticated RTU, particularly with its variable refrigerant flow system. Compared to standard one or two stage thermostatic control, the Rebel controller has many more configuration options. NAVFAC HVAC technicians will need to have training specific on the Rebel, particularly on interfacing with the controller to change control and troubleshoot by leveraging the Rebel's extensive AFDD capabilities. The Rebel supplier in Hawaii, Norman S. Wright, has a field technician who has received the advanced training on the Rebel. At first, NAVFAC will need to rely heavily on external HVAC technicians, who have been specifically trained on these high-efficiency RTUs to resolve advanced maintenance issues. Eventually, NAVFAC HVAC technicians will achieve the skills and confidence necessary to perform the same level of maintenance they currently perform on code minimum RTUs.

To leverage the full performance of the WeatherExpert, the unit should be controlled using Carrier's ComfortLink interface or by a building management system to enable the supply fan's variable speed capability and separately control each cooling stage. The WeatherExpert's incorporation of belt-driven supply fans and standard fixed-speed compressors may be less of a technology jump for NAVFAC HVAC technicians compared to the Rebel. As the Navy continues to demonstrate these types of high-efficiency RTUs, the performance impacts should be analyzed and captured for incorporation into revisions of the UFGSs and UFCs.

8 Recommended Next Steps

The Rebel RTU showed significant (34%–37%) energy savings compared to the code-minimum, baseline RTU meeting UFGS 23 81 00 00 20. For the Hawaii climate, the year-round demand for cooling and dehumidification translates these large percentage savings into larger kilowatt-hour savings compared to RTUs in less cooling dominated climates. Because high-efficiency RTUs are new to the industry (2 years for the Rebel and 1 year for the WeatherExpert), they have a significant cost premium, which reduces their cost effectiveness.

Yet, NAVFAC new construction or retrofit projects should find that high-efficiency RTUs meeting the DOE RTU challenge specification will meet the DOD's ROI criteria based on life cycle cost analysis, not just using the simple payback metric. Life cycle cost analysis is required according to UFC 1-200-02 for either new construction or replacement activities.

Based on NAVFAC's adoption of high-efficiency RTUs, NREL has three recommendations:

1. Conduct field demonstrations of other high-efficiency RTUs that meet the DOE RTU Challenge (such as the Carrier WeatherExpert) in Hawaii and leverage the results of other ongoing demonstrations. More specifically, DOD is partnering with the DOE on additional field demonstrations of DOE Challenge RTUs. These demonstrations should be completed by spring 2015. NAVFAC is participating in three of these demonstrations within the continental United States. NREL recommends comparing the energy savings discussed in this report with these other demonstrations in different climates.
2. In a coordinated manner, train NAVFAC HVAC technicians on these high-efficiency RTUs. To be successful over the long term, the NAVFAC HVAC technicians will need specific training to provide the same level of maintenance they provide on code-minimum RTUs. Appendix I provides a summary of typical maintenance procedures NAVFAC technicians provide quarterly on RTUs. The nature of HVAC, particularly in Hawaii and Guam where cooling is continuous, is that maintenance issues will always arise. Daikin Applied offers 2.5-day training classes on the Rebel at its facility in Plymouth, Minnesota.[18] At the time of writing this report, NREL was not aware of specific WeatherExpert training by Carrier. NREL recommends NAVFAC contact its local HVAC distributors to learn about local, on-site training. NREL contacted Rebel and Carrier distributors for Hawaii and was told that custom training can be provided to NAVFAC HVAC technicians.
3. Incorporate 2 to 4 hours of additional commissioning time for each high-efficiency RTU installation. The greater control complexity of these RTUs needs additional attention from a commissioning agent to maximize comfort and energy savings. In addition, Carrier and Daikin Applied stated that they can pre-program their controllers in the factory based on NAVFAC's specific control requirements, thereby reducing installation time and maintaining consistent high performance in the field. Moreover, Daikin Applied has started to offer remote on-going commissioning by connecting to their controller over a cellular modem. NAVFAC should investigate these on-going services from manufacturers or third parties, incorporating the potential deferred O&M costs and improved energy savings within their life cycle cost analysis.

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[18] "Rebel Rooftop Training Course." Daikin Applied, 2014. http://www.daikinapplied.com/training.php.

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Appendix A: ClimaCheck Methodology

Figure A-1 and Figure A-2 show the schematics of the Rebel and baseline RTUs through the ClimaCheck website. For each minute of DX operation, the ClimaCheck methodology utilizes refrigerant pressure, refrigerant temperature, and compressor power measurements to calculate real-time EER and cooling capacity.[19]

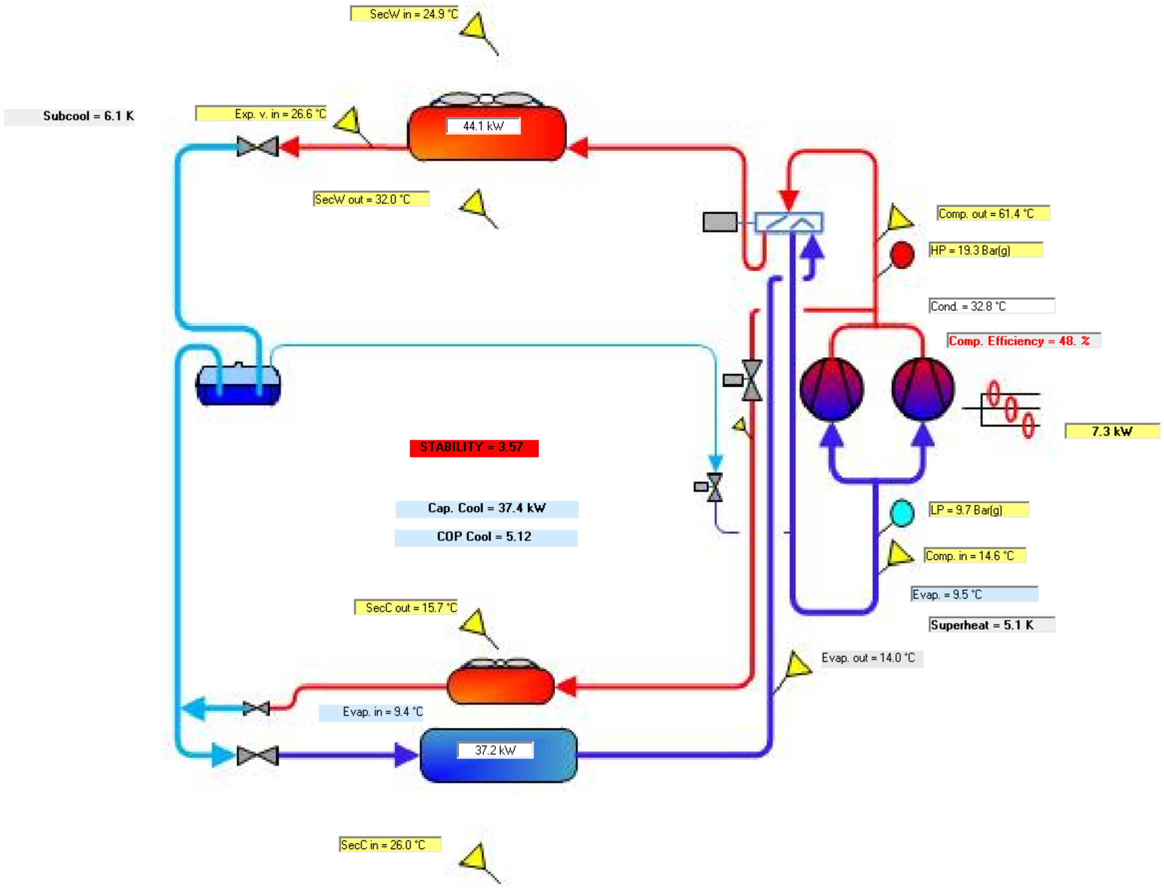


Figure A-1. Rebel refrigerant-side monitoring (instance December 10, 2013 6:40)

Source: ClimaCheck

[19] Berglof, K. *Performance Inspections with Innovative Analyzing Equipment Results in Significant Energy Savings in Air-Conditioning and Refrigeration Systems.* Accessed January 10, 2013: www.eeswest.com/wp-content/themes/xero/pdf/pr-berglof-performance-inspections-iir-prag-2011(v2).pdf.

