Exploring a Multizone To Variable Volume HVAC Controls Retrofit

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The U.S. Department of Defense (DOD) has thousands of 10 to 40+ year old multizone air-handling units (AHUs) in operation. These constant volume, variable temperature units are quick to meet space temperature needs, but they can be very energy inefficient. Multizone units deliver a constant volume of air to the building zones serviced, regardless of the actual cooling, heating and ventilation requirements of each zone. Further, the conventional two-deck multizone uses continuous, simultaneous operation of the heating and cooling coils, even when additional heating or cooling is not needed. Modern alternative system replacements (such as variable air volume systems) help address these inefficiencies but are costly and disruptive to install. This article presents an energy savings retrofit of the multizone control system that provides variable volume airflow at significantly lower expense and with less disturbance than a complete system change out.

The basic components of the variable volume retrofit include the addition of a variable frequency drive for the fan(s), an outside airflow measurement array and controls programming. This retrofit is designed to limit the required changes to the system and can serve as an interim solution to help meet DOD energy-efficiency and resilience requirements within limited budgets.

The DOD Environmental Security Technology Certification Program (ESTCP) sponsored a field demonstration of the retrofit technology during 2016–2017, as well as an extensive technology transfer effort for the retrofit during 2019–2022. Previous publications about this effort included a detailed technical report from the ESTCP demonstration project[1] and an overview ASHRAE conference paper.[2] This article unpacks the details of the retrofit and results described in the conference

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paper. It covers the retrofit design, demonstration methodology, performance analysis, applicability insights and a suite of technology transfer support tools.

Background

Constant volume multizone (MZ) HVAC systems were common in the 1950s and '60s prior to the introduction of more energy efficient variable air volume (VAV) systems in the '70s. MZs have parallel paths (decks) inside the air handler for heating and cooling airflows. The airstreams are mixed at the outlet of the air handler based on zone demands and then delivered to each zone via dedicated ducts, making them quick to respond to the needs of the space.

Attempts at improving MZ efficiency over the years included adding setpoint reset to the originally fixed deck temperatures based on outside air temperature or shutting off decks seasonally to allow only heating in the winter and cooling in the summer. New designs emerged that removed the hot deck coil and added heating coils to the zone ducts resulting in a bypass configuration* or configurations that added a third (neutral) deck, but both still retained the constant volume feature. (See the next section, "Multizone Configurations.")

One retrofit solution consisted of installing VAV box terminal units in the branch duct serving each zone along with a VFD on the supply fan with capacity control based on static pressure sensed at the fan discharge. A similar packaged retrofit product provided a "slide-in retrofit terminal unit" for each zone where variable air volume was achieved through terminal unit adjustment of airflow. This retrofit also included the addition of a VFD with capacity regulation again based on duct static pressure at the fan discharge. Another marketed product was a self-adjusting diffuser. Use of this product was more sophisticated as it required modification of the existing damper control signals such that the dampers supplied either full heating or full cooling based on a (modified) thermostat signal. This retrofit also called for installation of a control damper in each zone's branch duct, a VFD and duct static pressure sensors at the fan discharge as well as in each zone's branch duct.

Retrofits also emerged that varied fan speed based on measurements of damper position or discharge air temperature. Yet another approach for conversion to VAV broke the mechanical linkage/shaft connecting each zone's hot and cold damper and then used separate actuators for the hot and cold dampers. This approach allowed for sequencing of the dampers so only one deck was open at a time and modulated fan speed based on static pressure in the open deck or discharge air temperature.[3–7]

The collective observation of the project team, based on three decades of working with dozens of DOD and state government sites that have multizones, is that most of these facility energy professionals aspire to upgrade their MZs by replacing them altogether with VAV systems, but that this expensive option is not practical with limited budgets. To address the needs of these government coworkers, the team developed a simple, low-cost remedy to the multizone energy inefficiencies and field tested the proposed solution. This low-cost approach minimized the physical changes to the systems and attempted to reign in the complexity of the solution to allow staff, including those with limited time or controls experience, to implement and manage the resulting system.

Multizone Configurations

Multizone AHU systems have three typical configurations: conventional two-deck, bypass and neutral deck. Common features of multizone systems include serving multiple spaces, a constant volume fan, multiple parallel air decks and dedicated sets (assemblies) of zone dampers (one set for each zone) to mix air at the air handler for a customized blend of air at the right temperature for each zone. A summary of each is in *Table 1*.

Each of the typical configurations has a supply fan that operates at a single speed delivering a constant volume of air. Each uses multiple sets of dedicated zone dampers to mix parallel airstreams in the desired proportions for delivery to each zone. Zone damper pairs are two dampers mechanically linked and offset by 90° such that as a damper opens to one deck, it closes its linked deck damper proportionally in reciprocal fashion. (See *Figure 1* for zone damper sequencing of the assorted MZ units in a proportional only control scheme.†) AHUs with two decks have one pair of dampers (with a common

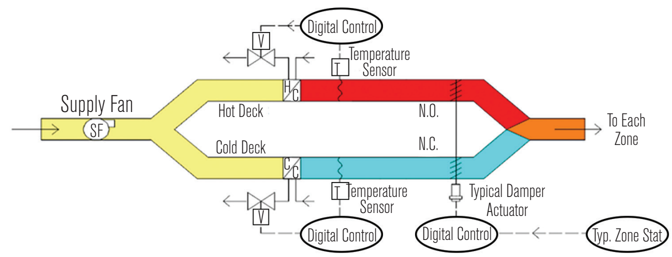
*This configuration was especially popular in hot/humid climates where primary heating was seldom required. It was also often called the "Texas Multizone."[8]

†Although the retrofit uses proportional-integral (PI) control, the graphical representation of proportional-only control is shown to depict the relative position of the dampers as they actuate.

TABLE 1 Common multizone configurations and features.

