ESTCP
Cost and Performance Report

(EW-201152)

Converting Constant Volume, Multizone Air Handling Systems To Energy Efficient Variable Air Volume Multizone Systems

June 2017

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A low-cost technique to retrofit a constant volume multizone system to a more energy efficient variable volume system was demonstrated on five systems at Fort Bragg, NC, and the U.S. Army Engineer Research and Development Center-Construction Engineering Research Laboratory –(ERDC-CERL) in Champaign, IL. When starting with a constant volume multizone air handler with modern Direct Digital Controls (DDCs), the conversion requires programming changes to the control strategy executed by the control system as well as the installation of an Air Flow Measurement Array (AFMA) and Variable Frequency Drives (VFD)s for the supply and return fans (if so equipped). A key feature of this approach is that the physical system is only minimally affected and except for the location at which the AFMA is installed, the ductwork is not modified.

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ACRONYMS AND ABBREVIATIONS

AFMA	Air Flow Measurement Array
AFMS	Airflow Measurement Station
AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineer
BBTU	Billion British Thermal Unit
BTU	British Thermal Unit
CERL	Construction Engineering Research Laboratory
CFM	Cubic Feet per Minute
CONUS	Contiguous United States
DCV	Demand Controlled Ventilation
DDC	Direct Digital Control
DPW	Directorate of Public Works
ERDC-CERL	U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory
ESTCP	Environmental Security Technology Certification Program
HVAC	Heating, Ventilating and Air Conditioning System
kWh	kilowatt per hour
MZ	Multizone
O&M	Operations and Maintenance
OA	Outdoor Air
PID	Proportional, Integral, Derivative
SERDP	Strategic Environmental Research and Development Program
Sf	Square feet
SIR	Savings to Investment Ratio
UFGS	Unified Facilities Guide Specification
UMCS	Utility Monitoring and Control System
USACE	US Army Corps of Engineers

VAV	Variable Air Volume
VFD	Variable Frequency Drive
WBDG	Whole Building Design Guide

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

A low-cost technique to retrofit a constant volume multizone system to a more energy efficient variable volume system was demonstrated on five systems at Fort Bragg, NC, and the U.S. Army Engineer Research and Development Center-Construction Engineering Research Laboratory – (ERDC-CERL) in Champaign, IL. When starting with a constant volume multizone air handler with modern Direct Digital Controls (DDCs), the conversion requires programming changes to the control strategy executed by the control system as well as the installation of an Air Flow Measurement Array (AFMA) and Variable Frequency Drives (VFD)s for the supply and return fans (if so equipped). A key feature of this approach is that the physical system is only minimally affected and except for the location at which the AFMA is installed, the ductwork is not modified.

TECHNOLOGY DESCRIPTION

The updated control strategy varies the fan speeds based on the zone demand as determined by zone damper position, minimizing the fan energy used as well as the cooling and heating energy required to maintain occupant comfort by reducing the amount of simultaneous heating and cooling that occurs in a zone. Heating and cooling energy savings are most pronounced in traditional multizone systems with a hot deck and cold deck that operate simultaneously, but are also realized in systems with a neutral deck.

The five demonstration systems were retrofitted and operated for a period of approximately one year, alternating between three test modes. Test Mode 0 simulated the pre-retrofit condition and operated the system as a constant volume multizone with a fixed outside air damper position. Test Modes 1 and 2 employed variable volume control strategies. Test Mode 1 operated with a fixed outside air flow setpoint, and test Mode 2 introduced demand controlled ventilation schemes for determining the outside air flow setpoint. Additional instrumentation including British Thermal Unit (BTU) and electric meters was installed on the demonstration system at the time of retrofit to provide data for analysis of system performance. The existing Utility Monitoring and Control Systems (UMCS[1]) were used to log data from the system throughout the demonstration period.

DEMONSTRATION RESULTS

The five systems were analyzed for energy savings, life cycle cost, occupant thermal comfort, and maintainability, where each of these factors were compared to the baseline constant-volume system.

> *Energy Savings:* All systems easily met the energy savings goals of 10% energy use reduction, with energy reduction ranging from 24%-60%.

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[1] A utility monitoring and control system (UMCS) is a base wide control system including one or more building control systems and a front end which provides a user interface and supervisory functions such as scheduling, alarming, and trending.

Life Cycle Cost: One of the five systems met the life cycle cost goals of a 3-year payback period assuming the conversion is added to an existing DDC system or planned renovation ("incremental retrofit") and 10-year payback for the complete renovation of a system from non-DDC to DDC with variable volume control. Three other systems had longer payback periods less than the system life for the incremental retrofit; however, demonstrating that the addition of variable volume control to a DDC retrofit is still economical in those cases. Since retrofit costs are relatively static across system sizes, the long payback periods for smaller systems can be expected and demonstrates that some care should be exercised in selecting appropriate systems on which to apply this technique.

Thermal Comfort: The two systems at CERL performed nearly the same across all three operating modes. The difference across modes was more significant at Fort Bragg, where two had worse comfort performance in the variable volume modes, where one system spent 29-33% of time within the thermal comfort range in Modes 1 and 2 versus 39% of time the time for Mode 0, and the other system spending 55% of the time in the comfort range in Modes 1 and 2 versus 61% in Mode 0. The third system at Fort Bragg performed significantly better in Modes 1 and 2, however, with 53-54% of the time in the comfort range versus 34% for Mode 0. In all systems, however, the average deviation from zone setpoint did not increase more than 0.5 °F in Modes 1 and 2 versus Mode 0, which is well within the normal variation of space temperatures in a building indicating that the occupants were highly unlikely to notice a difference between modes. Although individual system results were mixed, the variable volume modes did not perform significantly worse overall than the constant volume system and comfort performance was considered acceptable.

System Maintenance: System maintenance was acceptable as neither demonstration site reported any maintenance concerns with the retrofitted systems.

IMPLEMENTATION ISSUES

Overall, the demonstration of the conversion of a constant volume multizone to variable volume was successful as the results demonstrate the potential for the conversion to meet energy savings, comfort, cost, and maintenance requirements. Selection of systems for application of this technique should consider multizone type and size, with preference given to larger multizone, and traditional 2-deck multizone systems.

1.0 INTRODUCTION

This project demonstrated a low-cost technique to convert a constant volume multizone system to a more energy efficient variable volume multizone system. The primary motivation for the project was to measure the performance and document the technology to help promote its use. This included defining the applicability, project specifications, and implementation requirements leading to design guidance.

1.1 BACKGROUND

The current design practice for new Heating, Ventilating and Air-Conditioning (HVAC) systems that serve multiple zones is to use variable air volume technology. Still, the Army (and DoD) has a large existing inventory of energy inefficient constant volume multizone systems, an older technology also used to serve multiple zones. A constant volume multizone system can be converted to function as a variable air volume multizone system. Although there are various ways to perform this conversion, this project focused on an inexpensive technique that can be bundled with a Direct Digital Control (DDC) retrofit and is known to be minimally disruptive to building occupants.