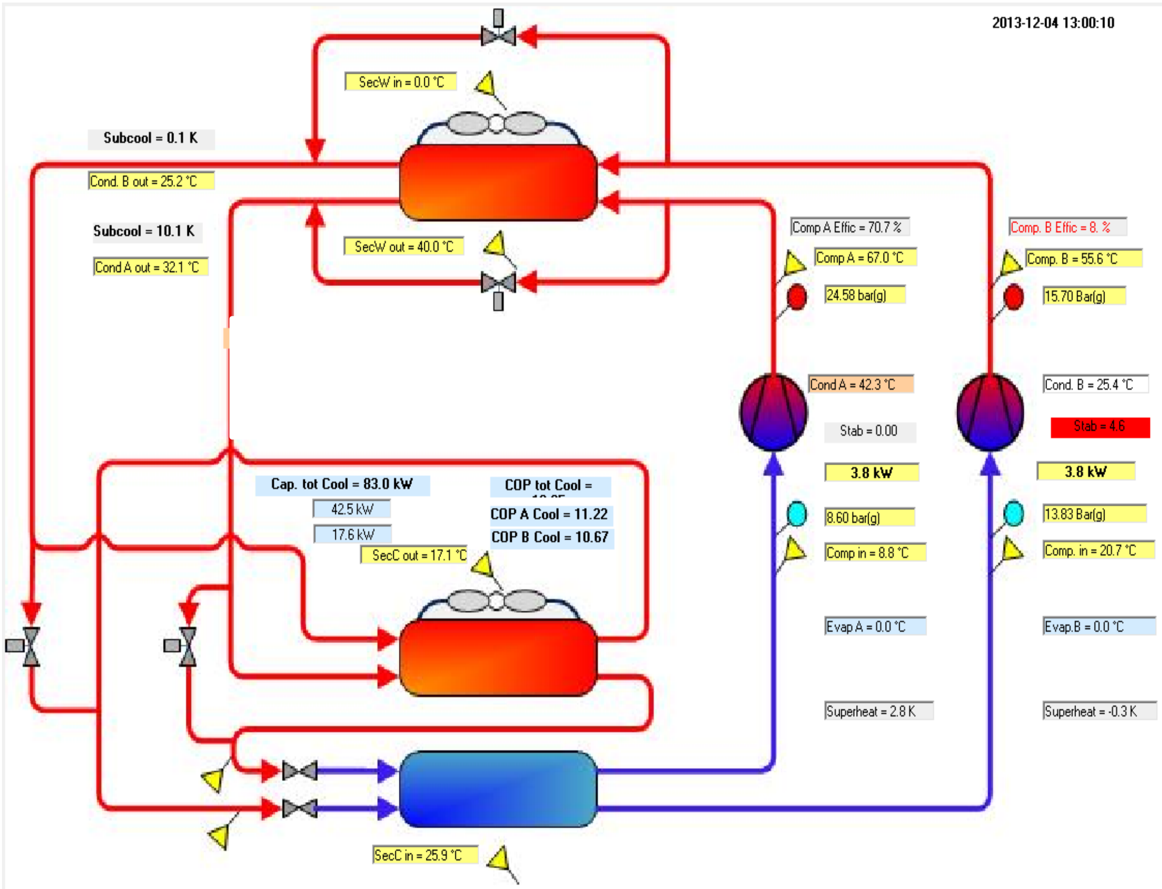


Figure A-2. Baseline refrigerant-side monitoring (instance December 4, 2013 13:00)

Source: ClimaCheck

Appendix B: Model Geometry, Envelope, and Internal Loads

NREL dimensioned the entire space and developed a three-dimensional model of building 550, as shown in Figure B-1. Based on the actual air distribution layout, the space was split into two separate thermal zones. The southern zone (dimensioned 60 feet × 43 feet) was served by the Rebel. The northern zone (dimensioned 60 feet × 40 feet) was served by the baseline RTU. The two zones were simulated to exchange air based on a 1 flow per minute air cross-flow through the imaginary wall that split the space. The southernmost wall was simulated as adiabatic (no heat transfer) as the actual wall abutted a separately conditioned space on the other side of the building.

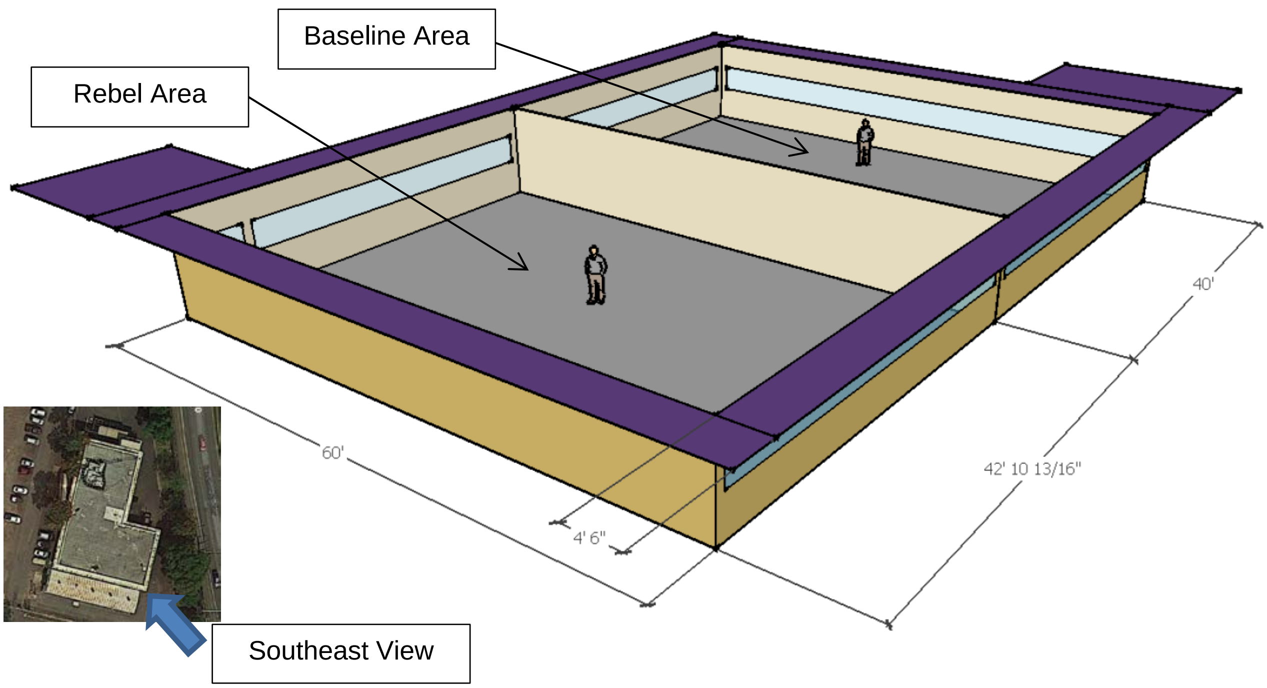


Figure B-1. Southeast view of building 550 model

Source: Google Maps and NREL SketchUp Model

Table B-1 summarizes the model parameters that significantly influence building sensible and latent heat loads. The model included the 4.5-foot overhang around the entire building's perimeter to capture the shading impacts (purple in Figure B-1). The internal sensible and latent loads were based on the artificial loads actually set up in the space during the demonstration period using heat lamps and humidifiers on timers (see Section 3.4). Two of the model inputs, infiltration rate, and window properties (SHGC and U-value), were not known or measured. Therefore, NREL adjusted these parameters within appropriate bounds for calibrating the models. All the assumptions are specified in Table B-1.

Table B-1. Summary of Building Envelope and Internal Load Parameters

Parameter	Comments
Total Area = 4,976 ft^2	Total model dimensions 60 ft × 83 ft; Rebel side 2,576 ft^2; Baseline side 2,400 ft^2
Floor = Carpeting over 8-in. Concrete[a] Slab	Based on structural drawings; underside of slab set to adiabatic (no heat transfer) as first-floor space was separately conditioned to 76°F
Wall = 10-in. Concrete[a]	Based on structural drawings; no wall insulation
Roof = Black Asphalt over 8-in. Polystyrene above 6-in. Concrete[a] Slab	Based on structural drawings and measured roof insulation during RTU installation; total construction R-value = 42 h-ft^2-F/Btu
Window Area = 668 ft^2	Window wall ratio = 0.23; SHGC = 0.5 (double pane with some low-e coating); U-value = 0.50; SHGC and U-value assumed, no data available regarding window construction type other than being double paned
Nominal Infiltration Set to 0.10 cfm/ft^2 of Exterior Wall Area; Equates to 0.34 Air Changes per Hour for Building 550	Based on typical building envelope pressure of 0.02 in. WC with typical leakage values[b] for commercial buildings equal to 0.10 cfm/ft^2 of exterior wall area; nominal infiltration rate is modified; each model time step based on the DOD BLAST program's (predecessor to EnergyPlus) recommended equation: 0.606 + 0.03636 (T_{zone}-T_{OAT}) + 0.1177 (WindSpeed)
Overhead Lighting = 1 W/ft^2	Based on count of 151 T-8 fluorescent lights throughout the office space; manually operated by NAVFAC personnel during business weekdays from 0700 to 1500
Occupancy Sensible + Plug Loads = 0.9 W/ft^2	Occupancy sensible and plug loads were based on 4,625 W of heat lamps distributed throughout the space (32 × 125 W and 5 × 75 W); all lights on timers from 0700 to 1700 daily
Occupancy Latent	Installed six humidifiers throughout the space that deliver 1.5 gallons of moisture each per day—therefore, total latent load of 9 gallons delivered each day; total moisture load based on 34 occupants (146 ft^2/occ) at 200 Btuh latent load per occupant; humidifiers are started at 0700 by NAVFAC personnel when the overhead lights are turned on; moisture load in the model is spread across 24 hours as NAVFAC personnel notified NREL that humidifiers were not empty by 1500 when they came to turn the lights off but were empty the following morning

[a] Concrete thermal properties based on 2,300 kg/m^3 density.
[b] Tamura, G.T.; Shaw, C.Y. (1976). "Studies on Exterior Wall Airtightness and Air Infiltration of Tall Buildings." *ASHRAE Transactions* 82(1):122.