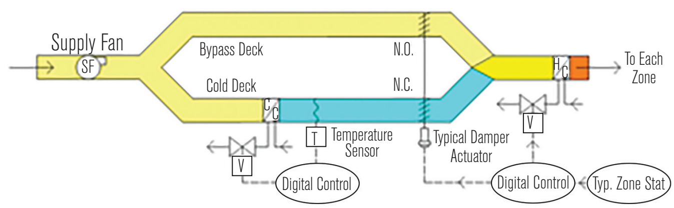
CONVENTIONAL (HOT DECK/COLD DECK) MULTIZONE

- Two decks: one hot, one cold.
- Heating and cooling coils in respective decks.
- Both decks typically operated continuously, even when heating/cooling not needed.



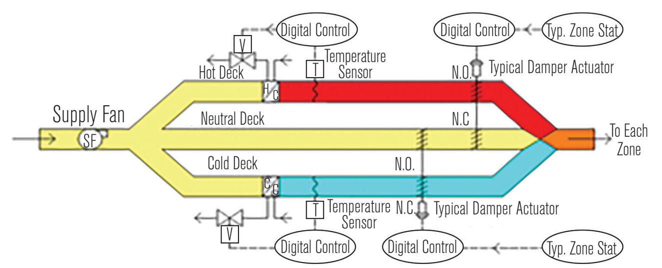
BYPASS (TEXAS STYLE) MULTIZONE

- Two decks: cold and bypass.
- No coil in bypass deck.
- Heating coil typically in each zone duct (allows heating in only zones that need it).
- Uses unconditioned air (e.g., recirculated and outside air) in bypass deck for partial "free heating" when not economizing, especially useful in hot/humid climates that cool to 48°F – 52°F for dehumidification needs.
- More efficient than Conventional Multizone (avoids simultaneous heating and cooling).
- More coils to maintain.



NEUTRAL DECK MULTIZONE

- Two decks: hot, neutral, and cold.
- Neutral Deck has no coil and introduces mixed air (recirculated and outside air)
- Uses unconditioned air (e.g., recirculated and outside air) in neutral deck for partial "free heating" when not economizing, especially useful in hot/humid climates that cool to 48°F – 52°F for dehumidification needs.
- More efficient than Conventional Multizone (avoids simultaneous heating and cooling).



actuator) for each zone to mix the air from the two available decks. AHUs with three decks may have two damper pairs for each zone (with two actuators, one for each pair) or an assembly of three linked dampers with a single common actuator to orchestrate the mixing of the three available decks. The key feature in the triple deck arrangement is that the hot deck and cold deck are not open at the same time, and the neutral deck is reciprocal to the operating conditioned deck. Each of the damper actuators receives its signal from its respective zone controller. The various types of multizone air handlers differ in the number of decks they have as well as the number and placement of heating and cooling coils. Some units also have return and/or exhaust fans.

Variable Volume Retrofit Design

The Basic Retrofit (*Figure 2*) reduces wasted energy through capacity control of the fan(s) and turning off the heating and cooling coils when not needed. Where direct digital control (DDC) hardware preexists, it requires the addition of two pieces of equipment and controls programming:

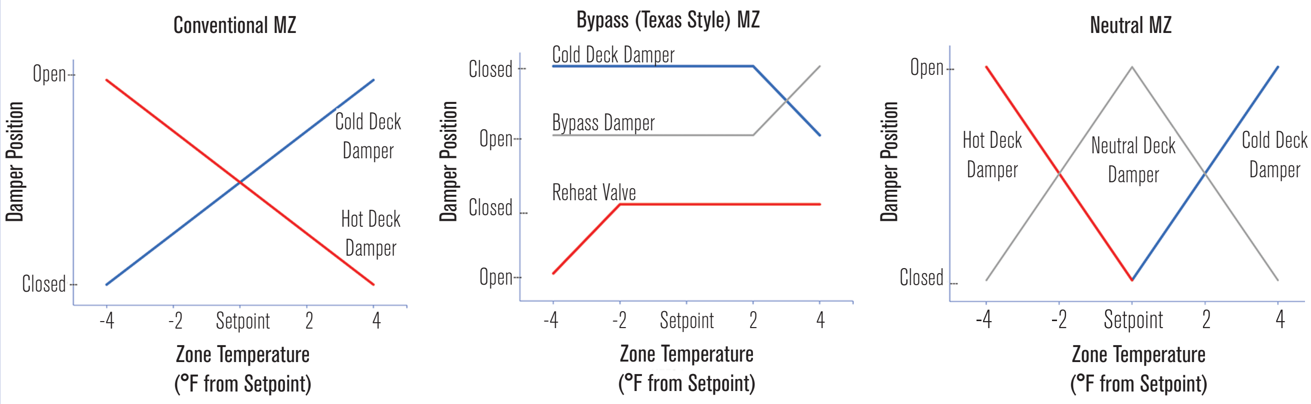
- A variable frequency drive (VFD) to allow for fan operation at reduced speeds;
- An airflow measurement array (AFMA) to measure and thereby control outdoor air intake to supply the required amount of ventilation and/or makeup air;
- Controls programming that implements the new functionality: variable fan speed control, outside airflow control and on/off heating and cooling coil control.

The control is novel in that it uses the damper command signals§ to establish the fan speed and inform decisions about enabling or disabling the coils.

The building zone with the greatest need for space

§Attempts by others to use the zone dampers to control fan speed used positioning sensors.[5] The proposed retrofit simplifies the control scheme and reduces costs of the retrofit by skipping the measurement of damper position and instead uses the damper command signals from the zone controllers to the zone actuators. It polls the maximum of all the zone damper signals as the process variable by which to set the fan speed.

FIGURE 1 Example zone damper sequencing (proportional-only control).



conditioning will have a damper control signal that calls for the greatest damper opening to either heating or to cooling. The fan adjusts speed until this most needy zone damper is near full open to its needed coil (i.e., heating or cooling). The control scheme also disables the heating or cooling coil (closing the respective control valve) when not needed as indicated by the zone damper commands.