When this project was conceived, using the number of installations, buildings, and square footage information from the 2009 Base Structure Report (BSR), the estimated savings of this technique if implemented at all Contiguous Unites States (CONUS) Army, Air Force, Navy, and Marine Corps installations was 817,984 million British Thermal Units (BTUs) a year, which is worth over $29 million. Since there is no firm data on how many Multizone (MZ) systems exist in the DoD, this estimate was based largely an early informal poll of three large Army installations (Fort Bragg, Fort Hood, and Fort Sill), which indicated that each had over 100 multizone systems, and on the general experience of the project team.

The large DoD inventory of multizone systems represents a significant potential for energy savings by converting these systems to variable air volume. This will also reduce greenhouse gas production, although the extent depends on the fuels used to generate electricity and heating and has therefore not been estimated.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objectives of the demonstration are briefly described below:

- Validate that variable volume multizone systems use at least 10% less energy than the constant volume multizone systems they replaced [OBJECTIVE MET]
- A payback period of less than 10 years for a full retrofit and a payback period of less than 3 years for the incremental retrofit [OBJECTIVE NOT MET for a full retrofit. OBJECTIVE MET for one system for an incremental retrofit]
- Comfort for the renovated system the same or better than the constant volume system; this criterion was analyzed by comparing the percentage of time the system was within the American Society of Heating, Refrigerating and Air-conditioning Engineer (ASHRAE) 55 comfort zone across modes and the average zone temperature deviation from setpoint across modes [Numerical OBJECTIVE MET for some units]

- The demonstrated technology has an acceptable level of maintenance [OBJECTIVE MET for all units.]

1.3 REGULATORY DRIVERS

There are numerous drivers for saving energy and reducing greenhouse gases:

- Energy Policy Act of 2005, effective as of 8 August 2005
- 2005 Army Energy Strategy for Installations
- Executive Order 13423, signed on 24 January 2007 (see also Executive Order 13514)
- Executive Order 13514, Federal Leadership in Environmental, Energy, and Economic Performance; October 2009 (expands on Executive Order 13423)
- 2006/2007 Defense Science Board Key Facility Energy Strategy Recommendations
- Energy Independence & Security Act, effective 19 December 2007

Many of these policies, directives, and executive orders overlap in their requirements. Collectively, the pertinent requirements are:

- Reduce energy by 20% by FY2015 (relative to 2003)
- Improve energy efficiency in buildings by 30% better than ASHRAE standards
- Reduce dependence on fossil fuels and make renewable energy at least 7.5% of total energy purchase by 2013 (DoD Internal Guidance calls for 25% by 2025)
- Improve energy security
- Construct or renovate buildings in accordance with sustainability strategies, including resource conservation, use, site criteria, and indoor environmental quality
- Set greenhouse gas (GHG) emission reduction goals for FY2020 based on a FY2008 baseline

2.0 TECHNOLOGY DESCRIPTION

This technology converts a constant volume multizone system into a variable volume multizone system by focusing almost entirely on instrumentation and controls rather than replacement of existing ductwork and installation of new terminal units.

2.1 TECHNOLOGY OVERVIEW

Converting a constant volume multizone system to a variable air volume system ordinarily requires re-ducting and re-zoning the system to accommodate “Variable Air Volume (VAV) box” terminal units and is a major renovation effort that can be very costly, time consuming, and disruptive to the building occupants. This complete overhaul renovation approach is seldom considered attractive; therefore, multizone systems are usually operated as constant volume systems until they fail or otherwise warrant replacement (due to a building renovation for example).

2.1.1 Typical Multizone Unit Types

There are three typical configurations of multizone air handlers – standard, bypass, and neutral deck:

1. **Standard Multizone:** In a standard multizone system the air handling unit contains a hot deck and a cold deck with associated heating and cooling coils.

2. **Bypass MZ**: A bypass multizone unit has a cold deck like a standard multizone unit, but in place of the hot deck it has a “bypass” deck. This “bypass” deck has no coil, and provides a path for unconditioned mixed air (return air and outside air) to flow to the zone dampers.

3. **Neutral Deck MZ**: A neutral deck multizone unit has a cold deck and hot deck like a standard multizone unit but it also has a “neutral” deck. This “neutral” deck has no coil and provides a path for unconditioned mixed air (return air and outside air) to flow to the zone dampers.

2.1.2 Control Logic Overview

The control logic (also referred to as ‘sequence of control’ or ‘control strategy’) consists of:

1. Adjusting fan capacity based on the position of the zone dampers where fan speed is decreased until one of the zone dampers is at or nearly fully open to either heating or cooling. Reduced fan capacity reduces fan energy and minimizes simultaneous heating and cooling inherent to conventional MZ systems.

2. Shutting-off the hot (or cold) deck valve completely when there is no call for heating (or cooling), respectively, based on the commanded position of all zone dampers.

2.1.3 Retrofit Overview

For an air handler without modern DDC controls, the complete retrofit to DDC controls implementing variable volume control requires:

1. Variable Frequency Drive (VFD) installation: Fan capacity control allows the ability to operate the fan at reduced speed provides energy savings.
2. Consideration of fan motor replacement: Fan motor replacement may provide for additional energy savings and compatibility with the VFD.
3. Outside air flow measurement station installation: The existing constant volume system likely does not have a flow station, but using the variable volume conversion requires control of outside air flow to maintain ventilation and/or makeup air.
4. Upgrade of control system via programming changes and/or controller replacement for variable volume operation as well as to include demand controlled ventilation, an air side (dry bulb) economizer, and scheduled start/stop.
5. Installation of new zone and air handling unit actuators and sensors as needed to support the conversion. It is generally advisable to replace pneumatic actuators with electric.

No ductwork alterations are required.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The demonstrated technique avoids or minimizes the inefficiency of simultaneous heating and cooling inherent to conventional multizone systems. It also saves energy by varying system air flow rates when at part load conditions. Further energy savings are possible through outdoor ventilation air flow control and demand controlled ventilation.

2.2.1 Cost Advantages

This technique focuses almost entirely on instrumentation and controls rather than replacement of existing ductwork and installation of terminal units, and is thus accomplished for a lower first cost, with less system down-time and less disturbance to building occupants.

2.2.2 Performance Limitations

The age and condition of the typical multizone system presents the potential for unexpected maintenance or performance problems. Also, a multizone system contains multiple zone dampers. The control scheme depends on the position of each zone damper serving its respective zone/rooms. If no damper is fully open, the fan speed is reduced. Statistically, the greater the number of zone dampers, the greater the odds that one or more dampers will be fully open, lessening the opportunity for energy savings.

2.2.3 Cost Limitations

The control sequence for a variable volume system is more complex than for a constant volume system, so there may be some additional costs associated with training and maintenance of the system. For the demonstrated systems, these additional costs were negligible.

2.2.4 Social Acceptance

This technology is expected to be well received. The only potential barrier to acceptance by operators, maintainers, or management is that in cases where digital controls are installed to replace non-digital controls, the system will be a bit more complicated and require training and familiarity with tools that maintenance staff may not have.