Appendix C: Rebel Model Summary

Based on the monitored data, NREL leveraged the Rebel's capability to maintain a constant DAT set point to develop a simple modeling procedure. By always knowing the leaving air dry-bulb temperature, the Rebel RTU model would calculate the total cooling based on the mixed-air conditions (entering the evaporator), ambient dry-bulb (entering the condenser), and supply air flow rate. The Rebel RTU model's supply air moisture content was maintained at 85%–95% RH based on DOE's lab test results of a 10-ton Rebel (Wang et al 2013). The supply air humidity was not monitored in this demonstration because of the significant uncertainty caused by the insufficient accuracy of field RH sensors and difficulty of ensuring the supply air was sufficiently mixed at a single RH sensor location.

The Rebel was modeled exactly as it was controlled during the demonstration period. The supply fan modulated between minimum and maximum flow rates according to a PI control that is summarized below. The Rebel ventilation rate was modeled as if the OA damper opened from 5%–15% as the supply air flow changed from 100% to 40%, respectively. The ventilation rate maintained at all supply fan and OA damper configurations met the minimum ventilation requirements per ASHRAE Standard 62.1 without DCV operation. The Rebel was not modeled with DCV operation per UFC 3-410-01 (dated July 1, 2013). The compressors were controlled to maintain the constant DAT at 60°F (post-supply fan), regardless of the supply air flow rate. If the Rebel compressors at 100% capacity could not achieve a 60°F DAT at a given set of mixed-air conditions and supply air flow rate, the discharge air condition was calculated based on the maximum cooling rate the Rebel could provide.

The Rebel cooling capacity was limited in the model based on the maximum cooling capacity measured during the demonstration period. NREL found the Rebel would peak at 13 tons when the variable-speed compressor was at 100% capacity and the second-stage compressor was operating. These measured maximum cooling capacities occurred for the first 5–10 minutes of the initial morning cooldown period and the first 1–3 minutes that both compressors would turn on after both were off. Therefore, the Rebel's model was limited to 13 tons. Although the Rebel RTU installed had a nominal 10-ton capacity, it could overdrive the variable-speed compressor to achieve 12 tons capacity under nominal conditions. Then, based on the mixed-air conditions (entering the evaporator coil) and ambient dry-bulb (entering the condenser coil), the Rebel RTU can achieve an additional 10% capacity above 12 tons.

The following subsections summarize the Rebel RTU modeling and then summarize the calibration procedure and results. The DX model summary is provided in Section 4.1.

Supply Fan Model

NREL used the TAB report to correlate the fan speed setting at the MicroTech controller to the supply flow rate. Table C-1 summarizes the Rebel model's supply fan performance at different controller fan speed settings. NREL developed a correlation between the controller fan speed setting and supply air flow rate (equation C-1 and Figure C-1).

Table C-1. Rebel RTU Supply Fan Performance Based on TAB Report

Fan Speed Setting on MicroTech Controller	Total Static Pressure	Supply Air Flow[a]	Fan Power[b]	Total Fan+ Motor Static Efficiency
100%	2.54 in. WC	4,069 cfm	2,144 W	63%
88%	1.96 in. WC	3,575 cfm	1,578 W	59%
63%	1.24 in. WC	2,547 cfm	693 W	50%
34%	0.37 in. WC	1,601 cfm	214 W	42%

$$\dot{V}_{SA} = \left(4{,}114 \cdot fan_{setting}\right) - 45 \qquad \text{(C-1)}$$

where
$\dot{V}_{SA}$ *is the supply air flow rate (cfm)*
$fan_{setting}$ *is the control fan speed setting.*

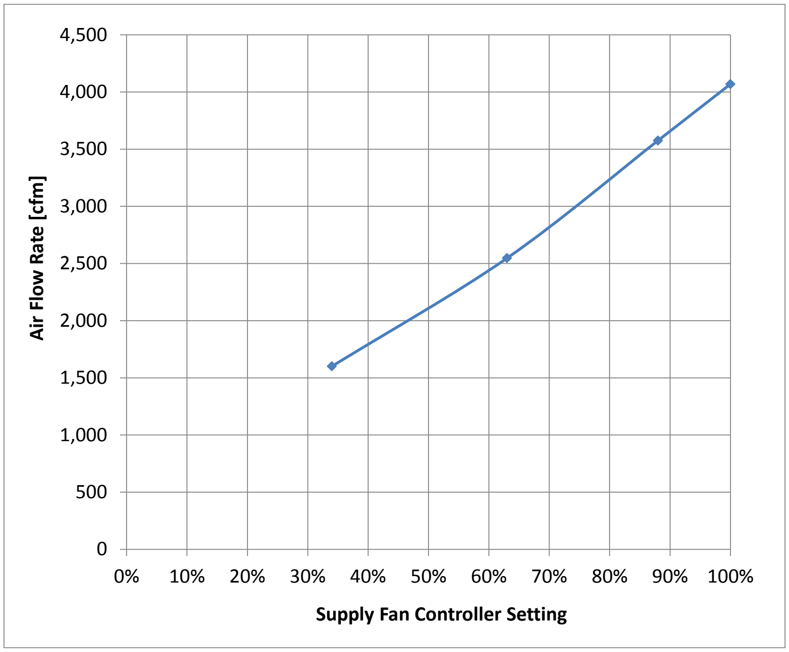


Figure C-1. Correlation between supply fan controller speed setting and supply air flow rate based on TAB

At each fan speed, the model needs the associated total static pressure and total static efficiency to calculate fan power. Equation C-2 and Equation C-3 provide regression models of total static pressure and fan efficiency versus flow fraction, respectively (Figure C-2a). At each time step, the EnergyPlus Rebel RTU model will calculate the supply fan power based on the supply air flow fraction, static pressure, and fan efficiency (Figure C-2b).

$$Pressure\ Fraction = 1.0518 \cdot ff^{2.0269} \tag{C-2}$$

where
Pressure Fraction is the fraction of the peak 2.57 in. WC (639 Pa) pressure at 100% fan speed
ff is the flow fraction of the 4,069 cfm (1.92 m^3/s) supply air flow at 100% fan speed.

$$Fan\ Efficiency\ Fraction = (0.5076 \cdot ff) + 0.5081 \tag{C-3}$$

where
Fan Efficiency Fraction is the fraction of the peak 63% efficiency at 100% fan speed
ff is the flow fraction of the 4,069 cfm (1.92 m^3/s) supply air flow at 100% fan speed.

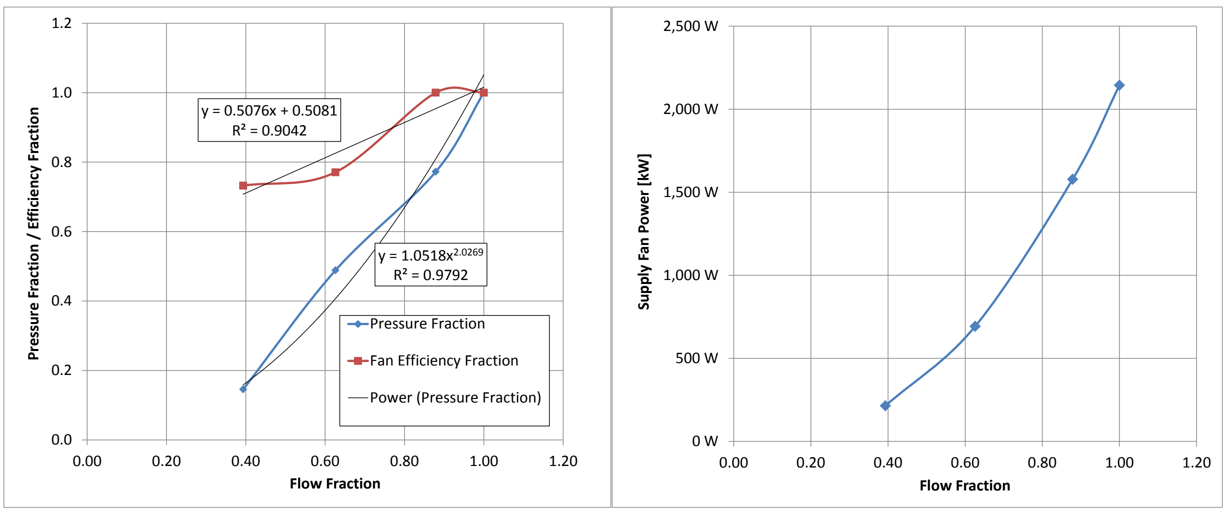


Figure C-2. (a) Regression model of supply fan pressure and efficiency as a function of flow fraction (b) EnergyPlus model of supply fan power based on flow fraction

The Rebel supply fan was controlled based on the single-zone variable-air zone control logic built into the MicroTech III controller. The supply fan modulates its speed between a specified minimum and maximum using a PI control based on space temperatures relative to set point. Rebel defines three PI control parameters including gain, sample time period, and projected ahead time. Due to unstable operation of the supply fan speed identified from the monitored data, on November 1, 2013, these control parameters were changed to the following:

- Gain = 0.8 (originally set to 1.5)
- Sample time = 60 seconds (originally set to 30 seconds)
- Projected ahead time = 400 seconds (originally set to 100 seconds).