The retrofit is noninvasive in that it takes place primarily in the mechanical room and on the building control system, so is less disruptive to building occupants than a complete system replacement that requires vacating building areas during construction.

The purpose of the retrofit control scheme is to turn components down or off when not needed and may be applied to different types of multizone units. This results in both electric savings at the fan(s) and thermal load savings at the coils (i.e., a reduction in the energy transfer at the coils, which translates into fuel savings for the supplying heating and cooling equipment such as boilers or chillers).

Fan Capacity Control

The control scheme adjusts fan speed based on both space conditioning requirements and outside air ventilation requirements.

Space Conditioning Requirements are dictated by the most open (to any deck) zone damper, where fan speed is decreased until one of the (multiple) zone dampers is at full or near-full open position. The zone dampers open and close based on deviation from the space temperature setpoint (*Figure 1*). The scheme reduces fan capacity until one of the zone dampers is near full open (by tracking the damper signal and targeting 95% as indication of near full open). The objective is to let the dampers open wide so the fan speed can be lower while

FIGURE 2 Basic retrofit schematic with added items marked in red.

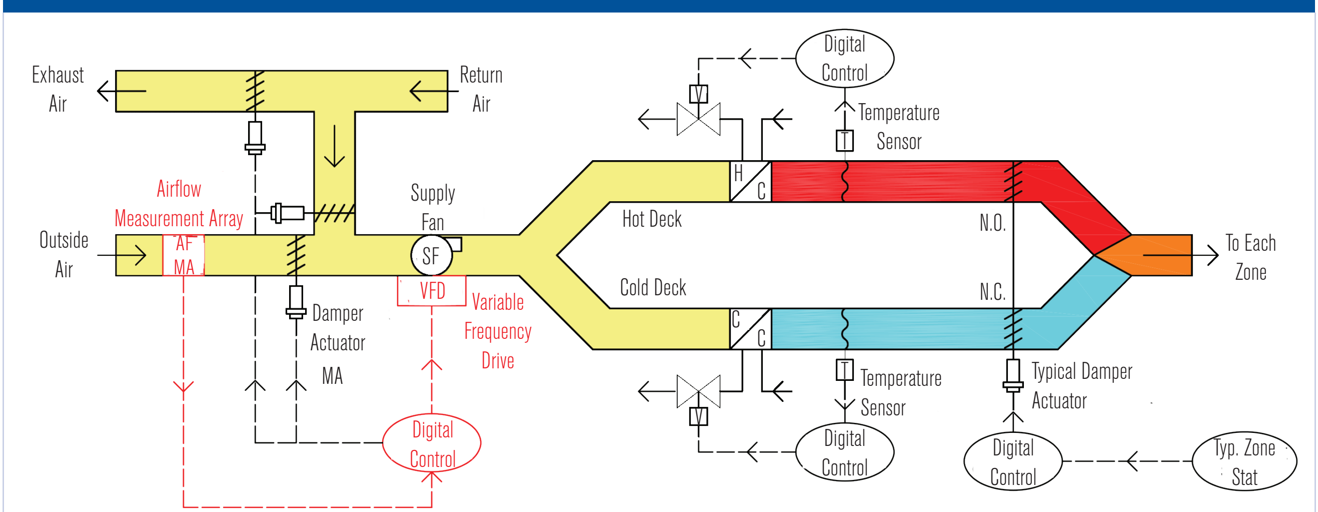
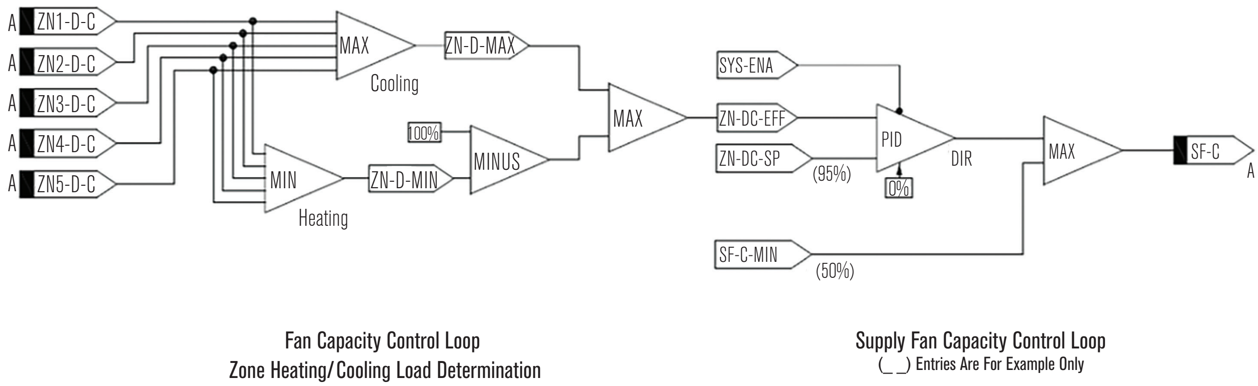


FIGURE 3 Fan capacity control loop (for conventional multizone system) Notes: A = Analog Signal, ZN = Zone, D = Damper, C = Command, SYS = System, ENA = Enable, EFF = Effective, SP = Setpoint, DIR = Direct Acting



still getting adequate heat transfer to provide the needed conditioning to the zone. If a damper opens beyond the target (typically 95%), that indicates that more conditioning is needed, and fan speed is ramped up. The most "needy" damper is determined with the control logic comparing the percent open (to either deck) from the whole collection of zone damper signals (*Figure 3*). The fan speed modulates between its high and low limits, typically set at 50% minimum and 100% maximum. The low limit may be reduced by the designer to about 30% if the motor is relatively new (e.g., a premium efficiency motor) and can accommodate that speed reduction without overheating.