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3.0 PERFORMANCE OBJECTIVES

The overall goal was to demonstrate an inexpensive conversion of existing multizone systems to variable volume multizone systems to reduce energy consumption without compromising occupant comfort. Reduced energy usage would result in reduced need for fossil fuels (used to power/supply the HVAC systems) and a corresponding reduction in greenhouse gas emissions.

The performance objectives described in Section 3.1 and summarized in Table 1 define metrics and data to quantify reduced energy usage and thus the return on investment for this technology.

3.1 SUMMARY OF PERFORMANCE OBJECTIVES

Table 1 summarizes the performance objectives.

Table 1. Project Performance Objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Energy Usage	Energy Savings	Heating energy Cooling energy Fan energy	More than 10% energy savings compared to constant volume	Objective met for all units
Life Cycle Cost	Simple Payback Period (years) Savings to Investment Ratio (SIR)	Energy savings Energy cost Investment cost Maintenance cost (est.)	10-year payback for full retrofit. 3-year payback when added to planned retrofit ("incremental retrofit")	Full retrofit objective not achieved Incremental retrofit objective achieved for one system
Alignment with ASHRAE Comfort Zone	Percent of time spaces are in the "Comfort Zone". Space temperature deviation from thermostat setpoint.	Space/zone temperature Humidity Zone temperature setpoint	VAV system comfort the same or better than a constant volume system	Numerical objective met for some units.
Qualitative Performance Objectives				
Maintenance Implications	Acceptable, unacceptable or tenuous level of maintenance	Input from maintenance staff, Service Order info, operational status of HVAC system	Acceptable level of maintenance	Objective met for all units.

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4.0 FACILITY/SITE DESCRIPTION

The demonstration was performed at Fort Bragg, NC, and the U.S. Army Engineer Research and Development Center-Construction Engineering Research Laboratory –(ERDC-CERL) in Champaign, IL. Three air handlers at Fort Bragg and two at CERL were selected based on detailed survey criteria and discussions with the local Operations and Maintenance (O&M) staff and other appropriate Directorate of Public Works (DPW) staff at each site. Many factors helped determine the best candidates; some of the more important criteria included preference for systems that:

- Were already remotely monitored via building automation system
- Were larger units that operated a lot of hours and provided more potential for savings
- Were units in reasonably good working order
- Had hydronic systems that allowed BTU meter installation

Detailed surveys were performed. Included in these surveys were mechanical system sketches, measured diffuser airflows and otherwise determined system capacities, and photographs of all system components, equipment, and hardware.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

4.1.1 Fort Bragg

Demonstration Site Description: Fort Bragg is a Forces Command installation located in Cumberland and Hoke Counties, North Carolina. Due to its age, it has numerous existing HVAC systems, including multizone systems. Fort Bragg consists of approximately 161,000 acres. Fort Bragg's facilities include 2,176 structures (with approximately 1200 considered 'major') and 25.2 million total sq. ft. of buildings. Many of Fort Bragg's permanent facilities/buildings contain multizone HVAC systems.

4.1.2 CERL

Demonstration Site Description: CERL is in Champaign, Illinois. This research facility consists of three main buildings housing laboratories, offices, and conference rooms. The two Air Handling Units (AHUs) used for this demonstration were in Mechanical Room 2127 and above Room 2014, and served offices and conference room spaces in Building 2. An existing Utility Monitoring and Control System (UMCS) network was in place and used in this demonstration.

4.2 FACILITY/SITE CONDITIONS

Table 2. Demonstration System Summary

Site	System	Floor area (sf)	Size (cfm)	No. of Zones	Comment
Fort Bragg Bldg. A-1985	AHU 1	2,983	4,620	3	~10 years old. Neutral deck MZ
	AHU 2	4,328	4,870	9	
	AHU 3	4,837	4,870	8	
CERL Bldg. 2	AHU 1	8,800	8,550	5	~40 years old. Traditional MZ. Mainly offices. DDC upgrade w/in past 3 years.
	AHU 2	2,400	3,475	3	~40 years old. Traditional MZ. Mostly conference rooms.

5.0 TEST DESIGN

The demonstrated systems were designed and tested to determine to what extent a VAV MZ system can save fan, heating, and cooling energy; the life cycle cost of the technology; if maintenance of the technology considered by the maintenance staff to be an issue or problem; and to what extent occupant comfort is affected.

5.1 CONCEPTUAL TEST DESIGN

Independent variable: The independent variable was the type of air flow system, either constant volume or variable volume.

Dependent variable(s): The dependent variable was the amount of HVAC energy used by the buildings. This included air handling unit fan electricity usage (kWh), cooling coil capacity (BTUs), and heating coil capacity (BTUs).

Controlled variable(s): The controlled variables included the heating and cooling loads such as occupancy, equipment, weather (outside air temperature, humidity, and wind speed), and solar radiation. We mathematically controlled these through normalizations or averaging. We compared the dependent variables while changing the independent variable by rotating between operating modes daily, with a switchover at midnight, for a period of 1 year. The nightly rotation ensured that each mode saw operation each day of the week and distributed multi-day duration weather extremes across the different modes.

In the constant volume, pre-retrofit mode (Mode 0) the units operated using only the pre-existing energy savings features and controls, and in the "post retrofit" mode they operated as a VAV system using all applicable energy savings features and controls.

To validate the energy savings from demand controlled ventilation there were two post retrofit modes for variable volume operation. In Mode 1, the quantity of ventilation air (outdoor air [OA]) was fixed at a specific flow rate, while in Mode 2 this quantity was varied based on zone occupancy as determined by occupancy or CO_2 sensors.

Hypothesis: A constant volume multizone system converted to a variable volume multizone system will use less energy, have an acceptable or reasonable life cycle cost, yield the same or better occupant comfort, and not be viewed as a maintenance burden.

Test Design: Constant volume multizone systems were converted to variable volume multizone systems. The existing UMCS systems were used to collect energy use data.

Test Phases:

- Select AHUs to include in the demonstration
- Design/specify each AHU retrofit including monitoring instrumentation
- Perform quality verification and commissioning
- Collect data in both constant volume and variable volume configurations
- Analyze data

- Report results

5.2 BASELINE CHARACTERIZATION

Reference Conditions: A total of five different AHUs were included. Below is a comprehensive list of the data points collected that were common to the units tested. Other data points were available depending on the configuration of the specific AHU/system:

- AHU fan electricity usage (watts)
- Cooling coil energy (BTUs)
- Heating coil energy (BTUs)
- Temperature in each zone (°F)
- Relative humidity in each zone (percent)
- Zone thermostat temperature setpoint (°F)
- Zone damper command/position (% open)
- Zone/space carbon dioxide (CO_2) levels (CERL AHU-1 only)
- Outside air temperature (°F)
- Outside relative humidity (%RH)
- AHU outside airflow (cubic feet per minute [cfm])

Baseline Collection Period: There was no baseline period, per se. The baseline was the constant volume (Mode 0) mode of operation. The systems were configured to automatically switch between this constant volume mode and the variable volume modes daily for one year. The data collected when the systems were operating in the constant volume mode was used to define the baseline for comparison to the variable volume modes.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

This conversion of constant volume multizone air handlers to variable volume multizone air handlers focused on commercially-available equipment, instrumentation, and controls - most notably the installation of variable speed fans. The conversion also included upgrading the controls via programming changes or controller replacements and the installation of new or replacement actuators and sensors – including the addition of outdoor airflow measurement - needed to support the conversion.