Upon startup, the supply fan sequence follows that shown in Table C-2. For the first few minutes, the supply fan goes from off (0), start (1), recirculation (2) to fan only (3). During off and start, the supply fan speed remains at 0%. During recirculation, the supply air flow speed is controlled to the keypad adjustable maximum heating speed (default 100%). When in cooling, the supply fan varies between minimum cooling speed (default 40%) and maximum cooling speed (default 100%) as space temperature changes. During heating, the supply fan speed varies between minimum heating speed (default 40%) and maximum heating speed (default 100%) as space temperature changes. During fan only and minimum DAT, the supply fan is controlled to the minimum cooling speed (default 40%) or minimum heating speed (default 40%), depending on which operation (cooling or heating) the RTU is moving toward.

Table C-2. Fan Operational Sequence Based on Startup

Unit State (BACnet enumeration)	Supply Fan Operation
Off (1)	Set to 0%
Start (2)	Set to 0%
Recirculation (3)	Controlled to keypad-adjusted maximum heating speed defaulted to 100%
Fan Only (4)	

The Rebel implements the PI loop as follows:

- The current space temperature is set at T1. The current error is calculated using equation C-4:

$$error_{current} = T_1 - Set\ Point \quad \text{(C-4)}$$

- The previous space temperature, sample time minutes prior, is set at T2. The previous error is calculated using equation C-5:

$$error_{previous} = T_2 - Set\ Point \quad \text{(C-5)}$$

- Rebel then calculates the projected error based on the rate the error is changing a function of the previous error and current error shown in equation C-6. Projected error equals:

$$Projected\_Error = Current\_Error + \left(\frac{error_{current} - error_{previous}}{ST} * PAT\right) \quad \text{(C-6)}$$

- The change in fan speed (Do) after each sample time period is calculated using equation C-7:

$$\Delta Speed = Gain \cdot (Projected\_Error) \quad \text{(C-7)}$$

Figure C-3 shows a schematic of the PI logic from the Rebel operations manual.

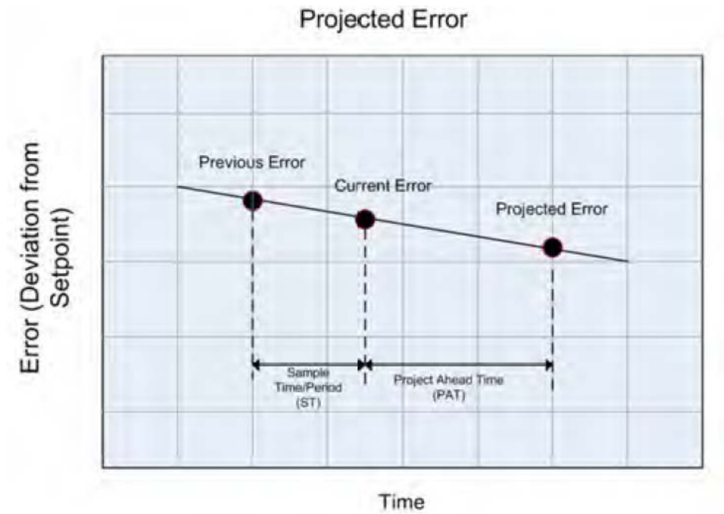
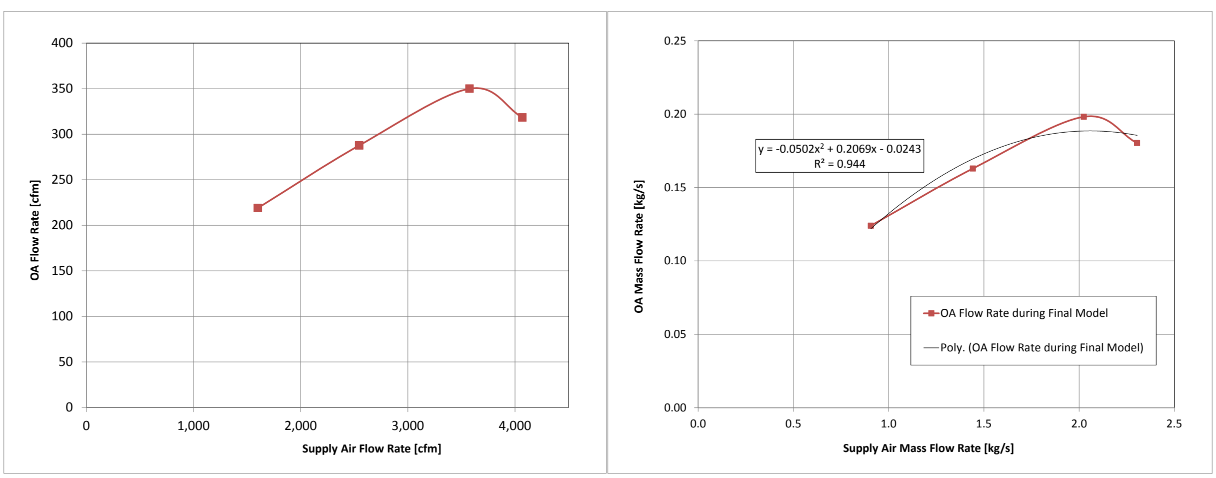


Figure C-3. Projected error timeline from MicroTech III unit controller operation manual

Outdoor Air Flow Rates

During the demonstration period, the OA damper position varied linearly from 5% open at 100% fan speed to 15% open at 40% fan speed. The 40%–100% fan speeds were based on settings on the MicroTech controller. Based on the TAB report, NREL developed a correlation between OA flow rate and supply air flow rate based on this OA damper control (equation C-8 and Figure C-4). The OA flow rates at all fan speeds meet the 219 cfm minimum ventilation requirement (non-DCV) per ASHRAE 62.1. For each time step in the Rebel RTU EnergyPlus model, the OA mass flow rate was calculated based on the supply air mass flow rate.

$$\dot{m}_{OA} = \left(-0.0502 \cdot \dot{m}_{supply}{}^{2}\right) + \left(0.2069 \cdot \dot{m}_{supply}\right) - 0.0243 \qquad \text{(C-8)}$$

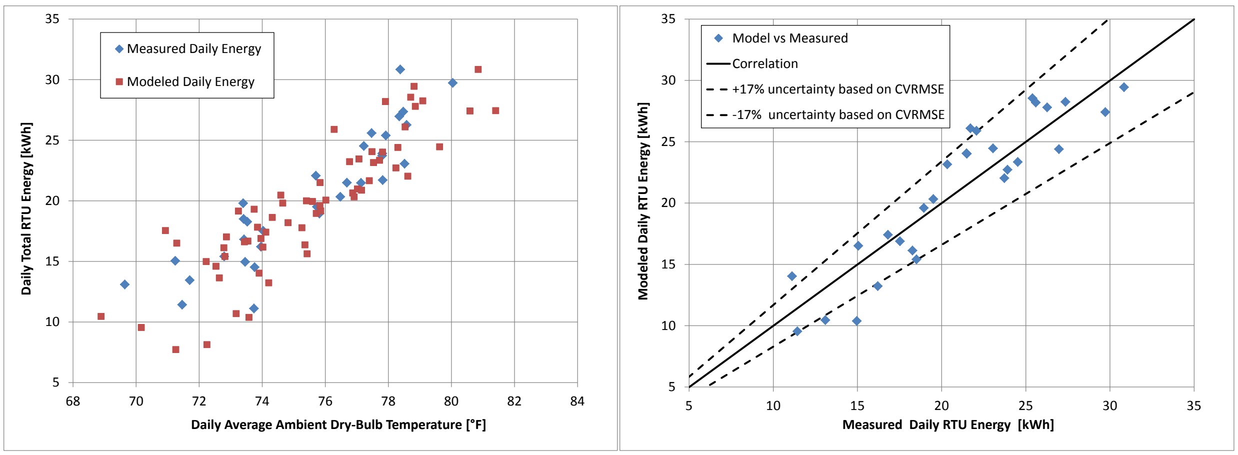


(a) (b)

Figure C-4. OA flow rates based on the supply air flow rate (a) shows flow rates in cfm and (b) shows regression equations relating OA mass flow rates to supply air mass flow rates used in the EnergyPlus model of the Rebel RTU