Figure 3 shows the control diagram for the supply fan VFD of a conventional MZ unit, which determines the zone with the greatest load to inform the capacity control of the fan. On the left, the zone damper commands from each of the zones are polled for the maximum and minimum signal. The maximum signal indicates the most open cooling damper position. The minimum signal indicates the most open heating damper position. The control logic compares the heating and cooling damper positions to determine which is most open where the minimum signal is subtracted from 100% to determine the heating damper "amount open" position. The most open damper position (either most open to heating or most open to cooling) is then used as the process variable for the PI[#] control loop, with a target damper open setpoint (typically 95%) to control fan speed. The desired fan speed from the PI control loop is compared to the minimum fan speed command, and the greater value is used as the supply fan command (thus ensuring the fan doesn't go below the minimum permitted speed).

Outside Air Requirements were met through measurement of outside airflow and modulation of the outside air damper (or mixed air dampers) to maintain ventilation requirements (e.g., ASHRAE Standard 62.1, *Ventilation for Acceptable Indoor Air Quality,* at the time of the demonstration[||]) and makeup air requirements. In the demonstration project, each system used either a fixed airflow setpoint or a demand-controlled ventilation (DCV) sequence of operation.

In the case of fixed flow setpoint, the outside air requirements were met using a flow setpoint in the control logic along with a designer selected minimum fan speed (*Figure 3*).

For the demonstration systems, the outside air ducts had such ample capacity (since they were originally sized for an economizer) that the ventilation requirements were met at the minimum fan speed that prevents motor overheating. During economizer mode, the control logic keeps the outdoor air damper sufficiently open to maintain minimum outside airflow.[**]

In the case of demand-controlled ventilation (DCV), the outside air requirements were accommodated using dynamic reset of the outdoor airflow setpoint. This included reducing outdoor airflow when spaces were at reduced or no occupancy. Either occupancy or CO_2

[#] Although a PID controller is often used in this application, only the proportional and integral features of the controller are used.

[||] Implementers should consider current ASHRAE guidelines to ensure acceptable indoor environmental quality.

[**] For systems with lower outside air capacity (e.g., those without airside economizer), control logic would be needed to ensure that the minimum fan speed is increased if ventilation requirements are not met when the outside air damper is fully open.

FIGURE 4 Enable/enable/disable of hot deck valve control..

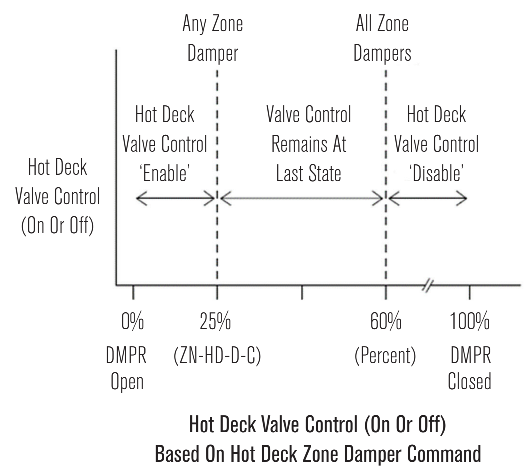
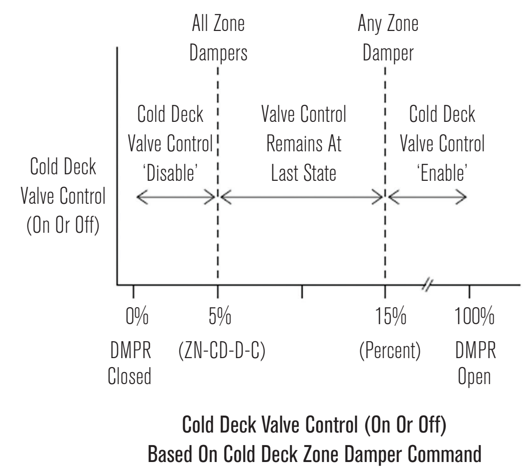


FIGURE 5 Enable/disable of cold deck valve control.



sensors were used in certain zones to adjust the system ventilation level based on space use. Where occupancy sensors were used, in classrooms and conference rooms, they were passive infrared (PIR) type and located on the ceiling. If any of these sensors sensed occupancy, the control system signaled the AHU to provide full ventilation as if all zones were occupied. In the CO_2 sensor scenario, the sensors were co-located with the thermostats in each densely occupied space (cubicled offices and conference rooms), and the ventilation airflow setpoint

Advertisement formerly in this space.

TABLE 2 System descriptions.

MZ AHU	LOCATION	TYPE	AGE OF UNIT (YR)	END USE	UNIT SIZE (cfm)	FLOOR AREA (ft^2)	FAN MOTOR SIZE (HP)
CERL 1	Central Ill.	Conventional	40	Office	15,190	8,800	8*
CERL 2	Central Ill.	Conventional	40	Conference Rooms	3,475	2,400	3
Bragg 1	Central N.C.	Neutral Deck	10	Classrooms	4,620	2,983	5
Bragg 2	Central N.C.	Neutral Deck	10	Office	4,670	4,328	5
Bragg 3	Central N.C.	Neutral Deck	10	Office	5,930	4,837	7.5

*5 HP supply fan and 3 HP return fan.

was adjusted using a linear reset schedule based on the zone with the highest CO_2 level. Similar to the "fixed flow setpoint" control described above, the system was operated at no less than a designer selected minimum fan speed and, during economizer operation, the OA damper was prevented from closing more than required to maintain minimum outside airflow setpoint.

Coil Valve Control

The control scheme adjusts coil output capacity by enabling/disabling coil water valves and using a binary hot deck reset.

Enabling/Disabling Valves. The hot/cold deck (heating and cooling) coil control valves are disabled (closed) when no heating (or cooling) is called for by any zone and otherwise enabled to modulate to the fixed deck air temperature setpoint.

Figures 4 and *5* show how the coil valve control is enabled and disabled by the zone damper command signals issued by the digital control system. *Figure 4* presumes that each zone damper is normally open (N.O.) to the hot deck; therefore, damper fail-safe position (upon loss of control signal or power) is to full open to heating. Similarly, *Figure 4* presumes that each zone damper is normally closed (N.C.) to the cold deck;, therefore, damper fail-safe (upon loss of control signal or power) is full closed to cooling.