Key components of the systems include the VFD, premium efficiency (not inverter duty) motors suitable for use with a VFD, outside airflow measurement stations, zone dampers and electric actuators, sensors, actuators, and the sequences of operation.

Where applicable, systems were enhanced by incorporating a demand controlled ventilation scheme including CO2 sensors in one or more zones/spaces.

In some cases, the retrofits replaced older controls with microprocessor based direct digital controls providing improved accuracy and reliability. Digital controls supported the application of other energy savings techniques such as automatic adjustment of the hot and/or cold deck discharge air temperature setpoints, after-hours (unoccupied mode) zone temperature setback and/or system shutdown, outdoor ventilation air flow control and demand controlled ventilation that might not have been in place with the existing/older systems.

5.3.1 Data Collection Equipment

All sensors and meters used to collect data were integrated into the UMCS which was used to log the needed data. This instrumentation included:

- Watt-hour meter - used to collect fan motor energy and electric chiller energy.
- BTU meter - used to measure water coil energy.
- Temperature measured at thermostats in each zone (°F).
- Relative humidity in each zone, (%RH) using wall mount sensors.
- Zone thermostat temperature setpoint (°F)
- Zone damper command/position (% open) - used the signal from the digital controller
- Outside air temperature (°F)
- Outside relative humidity (%RH)
- Duct airflow (cfm) - used duct-insertion multi-point hotwire anemometer flow sensors.

5.4 OPERATIONAL TESTING

Five systems were renovated. Commissioning (Cx) included quality verification testing of the system to ensure that it switched between the basic operational modes. Cx also included stepping through the sequence of operation for each mode to ensure that the controls functioned properly. A commissioning agent helped ensure that the renovation was properly accomplished.

No modeling or simulation was performed, although some estimation was performed to account for a minimal amount of lost or bad data.

Retrofits occurred between May and August 2015. Data collection began September 2015 and was completed September 2016.

5.5 SAMPLING PROTOCOL

Data Description: Data collected are listed/described in Section 5.3 “Reference Conditions.” Each data point was collected at 15 minute intervals for 1 year. There were no less than 40 data points per MZ system. The data was collected using the local UMCS.

5.6 SAMPLING RESULTS

The data collected for each system are described above.

Table 3. Example Trend Log

Timestamp	AHU Mode	AHU-1 SF VFD speed (%)	AHU-1 OAF SP (cfm)	AHU-1 SF VFD power (kW)	AHU-1 RAT (deg F)	AHU-1 RA CO2 (ppm)	AHU-1 RF VFD speed (%)	AHU-1 RF VFD power (kW)
9/10/2015 12:45	2	100.0	1,877.3	3.6	72.8	573.0	94.7	0.9
9/10/2015 13:00	2	100.0	1,957.8	3.6	72.9	570.0	86.7	0.7
9/10/2015 13:15	2	100.0	1,957.8	3.6	74.5	608.0	0.0	0.0
9/10/2015 13:30	2	46.5	2,038.4	1.2	74.4	620.0	58.3	0.3
9/10/2015 13:45	2	71.6	2,277.8	1.2	73.3	621.0	61.8	0.3
9/10/2015 14:00	2	80.8	2,197.3	2.9	73.2	613.0	91.7	0.8

6.0 PERFORMANCE ASSESSMENT

6.1 ENERGY PERFORMANCE

The Energy Performance Metric is for the renovated systems to use 10% less energy than pre-retrofit system.

6.1.1 Primary Metrics for Evaluating Energy Performance

To quantitatively determine whether the performance objective of more than 10% in total energy savings (compared to constant volume operation) was met, the following metrics were defined:

1. Fan energy usage as reported by the VFD was converted to kWh.
2. Heating energy used at the air handler was converted to kBtu.
3. Cooling energy used at the air handler was converted to kBtu.

Once energy usage data were collected by control mode (constant volume vs variable volume sequences) the data were normalized by equipment runtimes and weather conditions. Normalized data were used to determine if the 10% energy reduction target was met.

6.1.2 Collection of UMCS Trend Data in Baseline and Retrofit Modes

Existing UMCS systems were leveraged as built-in historians for the above variables. Fifteen-minute interval data were collected and exported as time-series spreadsheet data as shown in Table 3. Each system was rotated daily through the three operating modes, switching between modes daily at midnight:

1. Mode 0 (baseline operation): constant volume multizone operation
2. Mode 1 (VAV operation)
3. Mode 2 (VAV + Demand Controlled Ventilation [DCV] operation): Variable air volume operation with DCV

Data were collected for a period of 12 months at Fort Bragg and 13 months at CERL, and a subset of these data were used in the evaluation of energy performance. The data used for the analysis were processed to remove data collected during non-operational periods and to ensure comparable data sets for each operating mode. Our data analysis process is summarized below and described in detail in the Final Report.

6.1.3 Removing Data When Multizone Units Were Not Operating

Data that met at least one of the following criteria was filtered out and disregarded:

- Outside the normal daily operating hours
- Holiday hours
- Random off times (such as maintenance down time)

6.1.4 Statistical Analysis

We performed the following series of statistical analyses to assure that no statistically significant variation in energy drivers existed outside the mode changes themselves.

- Assumed that interior zone load fluctuations would have been distributed by the daily rotation of operation modes.
- Ensured an even distribution of days of the week between modes.
- Developed a refined data set for each site that equalized the count of data points within each temperature bin (5° F temperature bins were used due to their common appearance in HVAC applications).

6.1.5 Other Data Corrections

CERL's AHU-2 had a pair of 2-month long operational abnormalities: completely off in November/December of 2015 and the unit ran 24/7 in February/March of 2016 (instead of being scheduled off after hours). Similarly, Fort Bragg data for AHU-2 had a 2-month long operational abnormality in which no data was recorded for most of January and all of February. We compensated for these abnormalities at both locations.

Once statistically identical datasets were established for AHU-1 and AHU-2 at CERL, the following corrections were made to energy performance variables:

1. Adjusting non-zero heating or cooling energy at the BTU meter to zero when the air handler is off or coil valve is fully closed (0% HWV value)
2. Subtracting the baseload BTU meter error readings off nonzero runtime data
3. Removing data from Mode 0 when supply fan speed deviates from 100% (i.e., temporary maintenance-related overrides, equipment outages)
4. Outside air temperature jumps of more than 5F between 15-minute interval data (all jumps were flagged and removed from the studies as part of the statistical analysis phase)

6.1.6 Energy Performance for Processed Weather Data

After processing the data for statistical similarity and correcting data errors, the total fan and BTU meter energy usage for each mode was calculated for each system, and the reduction in energy use of Mode 1 and Mode 2 compared to Mode 0 was determined. These calculations were performed using 5°F temperature bins to aid further analysis.