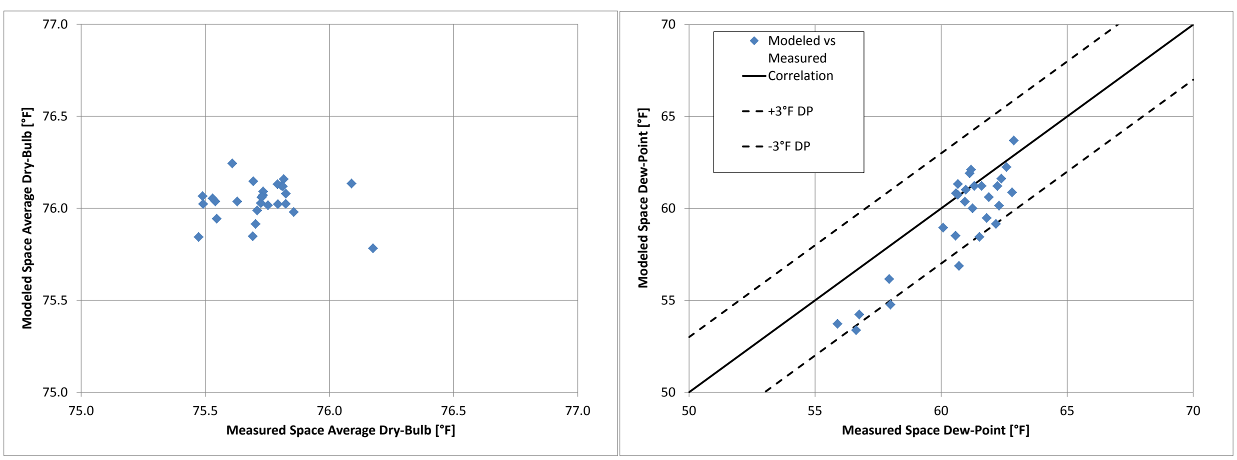
Calibration Results

Figure C-5b shows the whole-building energy model of the Rebel RTU calibrated against the 35 days of the calibration period. The modeled data compare well against the measured daily total energy versus daily average ambient dry-bulb (Figure C-5a). The 17% CVRMSE is the uncertainty of the model. This overlap reinforces the model is properly accounting for the impact of ambient conditions on RTU behavior. Finally, Figure C-6a and C-6b show the model meets the calibration specification of average space conditions within ±1°F dry-bulb and ±3°F dew point, respectively.



(a) (b)

Figure C-5. Rebel RTU model versus measured daily RTU energy usage



(a) (b)

Figure C-6. Rebel RTU model versus measured space dry-bulb and dew point

Appendix D: Baseline Model Summary

The baseline RTU was modeled conservatively without penalizing the cooling capability of the DX circuit for significant compressor cycling. Therefore, the first and second minute after a compressor would turn on, the cooling delivered to the air was modeled as if the compressor had already been operating for at least 3 minutes and had achieved steady state operation. NREL was not able to quantify the compressor cycling degradation, and therefore, did not want to incorporate any degradation in the model that was not supported by monitored performance data. Thus, the baseline RTU model annualized energy usage and performance may be slightly overstated in the final model.

The following subsection reviews the DX regression models that capture power and capacity. The calibrated results are presented next.

Direct Expansion System

The first set of regression equations that correlate DX cooling power were summarized in Section 4.1. The second set of regression equations correlate DX cooling capacity fraction to mixed-air wet-bulb and ambient dry-bulb temperatures (equations D-1 and D-2). Table D-1 summarizes these regression models' parameters. Although the R-squared for these two regressions are low for both stages, the absolute change in capacity is not significant; under first stage the range is 0.4–0.6 and under second stage the range is 0.9–1.2. Compared to compressor power, which was measured using a power transducer with a 3% accuracy specification, the cooling capacity was calculated using the ClimaCheck methodology which has a ±7% uncertainty. The low R-squared was due to a combination of the small variation in capacity at each stage and larger uncertainty of a calculated parameter rather than a measured one.

$$Stage\ 1\ Capacity\ Fraction\ 0.0077 + (0.0096\ \cdot T_{WB}) + (0.0334\ \cdot T_{OA}) + \left(-0.0008\ \cdot {T_{OA}}^2\right) \tag{D-1}$$

$$Stage\ 2\ Capacity\ Fraction\ -2.269 + (0.313\ \cdot T_{WB}) + \left(-0.008\ \cdot {T_{WB}}^2\right) + (0.022\ \cdot T_{OA}) + \left(-0.001\ \cdot {T_{OA}}^2\right) \tag{D-2}$$

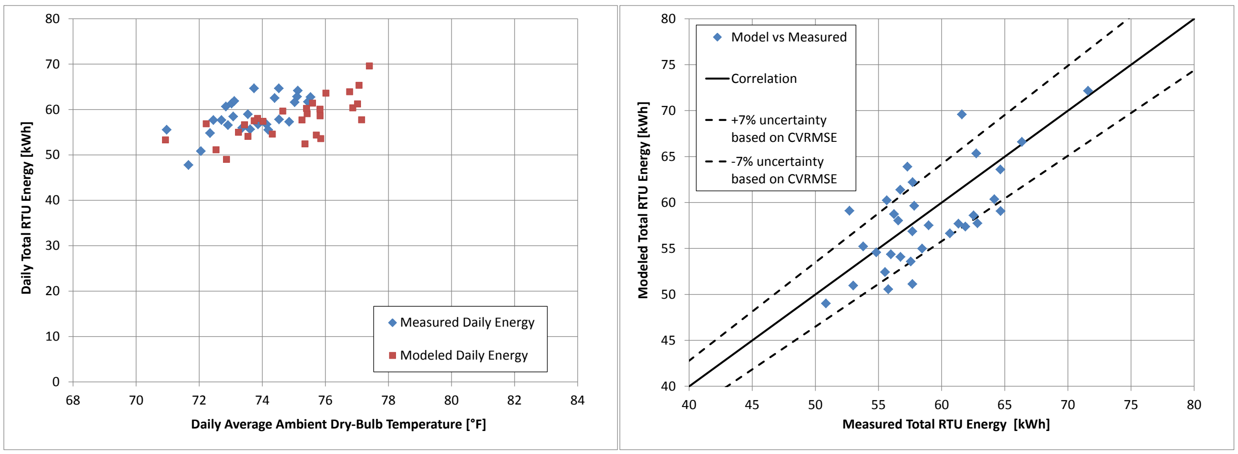
where
Capacity Fraction is the fraction of the nominal cooling capacity,
T_{WB} is the mixed-air wet-bulb temperature entering the evaporator coil (°C), and
T_{OA} is the ambient dry-bulb temperature (°C).

Table D-1. Baseline RTU Cooling Capacity Regression Parameters

	First-Stage DX	Second-Stage DX
Adjusted R-Squared	0.56	0.11
Capacity Fraction Range	0.4–0.6	0.9–1.2
Total RTU Operational Hours for Regressions	173 h	68 h
T_{WB}	62°–68°F	62°–69°F
T_{OA}	62°–86°F	63°–87°F

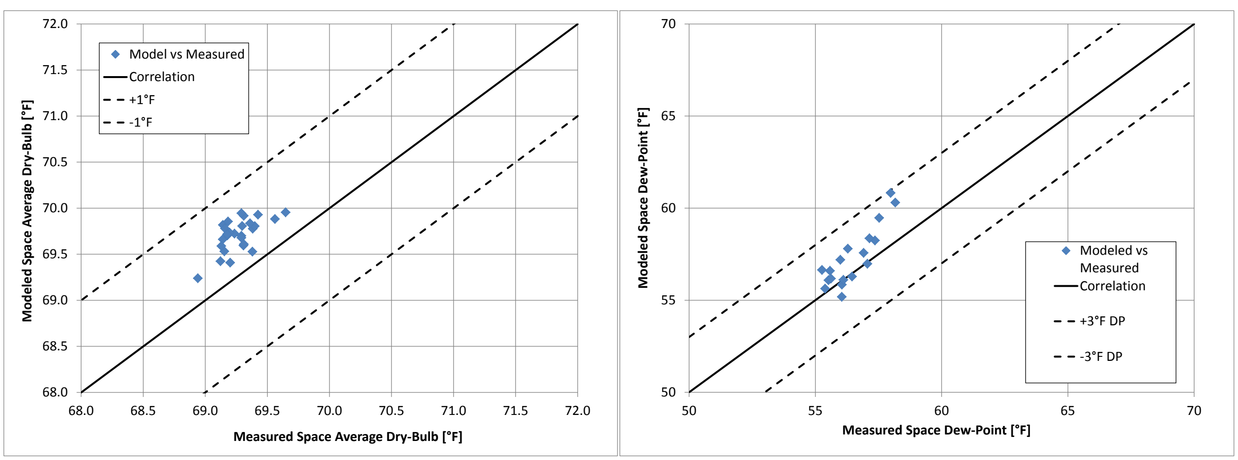
Calibration Results

Figure D-1b shows the baseline RTU model compares well against the measured data with respect to total energy usage per day. Based on the CVRSME, the baseline RTU daily energy usage realized a 75 uncertainty based on a 68% confidence interval. Figure D-1a shows the model captured the impact of dry-bulb temperature on daily energy usage. Figure D-2a and Figure D-2b show the baseline model met the space temperature and dew point specifications for calibration.