The control system sequencing diagram in *Figure 4* shows that the system polls all the zones served by the AHU and enables the hot deck valve when *any* of the system's multiple zone dampers receive an actuation command between 0% to 25% indicating a zone with a fairly significant call for heat. The valve remains enabled until all spaces are sufficiently satisfied. When *all* of the zone damper signals are commanded to be between 60% and 100%, none of the zones are calling for much heat, so the hot deck control valve is disabled (or "off"). The valve remains in its present state (now closed) until any one zone indicates a need for heating. In this way zone damper commands between 25% and 60% result in the hot deck valve enable or disable command remaining unchanged from its last state.

The threshold values of 25% and 60% in *Figure 4* are intended to improve performance and save energy by minimizing standby losses and the amount of conditioned air that leaks through zone dampers into the supply air to the zone. The triggering values for enabling and disabling the coils can be adjusted as needed to accommodate site-specific factors such as local climate. Note that for a bypass MZ unit there is no hot deck, so there is no hot deck enable/disable control.

The sequencing diagram in *Figure 5* shows that the cold deck valve is similarly enabled and disabled as the hot deck valve shown in *Figure 4*, but the thresholds of percent signal from the zone dampers are different. Here, if all zone damper signals are less than 5%, there is essentially no need for cooling, so the cold deck valve is disabled and closed. At 15% signal, there is sufficient need for cooling that the valve is enabled to modulate. Because every system is unique, all threshold values are configurable to meet the specific needs of the MZ unit, such as dehumidification needs, which may require the cold deck threshold to be turned off and set to 0% instead of 5%.

Using a Binary Hot Deck Temperature Reset to modulate to one of two fixed temperature setpoints instead of using the more common proportional hot deck temperature reset. A binary "reset" was used where the setpoint was adjusted to either a higher setpoint (e.g., 90°F [32°C]) or a lower (e.g., 80°F [27°C]) setting, depending on whether the outside air temperature was below or above 50°F [10°C], respectively. Without proportional reset, the upper binary setpoint provides for a hotter deck air temperature, allowing a lower airflow

FIGURE 6 Energy analysis of field data.

1. Gather Data, Rotate Modes Daily

M	T	W	R	F	Sa	Su
Mode 0 T, E1,E2…	Mode 1 T, E1, E2…	Mode 2 T, E1, E2…	Mode 0 T, E1, E2…	Mode 1 T, E1, E2…	-	-
Mode 2	Mode 0	Mode 1	Mode 2	Mode 0	-	-
Mode 1	Mode 2	Mode 0	Mode 1	Mode 2	-	-

2. Sort, screen, balance groups

Mode 0 Records Group — OA BIN

Mode 1 Records Group — OA BIN

Mode 2 Records Group — OA BIN

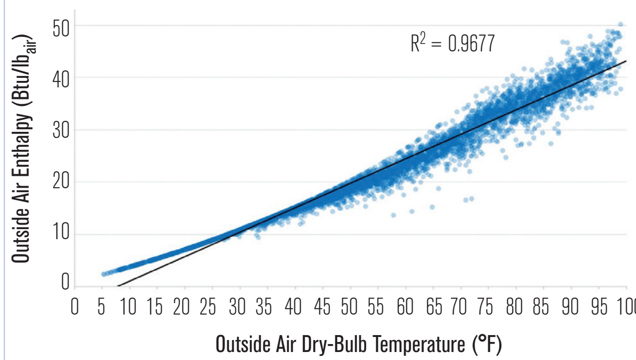
3. Calculate savings for each bin

Savings of basic VV = Mode 0 - Mode 1
Savings of VV w/ DCV = Mode 0 - Mode 2

4. Map savings to typical weather year (Example bins below)

Weather Bin	Hours	Hourly Savings	Annual Savings
60°F-65°F	189	51 kBtu/h	189*51=9,640 kBtu
25°F-30°F	118	133 kBtu/h	118*133=15,694 kBtu

FIGURE 7 Example correlation of OAT with enthalpy at CERL.



rate to meet zone heating load and resulting in additional fan energy savings. The lower temperature setting improves temperature control because it better matches the capacity of the coils with the reduced heating loads in warmer weather, and it reduces overheating common in older systems that often have oversized control valves, leaky control valves (e.g., worn valve seats), leaky dampers (e.g., bad or nonexistent damper blade edge seals), etc.

Demonstration Methodology

The variable volume retrofit was demonstrated on five air handling units in two different climate zones. The multizone types included the conventional two-deck (hot deck/cold deck) and the neutral deck (triple deck). *Table 2* shows system descriptions. Three operational modes were analyzed.

Mode 0. Base Case. Replicated preretrofit multizone operation with constant volume fan and typical energy efficiency control schemes including hot deck temperature reset (based on outside air temperature), airside economizer control (free cooling using outside air) and time-based equipment start/stop scheduling.

Mode 1. Variable Volume (VV) with Fixed Ventilation. Variable fan speed based on the most open zone damper. Fixed ventilation rate was maintained through modulation of the outside air damper. Heating and cooling coils were enabled (modulating to setpoint) or disabled (control valve forced closed) based on the demand for heating and cooling as indicated by the signal to the zone dampers. As with the Base Case, economizer control and equipment start/stop schedules were used. The binary reset on the deck temperature setpoint was implemented as described above.

Mode 2. Variable Volume with Demand Control Ventilation (DCV). Same as Variable Volume with Fixed Ventilation above, except the ventilation rate was based on space ventilation demand (according to CO_2 or occupancy sensors, depending on the system), by adjusting the outside air airflow setpoint.

The operation of each unit was rotated through the three modes, switching modes each day at midnight for approximately one year. The rotation of modes allowed for determining energy impact of each control scheme (mode) under a variety of environmental conditions and with comparable distribution of days for each mode within the limited time frame allotted for the demonstration. Operational data for each AHU and the zones it served, as well as local weather data were gathered at 15 minute intervals. These gathered data were processed to generate energy savings as described below.