The results of this analysis for all five demonstration systems is summarized in Table 4. For each system, the variable volume modes achieved significant energy reduction compared to the constant volume modes, exceeding the goal of 10% energy savings.

Table 4. Energy Savings for the Processed Data Set

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v Mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v Mode 0
CERL 1	564,044	443,309	21.4%	431,444	23.5%
CERL 2	554,146	209,530	62.2%	207,132	62.6%
BRAGG 1	34,614	18,658	46.1%	17,829	48.5%
BRAGG 2	31,517	25,469	19.2%	25,502	19.1%
BRAGG 3	39,258	27,471	30.0%	27,730	29.4%

6.1.7 Energy Performance for 2016 and Historic Weather-Normalized Data

The data processing steps described above resulted in a final data set that represents portions of the year and are not fully reflective of the actual year's outside air temperature distribution. Further analysis was conducted to map these savings percentages by bin onto the study year's recorded bin data. By calculating the savings per bin hour from the processed data and multiplying these savings by the number of bin hours recorded for the year, the predicted energy savings for the year is calculated Table 5 summarizes the results of this analysis for all five demonstration systems. This adjusted performance data represents a slight overall increase in the Mode 1 and Mode 2 energy savings (an additional 1.6% and 2.0%, respectively for CERL and 0.6% and 1.1% for Fort Bragg).

Table 5. Energy Savings for the 2016 Weather-Normalized Data

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v. Mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v. Mode 0
CERL 1	520,148	404,987	22.1%	396,660	23.7%
CERL 2	587,346	224,099	61.8%	208,389	64.5%
BRAGG 1	129,043	69,906	45.8%	66,015	48.8%
BRAGG 2	123,571	94,495	23.5%	94,468	23.6%
BRAGG 3	144,691	101,115	30.1%	100,932	30.2%

The analysis described above provides an estimate of energy savings for the demonstration year, but does not necessarily represent the energy savings in a **typical** year. Recognizing that the weather encountered during the study period may not be sufficiently representative of typical temperature patterns, nearby weather station averages were leveraged to normalize energy performance results against typical heating and cooling conditions to provide a more general evaluation for expected system performance.

Table 6 summarizes the results of this analysis historic weather-normalized data for all five demonstration systems. This historical weather-normalized data was used for the analysis of performance and cost.

Table 6. Energy Savings for the Historic Weather-Normalized Data Set

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v. Mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v. Mode 0
CERL 1	514,434	391,676	23.9%	367,642	28.5%
CERL 2	581,926	257,910	55.7%	233,881	59.8%
BRAGG 1	123,991	66,135	46.7%	61,084	50.7%
BRAGG 2	118,266	88,423	25.2%	88,411	25.2%
BRAGG 3	138,899	94,775	31.8%	94,086	32.3%

6.1.8 Total Energy Performance

The previous analyses addressed the energy consumption and savings at the air handler. In order to identify the total energy usage and savings, upstream system efficiencies were considered so that the final energy savings, as measured at the air handler, could be translated into expected energy savings as measured at the utility meter.

Based on equipment and system configurations at CERL, the following efficiency adjustments were made prior to life cycle cost analysis:

1. *VFD efficiency*
2. *Hot water system losses*
3. *Chilled water system losses*

Detailed information for Fort Bragg's equipment and configuration was not available, but the efficiency values calculated for CERL are considered typical, and therefore the CERL efficiency values were used for Fort Bragg. Table 7 shows the calculated total upstream energy use for each of the demonstrated systems based on the historic weather-normalized energy savings of each system. These values are used for the economic analysis in Section 7.

Table 7. Estimated Total Upstream Energy Savings for the Historic Weather-Normalized Data Set

AHU	Mode 0 Energy (kBtu)	Mode 1 Energy (kBtu)	Mode 1 % Reduction v. Mode 0	Mode 2 Energy (kBtu)	Mode 2 % Reduction v. Mode 0
CERL 1	406,836	292,397	28%	235,475	42%
CERL 2	787,517	312,814	60%	281,540	64%
BRAGG 1	70,953	26,027	63%	30,521	57%
BRAGG 2	62,962	43,953	30%	46,663	26%
BRAGG 3	79,722	47,828	40%	48,550	39%

6.2 COMFORT ASSESSMENT

The value of the multizone retrofit method is partially dependent upon the ability of the post-retrofit AHU to maintain indoor environmental quality including thermal comfort. The expectation was that thermal comfort would be equal to or better than the pre-retrofit AHU. The comfort performance metric used in our assessment was based on criteria defined in ASHRAE Standard 55 (2010) “Thermal Environmental Conditions for Human Occupancy”.

ASHRAE Standard 55 indicates that a survey of occupants is an acceptable method to determine occupant thermal comfort. Performing a survey throughout the 1-year duration of the test with the AHUs switching between the three modes daily would have been impractical if not impossible so only a numeric analysis of comfort was used.

6.2.1 Thermal Comfort Analysis

Based on ASHRAE Standard 55, six comfort condition variables (metabolic rate, clothing level, zone air temp, zone relative humidity, air velocity, and mean radiant temperature) were used to calculate thermal comfort in the spaces served by the retrofitted AHUs at Fort Bragg and CERL. The comfort calculation was performed at 15-minute time intervals for each of the three operating modes. Likewise, the zone temperature deviation from the temperature set point, was also calculated at 15-minute time intervals for each of the three operating modes.

6.2.1.1 Fort Bragg

The 75°F zone setpoint remains fixed for summer and winter periods of operation, likely resulting in periods of discomfort (irrespective of the operating Mode 0, 1, or 2) even though it appears fairly-well centered between the winter and summer comfort zones. The total amount of time each zone was in the comfort zone shown in Table 8. The table suggests Modes 1 and 2 yielded a somewhat less comfortable thermal environment than Mode 0.

Table 8. Time Spent Within the Comfort Zone for Each AHU, Zone and Mode for Fort Bragg

	AHU 1			AHU 2			AHU 3		
	MODE 0	MODE 1	MODE 2	MODE 0	MODE 1	MODE 2	MODE 0	MODE 1	MODE 2
Zone 1	35.1%	30.0%	25.9%	60.8%	56.0%	56.9%	31.7%	49.0%	47.7%
Zone 2	38.8%	34.9%	31.7%	35.7%	34.0%	32.6%	36.0%	58.5%	57.3%
Zone 3	44.4%	35.5%	31.4%	93.7%	89.4%	89.4%	26.3%	60.2%	61.8%
Zone 4				60.6%	57.3%	55.1%	25.8%	41.4%	41.7%
Zone 5				31.8%	22.6%	27.7%	31.0%	53.9%	51.3%
Zone 6				80.8%	69.6%	69.5%	57.8%	53.9%	54.5%
Zone 7				67.4%	63.0%	60.9%	38.7%	65.1%	62.3%
Zone 8				60.9%	62.4%	56.9%	21.2%	53.9%	46.9%
Zone 9				54.2%	44.7%	46.5%			
Total	39.4%	33.5%	29.7%	60.6%	55.5%	55.0%	33.6%	54.5%	52.9%
Delta from Mode 0		-6.0%	-9.8%		-5.2%	-5.6%		20.9%	19.4%

Note: Systems have different numbers of zones. Empty entries indicate that zone does not exist.