(a) (b)

Figure D-1. Baseline RTU model versus measured daily DX energy usage



(a) (b)

Figure D-2. Baseline RTU model versus measured space dry-bulb and dew point

Appendix E: Artificial Internal Sensible and Latent Loads

The heat lamps and humidifiers were configured to maintain a uniform distribution across the second-floor office space such that both RTUs would be exposed to nearly the same internal loads. Although the space is somewhat divided in two because of two separate air distribution systems, there is significant air mixing because there is no wall separating these spaces. As the Rebel conditions 176 ft^2 more than the baseline, the additional internal sensible gain was considered negligible. Table E-1 summarizes the number of air diffusers and the internal sensible load due to overhead lights, which NREL coordinated with NAVFAC to turn on and off during the demonstration period. Table E-2 summarizes how heat lamps were installed throughout the space to represent occupant and plug load heat gains. Table E-3 summarizes the combined overhead lights, occupant, and plug load sensible internal gains.

Table E-1. Overhead Lighting Power and Schedule Maintained During the Demonstration Period

	Area	4-Way Air Diffusers		Overhead Lights[a]		
Baseline RTU's Side of the Office Space	2,400 ft^2	12	200 ft^2/diff	73 T-8s	2,336 W	1 W/ft^2
Daikin Applied Rebel's Side of the Office Space	2,576 ft^2	9	286 ft^2/diff	78 T-8s	2,496 W	1 W/ft^2
Combined Second-Floor Office Space	4,976 ft^2	21	237 ft^2/diff	151 T-8s	4,832 W	1 W/ft^2

[a] NREL coordinated with NAVFAC to have the overhead lights turned on throughout the second-floor office space in the morning between 0630–0730 until the end of the day between 1600–1700. Each T-8 bulb consumes 32 W.

Table E-2. NREL Installed Heat Lamps to Represent the Sensible Loads from Occupants and Plug Loads

	Expected Full Occupancy[a]				Plug Load Power Draw Based on Full Load Occupancy[c]		Installed Heat Lamps[b]		
Baseline RTU's Side of the Office Space	17 occ	141 ft²/occ	4,250 Btuh	1,245 W	1,105 W	0.5 W/ft²	17 × 125 W heat lamps 3 × 75 W heat lamps	2,350 W	1 W/ft²
Daikin Applied Rebel's Side of the Office Space	17 occ	152 ft²/occ	4,250 Btuh	1,245 W	1,030 W	0.4 W/ft²	15 × 125 W heat lamps 2 × 75 W heat lamps	2,275 W	0.9 W/ft²
Combined Second-Floor Office Space	34 occ	146 ft²/occ	8,500 Btuh	2,490 W	2,135 W	0.4 W/ft²	32 × 125 W heat lamps 5 × 75 W heat lamps	4,625 W	0.9 W/ft²

[a] Based on the office layout and interviewing the original occupants, NREL determined the full load occupancy of the space, which resulted in a typical office space occupancy density of ~150 ft²/occupant. Note that per standard office activity metabolic rates and average occupant size, each occupant emits 250 Btuh.
[b] Based on the full load occupancy, NREL determined the typical plug load density throughout the space, which resulted in 0.4 W/ft².
[c] Beyond the sensible heat gains from the overhead lights, the internal heat gains come from occupants and plug loads. NREL installed heat lamps on timers to represent these sensible loads. The timers were set to operate from 0700–1700 daily.

Table E-3. Total Internal Sensible Heat Gain from Overheat Lighting and NREL's Installed Heat Lamps on Timers

	Area	Total Office Space Internal Sensible Heat Load including Overheat Lights, Occupant Heat Gain, and Plug Loads				
Baseline RTU's Side of the Office Space	2,400 ft²	4,686 W	15,993 Btuh	1.3 tons	2.0 W/ft²	6.7 Btuh/ft²
Daikin Applied Rebel's Side of the Office Space	2,576 ft²	4,771 W	16,283 Btuh	1.4 tons	1.9 W/ft²	6.3 Btuh/ft²
Combined Second-Floor Office Space	4,976 ft²	9,457 W	32,277 Btuh	2.7 tons	1.9 W/ft²	6.5 Btuh/ft²

Similar to the sensible internal loads, NREL calculated the latent load based on a fully occupied office space. Table E-4 shows how six 1.5-gal humidifiers were distributed throughout the space to represent the moisture load of 34 occupants. After the NAVFAC representative turned on all the overhead lights each morning between 0630–0730 they filled each humidifier and ensure they were plugged in. Each humidifier was on a timer and staggered across the day to ensure a consistent vaporization, rather than having all the humidifiers on at once in the morning.

Table E-4. NREL Set Up Humidifiers on Timers to Represent the Total Internal Latent Heat Gain from Occupants[e]

	Full Occupancy[a]		Latent Load[b,d]		Daily Moisture Volume[c]	Installed Humidifiers	
Baseline RTU's Side of the Office Space	17 occ	141 ft^2/occ	3,400 Btuh	996 W	4.2 gal/day	3 × 1.5-gal humidifier	~4.5 gal/day
Daikin Applied Rebel's Side of the Office Space	17 occ	152 ft^2/occ	3,400 Btuh	996 W	4.2 gal/day	3 × 1.5-gal humidifier	~4.5 gal/day
Combined Second-Floor Office Space	34 occ	146 ft^2/occ	6,800 Btuh	1,992 W	8.4 gal/day	6 × 1.5-gal humidifier	~9.0 gal/day

[a] Based on the office layout and interviewing the original occupants, NREL determined the full load occupancy of the space, which resulted in a typical office space occupancy density of 150 ft^2/occupant.
[b] Latent load based on 200 Btuh/occupant.
[c] Based on the number of occupants and 200 Btuh latent load per occupant, calculated the daily total gallons of water that should be vaporized to represent occupant latent loads for the office space.
[d] To represent the internal occupant latent load, NREL set up humidifiers staggered on timers that would vaporize sufficient gallons across the day starting at 0700. Note that floor fans were trained on the humidifiers to speed the diffusion of moisture throughout the office space.
[e] Regarding infiltration, NREL coordinated with NAVFAC to leave the entrance doors open while they were at building 550 in the mornings and afternoons to turn on/off the overhead lights and the humidifiers. One of the windows was left propped open to capture some additional infiltration from occupants entering/leaving the building during the workday.

Appendix F: Baseline and Rebel Monitoring Points

Table F-1 summarizes all the monitoring points maintained on the baseline RTU other than the baseline ClimaCheck monitoring points. Similarly, Table F-2 summarizes the Rebel RTU monitoring points in addition to the ClimaCheck monitoring points.

Table F-1. Baseline RTU Monitoring Points

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 variable frequency drive Output	unknown	Value is monitored 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)	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	±0.36°F	RTD in supply air ductwork
Analog-4	MA Temp Sensor	Add	ACI-AN Series	±0.36°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

Digital or Analog Signal	Monitoring Point	Catalyst Standard Sensor or Demonstration Add	Sensor Manufacturer/Model	Sensor Accuracy	Sensor Notes
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 return air ductwork
Analog-8	Space Temperature	Add	ACI A/1K-2W	±1.1°C (1.9°F)	Wall-mount temperature sensor located 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

Table F-2. Rebel Monitoring Points[20]

BACnet Variable Name	Description
Eq_ID	
Timestamp	
FanSpeedRebel	Remapped from "Supply Fan Capacity (SupFanCap)." This read-only attribute indicates the current supply fan capacity. The BACnet property reads only the subject attribute; however, the LONWORKS variable is only a part of the LONWORKS Unit Status network variable. See Unit State for details. This variable will read 0% whenever the fan is off. If the unit is configured as constant volume, this variable reads 100% when the fan is on. Otherwise, it will read the feedback from the variable-frequency drive.
OATempRebel	Remapped from "Outdoor Air Temperature (OutdoorTemp)." This read-only attribute indicates the current value of a unit-mounted outdoor air temperature sensor. This variable only applies if the unit is configured for an outdoor air temperature sensor.

[20] Daikin. March 2013. "MicroTech III Unit Controller for Rebel Commercial Package Rooftop Systems." Accessed April 3, 2013: http://lit.daikinapplied.com/bizlit/DocumentStorage/RooftopSystems/InstallationandOperationManuals/OM_1141-2_Rebel_DPS-MT3_Controller.pdf.