Performance Analysis

The retrofitted AHUs were evaluated for energy and economic impact and ability to maintain comfort conditions in the spaces they serve. These evaluations are presented below.

Energy Calculation Methods

For each operational mode, thermal energy transfer was measured at the hot and cold deck coils with a Btu

TABLE 3 Energy savings at air handler (combined Btus of fan and coils).

MZ AHU	BASE CASE CV	VV W/ FIXED VENTILATION (MODE 1)		VV W/ DCV (MODE 2)	
	Energy Use (kBtu/yr)	Energy Use (kBtu/yr)	Energy Savings vs. Base Case	Energy Use (kBtu/yr)	Energy Savings vs. Base Case
CERL 1	514,434	391,676	24%	367,642	28%
CERL 2	581,926	257,910	56%	233,881	60%
BRAGG 1	123,991	66,135	47%	61,084	50%
BRAGG 2	118,266	88,423	25%	N/A	N/A
BRAGG 3	138,899	94,775	32%	94,086	32%

meter (measuring water flow and temperature differential); electric energy was measured with an electric meter at each VFD to capture the the energy used by the combination of the VFD and motor. The system boundary of the air-handling unit was chosen for energy monitoring to determine the impact of the retrofit alone and not be impacted by efficiency of primary heating and cooling equipment (such as a boiler or chiller), which would vary depending on the application. Further, site fuel use at the primary heating and cooling equipment was not measured because that equipment served multiple AHUs, which would obscure the energy impact of the retrofit. Gathered data were sorted into their respective operational modes, described previously in the "Demonstration Modes" section.

Figure 6 shows the energy analysis of this field data. These data sets for each mode were then normalized by equipment runtimes and weather conditions to allow a valid side by side comparison of energy use between the three modes.

Data from off-hours operation, unoccupied holidays or known equipment or controls maintenance and malfunctions were eliminated. Data were sorted into 5°F (2.8°C) outdoor air temperature bins. Although both dry bulb and wet bulb conditions affect HVAC energy consumption, it was established through regression analysis of local weather data that outdoor air dry-bulb temperatures were sufficiently correlated to outdoor air enthalpy at the demonstration sites (with a linear regression correlation coefficient, $R^2 = 0.97$, *Figure 7*), and therefore dry-bulb temperature could be an adequate indicator of outdoor air conditions, and dry-bulb weather bins were adequate for data groupings.

A Kruskal-Wallis analysis of variance (ANOVA††) test was used to evaluate whether the weather data from each mode were statistically similar enough to allow comparison, and data records were pared down to balance the distribution of records for each mode of operation to avoid skewing performance assessment. Hourly savings (for both basic variable volume [VV] and variable volume with DCV) were mapped to the corresponding 5°F (2.8°C) temperature bins then multiplied by the number of hours of each bin according to (historic) weather data for a typical year and totaled for the two VV

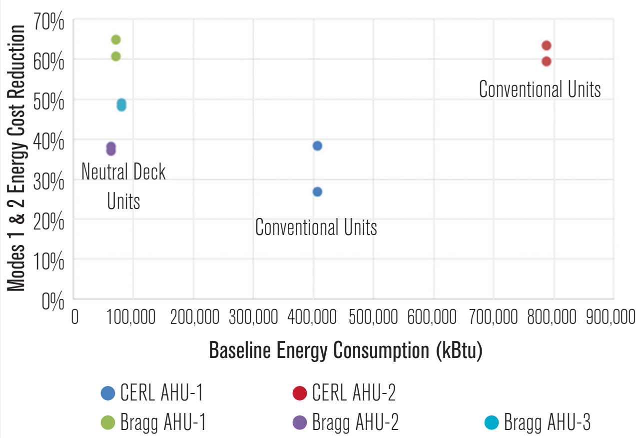
TABLE 4 Energy cost impact by operational mode and equipment type.

MZ AHU	BASELINE UTILITY COST	VV W/ FIXED VENTILATION (MODE 1) Mode Cost Savings	Fan Cost Savings	Chiller Cost Savings	Boiler Cost Savings	VV W/ DCV (MODE 2) Mode Cost Savings	Fan Cost Savings	Chiller Cost Savings	Boiler Cost Savings
CERL 1	$4,561	26%	5%	5%	17%	37%	6%	3%	28%
CERL 2	$6,906	59%	1%	0%	57%	63%	1%	1%	61%
BRAGG 1	$1,113	61%	45%	14%	2%	66%	45%	14%	7%
BRAGG 2	$1,069	39%	33%	6%	0.4%	N/A	N/A	N/A	N/A
BRAGG 3	$1,160	50%	37%	8%	5%	49%	36%	8%	5%

Production efficiency corrections applied to hot water load: distribution losses = 10%; boiler cycling losses = 15%; boiler combustion efficiency = 87%. Production efficiency factors applied to chilled water load: 0.71 kW/ton.

††Analysis of variance (ANOVA) is a statistical method for the evaluation of variance between two groups. The Kruskal-Kruskal-Wallis test with a significance level of $\alpha = 0.05$ was used in examining weather data.

FIGURE 8 Baseline energy consumption vs. energy cost reduction.



mode comparisons. The difference between the two retrofit modes (Mode 1 and Mode 2) and the baseline mode (Mode 0) was used as the experimental energy savings of the retrofit. These energy totals were then divided by average equipment efficiency estimates (for the chiller, boiler and water distribution system) to attain energy impact at the utility bill.