6.2.1.2 CERL

The 72°F zone setpoint remains fixed for summer and winter periods of operation, likely resulting in periods of discomfort (irrespective of the operating Mode 0, 1, or 2) during the warmer (summer) periods. Table 9 uses the updated comfort zone and shows the percent of the total amount of time each zone was in the comfort zone. In all modes, zone temperature and humidity are within the comfort zone nearly 100% of the time with only a slight decrease in thermal comfort in Modes 1 and 2 as compared to the Mode 0.

Table 9. Time Spent Within the Comfort Zone for Each AHU, Zone and Mode for CERL

	AHU 1			**AHU 2**		
	Mode 0	**Mode 1**	**Mode 2**	**Mode 0**	**Mode 1**	**Mode 2**
Zone 1	97.8%	97.2%	98.3%	96.7%	96.0%	98.9%
Zone 2	95.2%	95.1%	95.9%	95.6%	94.3%	97.5%
Zone 3	96.1%	95.7%	97.1%	100.0%	98.1%	100.0%
Zone 4	95.6%	92.0%	93.6%			
Zone 5	94.8%	93.4%	94.3%			
Total	95.9%	94.7%	95.8%	97.4%	96.1%	98.8%
Delta from Mode 0		-1.2%	-0.1%		-1.3%	1.4%

Note: Systems have different numbers of zones. Empty entries indicate that zone does not exist.

7.0 COST ASSESSMENT

The complete renovation of a non-DDC-controlled constant volume multizone air handler to a DDC-controlled variable volume air handler requires installing the following components:

- Premium efficiency supply fan motor
- VFD(s)
- Outdoor Airflow Measurement Station (AFMS)
- CO2 or occupancy sensors
- DDC controls upgrade

It is not expected, however, that the conversion from constant to variable volume will generally provide the impetus, or the justification, for this renovation. Rather it is likely that the conversion to variable volume will be an "add on" when the system is converted from non-DDC to DDC controls, or when the existing DDC controls are replaced. Therefore, all costs associated with the DDC upgrade are assumed to have been incurred, i.e., they are sunk costs, and the marginal financial burden of implementing the constant to variable volume retrofit will be limited to the following components:

- VFD(s)
- Outdoor airflow measurement station (AFMS)

The retrofit will require a UMCS programmer to update the air handler sequence of operations to allow the following functionality:

- Fan speed reduction until zone dampers are near fully open
- Outside airflow requirements are met as fan speed changes
- Heating and cooling valves are closed automatically when not needed
- Demand controlled ventilation (based on CO2 or occupancy sensors). This was implemented only in Mode 2, and not implemented for Fort Bragg AHU 2.
- After-hours (unoccupied mode) temperature setback / shutdown

The cost benefit of this retrofit comes from the reduction in energy use and associated costs from reducing both fan output and simultaneous heating and cooling. Although there can be a significant implementation cost associated with this retrofit, it is much more cost-effective than a full system replacement (see Table 15). The implementation costs are kept low because this retrofit technique focuses almost entirely on instrumentation and controls rather than demolition and installation of ductwork and terminal units. This approach also leads to limited system down time and little disturbance to building occupants.

7.1 COST MODEL

The elements of the cost model are described in paragraphs 7.1.1 through 7.1.6. The actual values used in cost analysis are shown in the tables in paragraph 7.1.7.

7.1.1 Hardware Capital Costs

Hardware capital costs are based on a multizone air handler with existing DDC retrofit components. In order to convert a constant volume multizone system to a variable volume multizone system a single airflow monitoring station and a VDF for each fan serving the air handler must be installed to allow the AHU to reduce fan speed while maintaining the necessary quantity of ventilation air. Detailed information on component costs was taken from Mechanical Costs with RS Means Data published by Gordian.

7.1.2 Installation Costs

Equipment installation and programming costs are all dependent on labor costs at the installation and detailed information on installation labor costs was taken from Mechanical Costs with RS Means Data, published by Gordian. Programming labor was estimated using the billable rate for CERL's UMCS contractor.

Should multiple retrofits of similar systems be performed at the same site, economy of scale may be expected to reduce costs due to the repetition of programmer implementation and the ability to use management funds over multiple projects.

7.1.3 Energy Costs

Energy costs for each air handler are broken into three modes representing the normalized annual energy costs if the AHU had not been retrofitted (Mode 0), if the AHU had been retrofitted and the outdoor airflow was fixed (Mode 1), and if the AHU had been retrofitted and the outdoor airflow was controlled based on occupancy sensors (Mode 2).

These costs embody all the savings from the retrofit. The utility rates used in this analysis were blended, meaning that the total annual utility bill costs (energy rates, demand charges, transmission charges, utility rebates, etc.) were divided by the total annual energy consumption.

7.1.4 Operator Training Costs

AHUs are subject to changes in operation under a wide array of circumstances, including when building operation schedules change or equipment must be replaced. Since the new UMCS sequences of operation implemented during the retrofit will be new to the building's mechanical crew, it makes sense to train them as to how to make operational changes to the new system.

Hourly rates are based on the billable rate for CERL's UMCS contractor. It is assumed that a full 8-hour day will be devoted to training the building's maintenance staff to operate the new system. These costs may only need to be incurred once if the upgraded systems are all similar and the same maintenance staff oversees each AHU that is upgraded, and thus multiple retrofits at the same installation may see a reduction in training costs per system.

7.1.5 Maintenance Costs

The conversion to variable volume does not impact typical maintenance procedures for the AHU.

7.1.6 Hardware Lifetime

The Energy Conservation Investment Program (ECIP) estimates that "EMCS or HVAC Controls" will have a 15-year lifespan, which is what was used for the total life of the project.

7.1.7 Cost Model Values

Table 10 and

Table 11 show the RS Means-based values used as the cost model for the air handler retrofits at CERL and Fort Bragg.