BACnet Variable Name	Description
RATempRebel	Remapped from "Return Air Temperature (RATemp)." This read-only attribute that indicates the current reading from the unit return air temperature sensor. This variable only applies if the unit is configured for a return air sensor.
DATempRebel	Remapped from "Discharge Air Temperature (DischAirTemp)." This read-only property indicates the current reading of the unit discharge air temperature sensor.
SpaceTempRebel	Remapped from "Space Temperature Input (SpaceTempInput)." This read/write attribute indicates the current space or zone temperature that is written from the network. If this network value becomes unreliable, the temperature reverts to the value provided by the attached space temperature sensor. This variable only applies if the unit is configured for a space temperature sensor.
UnitPower	This is not a BACnet point. This is monitored power from a separate meter.
AlarmValue	This object allows individual notification of the highest priority active alarm. The value in the table below is the largest number in its enumeration that corresponds to an active alarm. This object is set to zero if no alarms are active.
ActiveFault	
ActiveProblem	
ActiveWarning	
ClgCapacity	This read-only property indicates the current percentage of unit maximum cooling capacity. The BACnet property reads only the subject attribute; however, the LONWORKS variable is only a part of the LONWORKS Unit Status network variable. See Page 90 for details of LONWORKS network variable. The BACnet property only applies to the subject data point. The LONWORKS variable covers six other data points: Unit State, Heating Capacity, Reheat Capacity, Supply Fan Capacity, Economizer Capacity, and In Alarm. This variable only applies if the unit is configured for cooling.
ClgStatus	This read-only attribute indicates whether or not cooling is currently enabled. If cooling is disabled, the reason is indicated. 1=Enabled; 2=None; 3=Off Amb; 4=Off Alarm; 5=Off Net; 6=Off Man.
CmpClgHrs	

BACnet Variable Name	Description
Comp2Hrs	
ControlTemp	This read-only property indicates the current control temperature. As shown in the graph to the right, this parameter is set to "SpaceTempNet."
CurrentState	
DewpointSp	This read/write property sets the dew point set point via the network.
DischLn1Temp	This read-only property indicates the current reading of the unit inverter compressor (Comp. 1) discharge line refrigerant temperature sensor.
DischLn3Temp	Swap out with DischLn2Temp.
EconCapacity	This read-only attribute indicates the current economizer capacity or outdoor air damper position. The BACnet property reads only the subject attribute; however, the LONWORKS variable is only a part of the LONWORKS Unit Status network variable. See Unit State for details. The BACnet property only applies to the subject data point. The LONWORKS variable covers six other data points: Unit State, Cooling Capacity, Heating Capacity, Reheat Capacity, Supply Fan Capacity, and In Alarm.
EconoHrs	This read/write property indicates the economizer accumulated run hours. It can be reset via the network.
EconoStatus	This read-only attribute indicates whether or not the economizer is currently enabled. If the economizer is disabled, the reason is indicated. 1=Enabled; 2=None; 3=Off Amb; 4=Off Alarm (Not Used); 5=Off Net; 6=Off Man; 7=Off Dehum.
Eft_Lct	This read-only attribute indicates the current value of the unit entering fan/leaving coil air temperature sensor. This variable only applies to units configured for an entering fan temperature sensor.
EffectOccup	This read-only property indicates if the unit is currently in an occupied, unoccupied, or tenant override mode of operation. 1 = Occ; 2 = Unocc; 3 = TntOvrd.
EmergOverride	This read/write property shuts off the unit controller. If this property is set to Off, the unit controller cannot start based on a time clock or any other means. The only way to start the unit controller is to change the value to Normal. If a value other than Off or EMERG_SHUTDOWN, is written, this variable reverts back to Normal. 1 = Normal; 2 = Off.

BACnet Variable Name	Description
HumiditySp	This is a read/write property that the network can use to set the relative humidity set point from the network.
INVCMPHRS	This read/write property indicates the inverter compressor accumulated run hours. It can be reset via the network.
INVCOMPPRB	This read-only BACnet object indicates whether the Inverter Compressor Problem alarm is active (1) or not active (0).
RebelStatus	This output network variable indicates the operating status of the unit controller. 1 = Enabled; 2 = Off Man; 3 = Off ManCtrl; 4 = Off Net; 5 = Off Alarm; 6 = Off Fan Retry.
MINOAPOSNETIN	This read/write configuration property sets the Outdoor Air Damper Minimum Position set point for MicroTech III Unit Controller. The Minimum Outdoor Air Damper Position Input set point uses this value when it is not being set by any other function and when Min OA Type is set to Network. The controller internally limits the present value that is written between the DCV Limit and the Vent Limit (see the Min OA Damper menu on the keypad/display). This variable only applies to units configured with an airside economizer.
OccManCmd	This read/write property sets the unit into a different occupancy mode. The request is typically sent by a wall-mounted occupant-interface module or a supervisory node, typically used to manually control occupancy modes or to override the scheduled occupancy. This input is used with nviOccSchedule to determine the effective occupancy mode. Refer to Occupancy (nvoEffectOccup) section for more information. 1 = Occ; 2 = Unocc; 3 = TntOvrd; 4 = Standby (Same as Occ); 5 = Auto.
OccupiedCool	Remapped from "Occupied Cooling Set Point (OccCoolSP)." This read/write configuration property sets the Occupied Cooling Set Point is set to this value when it is not being set by another function. This attribute uses maximum and minimum limits. If the present value is set beyond these limits from the network, the value is ignored and the controller continues to control to the last valid value. The BACnet property only applies to the subject data point, but the LONWORKS variable is a structure that covers three other data points: Unoccupied Cooling Set Point, Occupied Heating Set Point, and Unoccupied Heating Set Point.
RefDischP	This read-only property indicates the current reading of the unit discharge line refrigerant pressure sensor.
RefSuctionP	This read-only property indicates the current reading of the unit suction line refrigerant temperature sensor.
ReheatCapacity	This read-only attribute indicates the current percentage of unit reheat capacity. The BACnet property reads only the subject attribute and only applies to the subject data point. The LONWORKS variable is only a part of the LONWORKS Unit Status network variable. See Unit State for details. The LONWORKS variable covers six other data points: Unit State, Supply Fan

BACnet Variable Name	Description
	Capacity, Cooling Capacity, Heating Capacity, Economizer Capacity, and In Alarm.
SpaceRHNETIN	This is a read/write property the network can use to set the relative humidity from the network. If the network value becomes unreliable, the humidity reverts to the value provided by the attached relative humidity sensor.
SucnRefTemp	This read-only property indicates the current reading of the unit suction line refrigerant temperature sensor.
TenantOrHrs	This read/write property indicates the tenant override operation accumulated run hours. It can be reset via the network.
UnitState	This read-only property indicates the current unit operating state. This is a LONWORKS only variable that covers six other data points: Supply Fan Capacity, Cooling Capacity, Heating Capacity, Reheat Capacity, Economizer, and In Alarm. 1 = Off; 2 = Start; 3 = Recirc; 4 = FanOnly; 5 = MinDAT; 6 = Htg; 7 = Econo; 8 = Clg.
UnoccupiedCool	This read/write configuration property sets the temperature above which the unit starts and provides cooling (night setup) during unoccupied periods. An optional space temperature sensor is required for unoccupied cooling operation. This attribute uses maximum and minimum limits. If the present value is set beyond these limits from the network, the value is ignored and the controller continues to control to the last valid value. The BACnet property only applies to the subject data point, but the LONWORKS variable is a structure that covers three other data points: Occupied Cooling Set Point, Occupied Heating Set Point, and Unoccupied Heating Set Point.
ChargeLossPrb	This read-only BACnet object indicates whether the refrigerant system charge has been completely lost (1) or not (0).
DirtyFilterSw	This read-only BACnet object indicates whether the Dirty Filter Warning alarm is active (1) or not active (0).
DuctHiLmtSw	This read-only BACnet object indicates whether the Duct High Limit Fault alarm is active (1) or not active (0). This variable only applies to units configured for supply fan VFDs. 0 – Normal; 1 – Alarm.
EmergencyOffSw	This read-only BACnet object indicates whether the Emergency Off Fault alarm is active (1) or not active (0).
ExpValveProb	This read-only BACnet object indicates whether the Expansion Valve Problem alarm is active (1) or not active (0).

BACnet Variable Name	Description
HiDlTempPrb	This read-only BACnet object indicates whether the High Discharge Temperature Problem alarm is active (1) or not active (0).
HiPress1Prb	This read-only BACnet object indicates whether the High Pressure Circuit 1 Problem alarm is active (1) or not active (0). This variable applies only to units configured for two or more mechanical cooling circuits.
HiPress1Sw	This read-only BACnet object indicates the condition of the High Pressure Circuit 1 Switch (Closed (1) or Open (0)). The ‘OffNormal’ state of this object indicates a High Pressure Circuit 1 Problem.
IFBCommPrb	This read-only BACnet object indicates whether the Interface Board Communication Problem alarm is active (1) or not active (0).
LoChargePrb	This read-only BACnet object indicates whether the Low Refrigerant Charge Problem alarm is active (1) or not active (0).
LoPress1Prb	This read-only BACnet object indicates whether the Low Pressure Problem alarm is active (1) or not active (0).
LoPressDiffPrb	This read-only BACnet object indicates whether the Low Pressure Differential Problem alarm is active (1) or not active (0).
OaFanPrb	This read-only BACnet object indicates whether the Outdoor Fan Problem alarm is active (1) or not active (0).
SupFanCtrl	This read/write property selects the supply fan airflow control used on a variable air volume unit. If this parameter is set to Duct Static Pressure (DSP), the supply fan airflow maintains the duct static pressure at the duct static pressure set point. If this parameter is set to Speed, the supply fan airflow is controlled to a variable frequency drive speed set via the Supply Fan Capacity Input. If this is set to 1ZnVAV, the supply fan airflow is controlled to maintain the Control Temperature at the Occupied Cooling Set Point or the Occupied Heating Set Point depending on the Unit State.
SpaceDewPt	This read-only attribute indicates the current dew point calculated from the current reading of the optional relative humidity sensor.