Table 3 presents the calculated energy savings at the AHU. These percentage changes in energy use represent the the energy impact of the retrofit technology. *Table 4* presents the resultant calculated upstream savings at the boiler and chiller plant and the impact on the utility bill. For the conventional hot deck/cold deck units at Construction Engineering Research Laboratory (CERL), boiler plant savings accounted for most of the savings. For the neutral deck units at Fort Bragg, reductions in fan energy were the primary savings. These savings are calculated for regular building operating hours (e.g., Monday through Friday 6 a.m. to 6 p.m.) for these particular facilities. The annual energy consumption of the demonstration units is lower than typical (compared to the Commercial Building Energy Consumption Survey [CBECS] data) and is not representative of typical multizone systems. Potential causes for the variation from typical CBECS consumption may include: off-hours energy use was not taken into account, which could be significant in some applications (such as units providing for conductive heat losses through the building envelope at night), the CERL units serviced fully interior zones and did not experience building envelope loads at any time during operation and the Fort Bragg units maintained more limited space conditioning than typical buildings in America by heating only to 68°F (20°C) and cooling to only 75°F (24°C).

Retrofit of a MZ system will require repair or replacement of components that are preventing correct operation (e.g., failed sensors, broken dampers). Additionally, the control sequence for the retrofit requires functional direct digital control (DDC) hardware and software. Accordingly, retrofit costs can vary widely among retrofit candidates. The cost analysis for the demonstration system retrofits was limited to the fundamental new components for the control scheme to accomplish the basic retrofit including: the VFD(s) on the fan(s), the airflow measurement array (AFMA) and the controls programming. Additionally, occupancy or CO_2 sensors were added to those costs for the DCV option. As such, the economic analysis treats the retrofit as an "add on" or incremental addition to a system that is already being

TABLE 5 Economic impact of an incremental (as an "add on" task to an existing DDC conversion or upgrade) retrofit.

MZ AHU	VV W/ FIXED VENTILATION (MODE 1)					VV W/ DCV (MODE 2)				
	Incremental Retrofit Cost	Net Present Value	Simple Payback (yr)	Savings to Investment Ratio	Energy Savings ($/yr)	Incremental Retrofit Cost	Net Present Value	Simple Payback (yr)	Savings to Investment Ratio	Energy Savings ($/yr)
CERL 1	$13,000	$4,452	11	1.4	$1,208	$13,823	$10,394	8	1.8	$1,684
CERL 2	$9,315	$48,685	2	6.6	$4,083	$9,690	$52,193	2	6.7	$4,357
BRAGG 1	$7,200	$2,673	11	1.4	$683	$7,584	$3,020	10	1.5	$734
BRAGG 2	$7,200	-$1,055	17	0.9	$420	N/A				
BRAGG 3	$7,200	$1,191	12	1.2	$579	$7,334[a]	$989[a]	13[a]	1.2[a]	$574[a]

Production efficiency corrections applied to hot water load: distribution losses = 10%; boiler cycling losses = 15%; boiler combustion efficiency = 87%. Production efficiency factors applied to chilled water load: 0.71 kW/ton. Real discount rate = 3%; life of retrofit = 15 yr, blended energy costs used. Fuel escalation rate = 3%; CERL unit energy costs were $0.0636/kWh and $0.84/therm. Bragg unit energy costs were $0.0733/kWh, $0.62/therm.

[a]Limited DCV (one conference room only).

converted from non-DDC to DDC controls, or when the existing DDC controls are replaced.

Life-cycle cost analysis was conducted for an incremental (i.e., limited scope "add on") retrofit of the demonstration units using mechanical cost data for equipment and installation costs and local energy and labor rates. Maintenance impact was deemed negligible by the operations & maintenance personnel, based on the number of issues that arose during the demonstration period and their ability to understand how the system operates.

Although significant energy savings percentages were seen across all air handlers for both variable volume operating modes (24% to 60% in *Table 3*), not all projects successfully reduced life-cycle costs (LCC), i.e., had a net present value, NPV > 0, or had a saving to investment ratio, SIR ≥ 1, which are typical economic objectives for government projects (*Table 5*); LCC analysis showed attractive returns for the conventional units and adequate returns for two of the three neutral deck units. The DCV option showed merit as it added approximately 5% to the retrofit cost and delivered an average 50% increase in NPV. The economic indicators of the neutral deck units at Fort Bragg are not as strong as those of the conventional units at CERL. This is because the neutral zone units, by design, have already eliminated the simultaneous heating and cooling of the conventional unit and because the baseline energy consumption of these units is uncharacteristically low since Fort Bragg adhered to the Army's strict energy conservation policies for zone thermostat setpoint temperatures.

The percent energy cost reductions were not strongly correlated to air handler size (in cfm) and corresponding energy use, technology model (conventional vs. neutral deck) or baseline consumption (*Figure 8*). The baseline utility costs preretrofit is the prime indicator of adequate payback. This is amplified by the fact that retrofit costs do not increase linearly with AHU size for the basic variable volume retrofit (Mode 1). The baseline utility bills of the AHUs at Fort Bragg (at ~$1,000/yr) were significantly lower than the CERL units, which had preretrofits utility costs of about $6,000/yr. The non-representative nature of the low annual consumption totals of all the demonstration units was addressed in the development of the technology transfer tools (see "Technology Transfer" sidebar), which reveal stronger economics for typical applications.

Larger utility costs will typically be seen on larger units or those with higher unit energy costs. Two contractor estimates for a full system replacement (to VAV) were received for a couple of similar CERL AHUs and both were over $500,000. These estimates are cited only to provide an indication of the significant cost of a full system replacement compared to the MZ-VV retrofit.

Comfort

To assess the impact of the controls retrofit on comfort conditions, each zone temperature (provided by the zone temperature sensing module) was compared every 15 minutes to its setpoint in each of the three demonstration modes. All systems, in all modes maintained zone setpoints, on average, within 0.5°F (0.3°C). Additionally, comfort conditions based on zone temperature and relative humidity and the corresponding ASHRAE Standard 55-2010 comfort zone (with constant values used for office clothing, sedentary activity level, still air speed and an assumed mean radiant temperature) were compared between the operating modes.