Table 10. RS Means-Based Cost Model for Multizone Air Handler Retrofit for CERL

		Estimated Costs	
Cost Element	**Data Tracked During the Demonstration**	**AHU-1**	**AHU-2**
Hardware capital costs	Component Costs for Renovation	AFMS: $1,462 3 hp RAF VFD: $1,272 5 hp SAF VFD: $1,447	AFMS: $1,462 3 hp SAF VFD: $1,272
Installation costs	Labor costs for Renovation	AFMS: $243 3 hp RAF VFD: $733 5 hp SAF VFD: $733 8 Programming Labor Hours: $940	AFMS: $243 3 hp SAF VFD: $733 8 Programming Labor Hours: $940
Energy Costs	Energy costs (first year)	Mode 0: $5,104 Mode 1: $3,728 Mode 2: $3,143	Mode 0: $8,269 Mode 1: $3,347 Mode 2: $3,019
Additional Commissioning & Operator Training Costs	Training costs for new system	4 Commissioning Labor Hours: $470 4 Training Labor Hours: $470	4 Commissioning Labor Hours: $470 4 Training Labor Hours: $470
Maintenance Costs	Frequency of required maintenance Labor and material per maintenance action	Negligible	Negligible
Hardware lifetime	Replacement time based on field experience	Greater than Expected Project Lifespan	Greater than Expected Project Lifespan
Misc. Costs	RS Means Overhead, Profit, Bond, and Contingency Costs	Inflation: $975, Subcontractor OH: $875, Subcontractor Profit: $656, Subcontractor Bond: $219, Prime OH: $1,049.48, Prime Profit: $524.74, Prime Bond: $262, Contingency: $617	Inflation: $702, Subcontractor OH: $629, Subcontractor Profit: $472, Subcontractor Bond: $157, Prime OH: $755.02, Prime Profit: $377.51, Prime Bond: $189, Contingency: $444

Table 11. RS Means-Based Cost Model for Multizone Air Handler Retrofit for Ft. Bragg

		Estimated Costs		
Cost Element	**Data Tracked During the Demonstration**	**AHU-1**	**AHU-2**	**AHU-3**
Hardware capital costs	Component Costs for Renovation	AFMS: $1,468 3 hp SAF VFD: $1,278	AFMS: $1,468 3 hp SAF VFD: $1,278	AFMS: $1,468 3 hp SAF VFD: $1,278
Installation costs	Labor costs for Renovation	AFMS: $134 3 hp SAF VFD: $406 8 Programming Labor Hours: $520	AFMS: $134 3 hp SAF VFD: $406 8 Programming Labor Hours: $520	AFMS: $134 3 hp SAF VFD: $406 8 Programming Labor Hours: $520
Energy Costs	Energy costs (first year)	Mode 0: $1,084 Mode 1: $415 Mode 2: $374	Mode 0: $1,050 Mode 1: $644 Mode 2: $652	Mode 0: $1,131 Mode 1: $569 Mode 2: $578
Additional Commissioning & Operator Training Costs	Training costs for new system	4 Commissioning Labor Hours: $260 4 Training Labor Hours: $260	4 Commissioning Labor Hours: $260 4 Training Labor Hours: $260	4 Commissioning Labor Hours: $260 4 Training Labor Hours: $260
Maintenance Costs	Frequency of required maintenance Labor and material per maintenance action	Negligible	Negligible	Negligible
Hardware lifetime	Replacement time based on field experience	Greater than Expected Project Lifespan	Greater than Expected Project Lifespan	Greater than Expected Project Lifespan
Misc. Costs	RS Means Overhead, Profit, Bond, and Contingency Costs	Inflation: $543, Subcontractor OH: $487, Subcontractor Profit: $365, Subcontractor Bond: $122, Prime OH: $584.24, Prime Profit: $292.12, Prime Bond: $146, Contingency: $343.24		

7.2 COST DRIVERS

7.2.1 Existing Components

Many multizone AHUs will have undergone incremental improvements over the years. If these improvements involve installation of any of the components necessary for upgrade, then the cost of the upgrade will be reduced.

7.2.2 Energy Costs

Electricity costs per kilowatt hour were 13% higher for Fort Bragg than for CERL and natural gas costs per therm were 26% higher for CERL than for Fort Bragg. The higher the energy costs, the faster the AHU retrofit investment will pay for itself.

7.2.3 AHU Size and Regional Heating and Cooling Loads

CERL is in Illinois and Fort Bragg is in North Carolina. Both locations are in the ASHRAE moist climate zones. Of the 7 ASHRAE temperature zones represented in the continental United States Fort Bragg is in Zone 3 and CERL is in Zone 5. Therefore, this study represents only a subset of the possible savings opportunities.

7.3 COST ANALYSIS AND COMPARISON

7.3.1 Basic Site Descriptions:

CERL is in Champaign, Illinois, and consists of three buildings interconnected by two hallways. AHU-1 and AHU-2 are in Building 2, above the ceiling of Room 2014 and in Mechanical Room 2127, respectively. The buildings primarily house laboratories and offices. The site has an existing UMCS which was used for data collection on site.

Fort Bragg is a Forces Command installation located in Cumberland and Hoke Counties, North Carolina with numerous existing multizone systems. Fort Bragg consists of approximately 161,000 acres. Fort Bragg's facilities include 2,176 structures and 25.2 million sq. ft. total buildings. The site has an existing UMCS which was used for data collection on site.

7.3.2 Results for Incremental Retrofit

Regardless of the significant energy consumption reductions seen across all air handlers and operating modes (see Table 12), not all air handler retrofit projects successfully reduced life-cycle costs over the study period of 15 years. The success of the retrofit at CERL is largely due to the relatively high baseline energy consumption of the CERL AHUs, making them good economic candidates for the retrofit. Even though Fort Bragg AHUs 2 and 3 could reduce energy costs by 38% and 49% respectively, due to their relatively low baseline energy consumption, the AHUs still failed to pay back in a 15-year lifespan.

Table 12. Reduction in Life Cycle Energy Costs for Incremental Retrofits

Life Cycle Costs	CERL AHU-1	CERL AHU-2	Ft. Bragg AHU-1	Ft. Bragg AHU-2	Ft. Bragg AHU-3
Mode 0 (Base Case)	$60,919	$98,702	$13,693	$13,176	$14,347
Mode 1 (Percent Reduction)	$57,403 (27%)	$49,250 (60%)	$12,574 (61%)	**$15,358** (38%)	**$14,515** (49%)
Mode 2 (Percent Reduction)	$50,415 (38%)	$45,340 (63%)	$11,994 (65%)	**$15,480** (37%)	**$14,633** (48%)

Although the sample size is small, there does not appear to be a strong correlation between air handler size (baseline energy consumption) and energy savings potential. Because retrofit costs do not increase linearly with AHU size, it is expected that large AHUs with high space conditioning loads will have faster payback periods (see Table 13).

Table 13. Simple Payback and Savings-to-Investment Ratios for Incremental Retrofit

Life Cycle Costs	CERL AHU-1	CERL AHU-2	Ft. Bragg AHU-1	Ft. Bragg AHU-2	Ft. Bragg AHU-3
Mode 1	Payback: 10 yrs. SIR: 1.27	Payback: 3 yrs. SIR: 6.32	Payback: 11 yrs. SIR: 1.16	Payback: N/A SIR: 0.70	Payback: 13 SIR: 0.98
Mode 2	Payback: 7 yrs. SIR: 1.81	Payback: 3 yrs. SIR: 6.74	Payback: 10 yrs. SIR: 1.24	Payback: N/A SIR: 0.68	Payback: 13 SIR: 0.96

7.3.3 Costs for Complete DDC Retrofit

Since CERL AHU-2 was fully renovated as part of this demonstration, actual installation costs were available (see Table 14).