Appendix G: Economic Analysis Details

Economic Analysis Information

eROI Analyses

Table G-1. Summary of Key Information Regarding the eROI Analyses Developed for This Project

Input Type	Demo Actuals
Date of Analysis	Feb. 11, 2014
eROI Version	v2.9.16B
Project Overview Tab	
Project Category	Fac. Energy Improv.
Regional Priority Project	No
Max. Financial Benefits Tab	
Salvage Value	$0
Provide Reliable Energy Tab	
MDI Critical Facilities	0
Regulatory & SH Expect. Tab	
Regulatory Compliance	2
Public Perception	1
Quality of Service, Goals	0
Quality of Service, # People	1
Develop. Enabling Infrast. Tab	
Question 1, Data Improvement	0
Question 2, Flex. Energy Inf.	0
Question 3a, Energy Indep.	2
Question 3b, % of Installations	75%
Project Risk Tab	
1. Timeline and Cost	±10%
2. Energy Reduction	±10%
3. a Facility Energy Reliance	±10%
3.b Facility Outages	±10%
3.c Backup Power	±10%
4. Regulatory & Stakeholders	±10%
5. Enabling Infrastructure	±10%
6. Aggregate Benefits	±10%
Impact of Deferring Tab	
Impact of Deferring 1 Year	No Change

BLCC Analysis

Table G-2. Summary of Key Information Regarding the Building Life-Cycle Cost Analyses Developed for This Project

BLCC Analyses: Key Information	
Input Type	**Value**
Report Type	MILCON/ECIP
BLCC Version	BLC 5.3-12
Location	Hawaii
Discounting Convention	Mid-Year Discounting
Analysis Type	Constant Dollar Analysis
Base Date	October 2013
Beneficial Occupancy	October 2013
Length of Study	15 Years
Energy Usage Indice	100% through Economic Life
Initial Investment Cost[a]	$13,419
Non-Annual Recurring Cost[b]	$1,100
User Rates Electricity Escalation[c]	0%
Real Discount Rate	3.0%

[a] Initial investment cost equal to the difference between the HE RTU and ASHRAE 90.1 code compliant RTU
[b] Additional training expense, occurring at time of beneficial occupancy.
[c] DOE, State specific escalation rates were not used due to recent, high variability in pricing

Appendix H: Uncertainty Analysis

All RTU field demonstration measurements and models based thereupon have inherent uncertainties that should be accounted for when discussing the predicted annual energy usage. The uncertainties in the measurements and models in this paper are discussed in this Appendix. All of these uncertainties contribute to the variations in the model predictions, expressed in confidence intervals.

The final uncertainty in the respective Rebel and baseline EnergyPlus models' annual energy prediction (annual kilowatt-hours) is shown in equation H-1. This uncertainty equation accounts for the power meter uncertainty, sample uncertainty (extrapolating several months of measured data to a yearly savings prediction) and modeling uncertainty. The following subsections discuss the calculation of each uncertainty term. The t-statistic was set to 2.04 based on an n-p of 70 and 95% confidence interval (2 standard deviations). NREL calculated the total uncertainty to be ±27% of the annual energy savings based on a 95% confidence interval.

$$U_T = t\sqrt{RE_{instrument}^2 + U_s^2 + U_m^2} \quad \text{(H-1)}$$

where
U_T is the total uncertainty of the EnergyPlus model's annual energy prediction,
$RE_{instrument}$ is the total uncertainty of the RTU power measurement based on the power meter manufacturer's stated accuracy,
U_s is the sampling uncertainty,
U_m is the uncertainty in the EnergyPlus model, and
t is the t-statistic.

Rooftop Unit Power Measurement Uncertainty

The baseline and Rebel RTUs total power were monitored using 100 hertz resolution WNC-3D watt-nodes with ACT current transducers on each phase. The manufacturer, Continental Controls, provides the calculation procedure for combining the accuracy of their watt-node and current transducers based on power factor. For the RTU power measurements, which are predominantly inductive motor loads, the lagging power factor will range from 0.8 to 0.9 (www.ccontrolsys.com/w/Metering_System_Accuracy). Based on the on-site power factor measurement being above 0.85 for the power entering both RTUs, NREL stipulated the uncertainty of the power measurement was 3% based on the calculated combined watt-node and current transducer measurement accuracy.

Sampling Uncertainty

There are two types of sampling uncertainties. The first is the sampling uncertainty based on measuring across a large cross-section of RTU characteristics found at NAVFAC facilities, including make, model, size, and building type served. The sample size of this field demonstration is 1. Because the scope of the study was to quantify the energy savings of one 10-ton Rebel against one 10-ton baseline, this sampling uncertainty was not considered. While the savings numbers presented in this report can be indicative of energy savings realized on a larger sample set, these energy savings are by no means representative of a random sample set representing the entire RTU sample set at NAVFAC facilities.

The second type of sample uncertainty deals with the fact the annual energy savings is based on a model that was calibrated against several months of field demonstration data (November 2013 through January 2014). The data samples are compared in "days" as NREL used daily total energy usage (kilowatt-hours) when calibrating the models. The baseline EnergyPlus model was calibrated against 36 days measured during the demonstration period. The Rebel EnergyPlus model was calibrated against 35 days measured during the demonstration period. The EnergyPlus calculation of annual energy usage is based on 260 days (5 days per week multiplied by 52 weeks).[21]

Equation H-2 shows the calculation of this sampling uncertainty for the baseline and Rebel annual energy usage. This methodology is based on Equation 5.1 in ASHRAE Guideline 14.[22] Because the energy savings is the difference between the baseline and Rebel model energy outputs, the sampling uncertainty was calculated by combining both together. Therefore, the total number of data samples (Q) was 520 days (1 year at 260 days for the Rebel Model plus 1 year at 260 days for the baseline model). The number of measured samples (q) was 71 days (36 days for baseline plus 35 days for Rebel). The combined sampling uncertainty was 8%.

$$U_s = \frac{100}{\bar{y}} \times \sqrt{(1 - q/Q)\left[\sum_{i=1}^{n}(y_i - \bar{y})^2 / (q-1)\right] / q} \tag{H-2}$$

where
U_s is sampling uncertainty (%),
$\bar{y}$ is mean of the measured data (kWh/day),
q is number of samples in the measured data,
Q is total number of data samples for both annual models (520 days), and
y_i is measured data sample (kWh/day).

EnergyPlus Model Uncertainty

During the calibration process, NREL compared the daily modeled energy usage (kilowatt-hours) versus the daily measured energy usage (kilowatt-hours). Equation H-3 shows the calculation procedure for the coefficient of variation of the root mean squared error CVRMSE, based on the measured versus modeled daily energy usage. Similar to the sampling uncertainty calculation above, the CVRMSE was calculated combining the measured versus model with both baseline and Rebel RTU calibration data sets. The CVRMSE for the combined baseline and Rebel calibration periods was 10%. When calculated separately, the CVRMSE of the Rebel model was 17% and 7% for the baseline model.

[21] NREL did not include holidays when running the annual models because typical thermostat controls can only handle a 7-day schedule, not incorporating holidays. Therefore, even though the buildings are empty on holidays, the RTUs will continue to run. However, the energy models did account for reduced building loads on 10 holidays across the year.
[22] ASHRAE. ASHRAE Guideline 14-2002. Measurement of Energy and Demand Savings. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2012.

$$U_m = \text{CVRMSE} = \frac{\sqrt{\sum_{i=1}^{n}\left(y_i - \tilde{\hat{y}}\right)^2/(n-p)}}{\bar{y}} \quad \text{(H-3)}$$

where

y_i is the measured daily energy usage during the calibration period,
$\tilde{\hat{y}}$ is the model daily energy usage during the calibration period,
n is the total days in the Baseline and Rebel calibration periods, and
p is equal to 1,
$\bar{y}$ is the average measured daily energy usage during the calibration period.

Appendix I: Naval Facilities Engineering Command Routine Rooftop Unit Maintenance Procedures

The NAVFAC PAC HVAC shop provided its quarterly *Job Plan and Task Report*, which is shown in Figure H-1.

Job Plan and Task Report

JPNum FY2A-2M

Description 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 H-1. NAVFAC quarterly RTU maintenance procedure