The CERL systems showed little difference in ASHRAE comfort between the different modes. Two of the three Fort Bragg systems had slightly worse ASHRAE comfort performance where Mode 0 (constant volume mode) comfort was maintained about 5% to 10% more of the time than when in Mode 1 or Mode 2 (variable volume modes). This was subjectively attributed to lower airflow rates and slow fan speed response in Mode 1 and Mode 2. Overall, retrofit thermal comfort conditions did not vary significantly from base case conditions and were deemed acceptable by the project team and site O&M staff.

Discussion and Conclusions

Retrofit of an existing constant volume multizone air-handling unit control system to convert it to variable volume can be a simpler and less costly means of increasing energy efficiency compared to completely changing out the system. This variable volume retrofit technique minimally impacts the physical system by focusing on instrumentation and controls rather than a full system change out requiring demolition and replacement of the central unit and installation of new ductwork and terminal units in the spaces. The retrofit includes adding a VFD and AFMA plus controls programming for the basic

Technology Transfer

A technology transfer effort was conducted to facilitate implementation of the variable volume technology by providing accessible technology description documents, pertinent application tools and a broad-spectrum outreach. This multifaceted support steps a user through the entire process of evaluating, procuring and implementing the technology.

The technology evaluation products help users determine if this technology is the right fit for their circumstances. Products include a project overview poster and fact sheet, a technical note (a brief distillation of the detailed research report), a field scoping guide spreadsheet (to conduct an installation-wide screening as well as individual unit evaluation to assess a potential unit's operational status and suitability for retrofit, including prompts to help identify needed repairs/upgrade of system equipment that would prevent successful retrofit performance [such as broken dampers or failed motors]), an economic estimator spreadsheet (to help gauge the expected energy and cost impact of a retrofit) and a pitch briefing (ready slides and script to convey the retrofit opportunity to decision makers).

The estimator allows a potential user to apply the energy results of the technology demonstration to their particular situation. It applies the field derived percent energy savings on the fan and at the coils to typical energy use for the candidate site's location and facility end use, along with local utility rates and site-specific system efficiencies to estimate the impact of the change. It calculates key LCC values based on multiple inputs:

- User-provided system specifics such as unit size, area served, system configuration, retrofit/repair choices and local utility costs;
- Typical HVAC energy requirements (i.e., $kBtu/ft^2$) for their designated building activity (e.g., office) and locality from CBECS data;
- Technology demonstration savings percentages; and
- Cost data.

Calculations are customizable with common upgrade activities (e.g., retrocommissioning, addition of scheduling and/or economizer function, needed equipment repair, etc.). Default values support preliminary scoping analysis with limited data input. The estimator supports user override of many parameters to refine output. The estimator provides for review of retrofit measures as stand-alone activities or combined with other potential upgrade activities into a retrofit package to determine the full budget requirements and estimated energy impact.

A procurement package provides a coordinated approach to consider best practices and reduce piecemeal one-off efforts. The products include a design guide, template drawing set, specification template and sample contracting language for a performance work statement (PWS). The template drawings, specification and points schedules allow quick production of procurement requirements with minimal edits.

A commissioning guide helps establish and verify proper operation of the system, including sample procedures verifying the updated sequence of operation.

Outreach efforts have been used to raise awareness of the technology and encourage adoption through published papers and articles, email/phone contacts of DOD personnel already indicating interest, conference/webinar presentations and online posting of documents. All the technology transfer products have been vetted with subject matter experts and potential users for usability and pertinence. Products of the technology transfer are available at the Whole Building Design Guide, https://www.wbdg.org/ffc/army-coe/design-guides/mz-vv-hvac-controls-retrofit.

retrofit and some additional room sensors and programming for the DCV option.

The field demonstration took place in 2016–17 before the 2020 COVID pandemic, so the consequences of new ventilation guidelines were not considered and could be appropriate for further exploration. The addition of outside air ventilation measurement and control, not present in the preretrofit systems, is advantageous for ventilation monitoring and ready ventilation adjustments in situations where this functionality might be beneficial as a pandemic mitigation measure.

The retrofit includes several novel aspects including limited requirement for new equipment (just two pieces of equipment), use of zone damper control signals as an indicator of space loads thus avoiding the need for damper position sensors and simplification of the hot deck temperature reset, which prioritized saving costly fan electricity over less expensive heating using natural gas. Further, the experimental set up of rotating through operational modes on a daily basis and mapping hourly energy savings to a typical weather year allowed measuring not only the baseline energy use but also the impact of the retrofit in two modes (with and without DCV) in a compressed schedule of one year.

The proposed retrofit is a fraction of the cost of full system replacement and reduces energy consumption now, while putting off full system replacement. The necessary complementary repair of failed equipment that occurs at the time of retrofit enables the controls changes to be effective and readies the equipment for continued service. The technology demonstration project showed significant energy savings (24% to 60%) at the AHU across the five units. And, it was deemed to have negligible O&M impact and inconsequential impact on comfort. LCC analysis showed attractive returns for the conventional units and adequate returns for two of the three neutral deck units. Conventional units in fairly good shape with large energy costs and variable occupancy should be given highest priority. The DCV option showed merit as it added approximately 5% to the retrofit cost and delivered an average 50% increase in NPV. The technology transfer effort is expected to ease deployment of the retrofit and scale savings across the DOD's large inventory of MZs.

The retrofit, in some cases, may provide additional energy savings and performance improvements beyond those described in this article when replacing older controls that often are out of calibration or failing/failed in DOD facilities and exhibit operational faults that are energy intensive. For example, in one of the demonstration units, the economizer was not working and did not take advantage of free cooling in temperate weather. This failure was repaired prior to initiating the field demonstration and reduced the baseline energy consumption of the unit. Further, DOD units often do not have any equipment scheduling implemented and remedying this as part of the retrofit presents a significant opportunity for energy and cost savings by matching equipment run times to facility operational hours. These ancillary improvements would improve the financial impact of the retrofit effort.

The currently implemented policy[9] that allows military installations to retain a portion of the energy cost savings for use on other projects allows the retrofit to serve as a partial source of funding for future system upgrades and makes implementation particularly attractive.

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