Table 14. 15-Year Life Cycle Costs for Complete DDC Retrofit for CERL AHU-2

Life Cycle Costs	Life Cycle Costs	SIR	Simple Payback
Base Case (Mode 0)	$98,702	n/a	n/a
Mode 1	$88,189	1.22	11 years
Mode 2	$84,279	1.30	10 years

7.3.4 Comparison to Renovation to Variable Air Volume (VAV) System (with VAV Boxes)

Table 15 summarizes estimates from a local contractor for a full system renovation on the two systems at CERL and indicates the large amount of money the CERL retrofit approach can save.

Table 15. Replacement/Retrofit Cost Comparison

CERL Initial Upgrade Costs			
System Replacement		**System Retrofit (CERL Approach)**	
CERL Executive Office VAV (2014)	**CERL Room 2120 VAV (2015)**	**CERL AHU-1 MZ to VAV retrofit (2015)**	**CERL AHU-2 MZ to VAV retrofit (2015)**
$535,000	$750,000	$20,500	$48,239

8.0 IMPLEMENTATION ISSUES

In order to identify the applicability and interest in constant to variable volume multizone retrofits within DoD, a questionnaire was sent to many CONUS installations. After accounting for duplicated responses, there were 78 individual respondents representing more than 39,000 Billion British Thermal Units (BBTUs) of installation energy consumption and between 14,816 and 26,475 individual multizone air handlers. Most installations (25 of 48) that indicated their level of interest in the constant volume to variable volume retrofit responded with “very interested” as shown in Table 16. This represents a large potential for cost and energy savings if large and energy-intensive multizone air handlers are targeted for retrofit.

Table 16. Questionnaire Summary

	Army	**Air Force**	**Navy**
# of Responses	47	27	4
Annual Energy Consumption (BBTU)	21102	15452	2470
# of Buildings with HVAC	10,252 – 16,350	4,529 – 9,325	353 – 800
# of MZ AHUs	2,597 – 3,266	1,293 – 1,665	26 – 35
Level of Interest in MZ-to-VAV Retrofit	Very Interested: 16 Moderately Interested: 4 Somewhat Interested: 6 Not Interested: 3	Very Interested: 7 Moderately Interested: 3 Somewhat Interested: 4 Not Interested: 2	Very Interested: 2 Moderately Interested: 1 Somewhat Interested: 0 Not Interested: 0

8.1 FAN SPEED CONTROL – SEQUENCE OF OPERATION LOGIC

Reduction in AHU fan speed is one of the biggest benefits of this technique. The sequence of operation is a bit complex and should be checked to verify that the control logic programmed into the digital controller performs properly.

8.2 FAN SPEED CONTROL – ZONE DAMPER COMMAND

Zone damper command has a significant impact as it is used to set the AHU fan speed. Things that can negatively impact damper command include:

- - Zone damper Proportional, Integral, Derivative (PID) tuning constants
- - Zone heating or cooling load imbalance
- - Zone controller or sensor malfunction

Fan speed performance should be checked during commissioning, perhaps through a 1-week long endurance test where fan speed and damper commands are logged and then inspected.

8.2.1 Zone Damper PID Tuning Constants

In its pre-commissioned state, Figure 1 shows that the AHU-2-001 supply fan was cycling fairly frequently on a daily basis. Inspection revealed that the individual zone dampers were cycling due to an aggressive integral gain setting, resulting in the fan cycling. The aggressive integral gain setting was present in the pre-retrofitted, and therefore was a product of prior commissioning (or lack thereof). This suggests zone damper PID control 'tuning' is important. The figure also shows that the minimum fan speed was initially set too high in the system's pre-retrofit state.

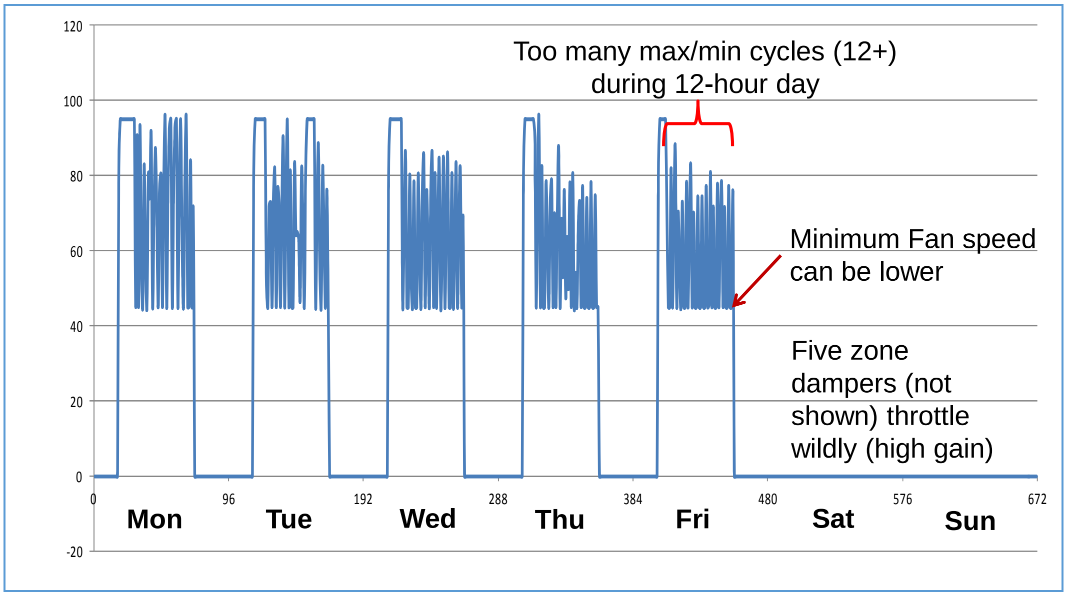

Figure 1. Daily Cycling of AHU-2-001 Supply Fan.

8.2.2 Zone Heating or Cooling Load Imbalance

If the heating or cooling load in one or more zones is rarely or never met, this can impact performance. The byproduct is that the temperature set point is not met and the thermostat/controls will always or frequently be commanding the zone damper to fully open to heating or cooling. This will cause the AHU fan to run at full speed most, if not all, of the time. This project considered this possibility and Section 6 showed this was not a problem in the demonstration systems, but it should be considered a distinct possibility.

8.2.3 Zone Controller or Sensor Malfunction

Similar to heating or cooling load imbalance, a malfunctioning controller can also command the zone damper to fully open to heating or cooling.

9.0 REFERENCES

ANSI/ASHRAE Standard 55-2010. Thermal Environmental Conditions for Human Occupancy.

Whole Building Design Guide (WBDG) web site: http://www.wbdg.org/

Unified Facilities Guide Specification (UFGS) 23 09 23. ‘LonWorks Direct Digital Control for HVAC and Other Building Control Systems’

Guide Specification (UFGS) 25 10 10. 'LonWorks Utility Monitoring and Control System (UMCS)'

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