Technical Note

Multizone to Variable Volume HVAC Controls Retrofit for Energy Efficiency

ESTCP Projects EW 201152 and EW19-5026

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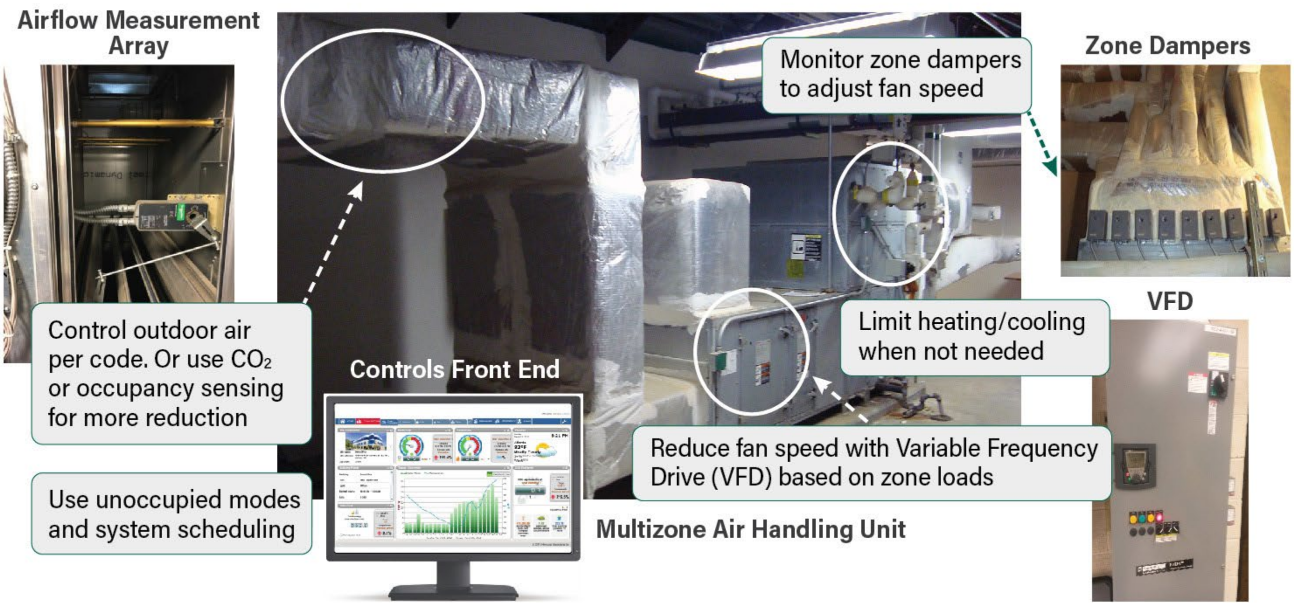


Highlights of Control Changes to Multizone Air Handler

The Challenge

The DoD has a large inventory of older (10-40+ yr.) multizone air handlers which are used for building heating, cooling, and ventilation. Although these units are quick to respond to changes in temperature needs, they are very inefficient with energy use. Multizone units deliver a constant volume of air to the spaces/zones, regardless of actual requirements in the spaces. Further, the conventional 2-deck multizone units call for 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 very costly and disruptive to install.

Controls Retrofit Solution

The Engineer Research Development Center’s Construction Engineering Research Lab, ERDC-CERL, developed an alternate route to energy savings at a significantly lower cost and with less disruption than a complete system change out. A variable volume controls retrofit can serve as an interim solution to help meet energy efficiency and resiliency requirements within limited budgets. The retrofit technique minimally impacts the physical system as it focuses on instrumentation and controls as opposed to the typical demolition and replacement of the central air handling unit and installation of new ductwork and terminal units that would be required for a full system change out. The basic retrofit requires adding two pieces of equipment and controls programming to systems with existing direct digital controls (DDC). An optional demand controlled ventilation (DCV) feature can be implemented using either occupancy or CO_2 sensors in the spaces[1] for more savings.

[1] Currently, the use of CO_2 sensors requires approval in Army and Air Force projects. Occupancy sensors are allowed for DCV.

Multizone air handlers mix a zone specific air temperature for each zone, which has its own dedicated duct

Basic Retrofit - *The fundamental improvements needed to implement the variable volume technology:*

1) Variable Frequency Drive (VFD): Installation of a VFD will allow for fan operation at reduced speeds which provides energy savings.
2) Airflow Measurement Array (AFMA): Installation of an AFMA allows monitoring of outdoor air intake to supply the required amounts of ventilation and/or make-up air.
3) Controls Programming: Programming changes to implement the new functionality: variable fan speed control, outside airflow control, on/off heating/cooling coil control and binary hot deck reset.

The retrofit control scheme turns components down or off when not needed. It may be applied to different types of multizone units.

In particular, the scheme adjusts fan speed based on:

- Space Requirements: Dictated by the most critical (most open) zone damper, where fan speed is decreased until one of the (multiple) zone dampers is at fully or near fully open position
- Outside Air Requirements: Through measurement of outside airflow and modulation of the outside air (mixed air) damper(s) to maintain ventilation and/or makeup air requirements.

Additionally, the scheme adjusts coil output capacity to:

- Open/Close Water Valves: Closes hot/cold deck heating (and cooling) coil valves when no heating (or cooling) is called for by any zone. This helps save energy by minimizing the amount of conditioned air that leaks through zone dampers into the supply air to the zone.
- Use a Binary Hot Deck Temperature Reset: Modulates deck temperature to a high or low set point depending on weather. At the warmer setpoint (in colder weather), a 'hotter' deck air temperature allows a lower airflow rate to meet zone heating load. Resulting fan energy savings is typically more beneficial than thermal savings because of the greater cost of electricity versus natural gas. At the cooler setpoint (during warmer weather), excess heating in the coil (and excess standby loss) is reduced as coil capacity better matches warm weather needs.

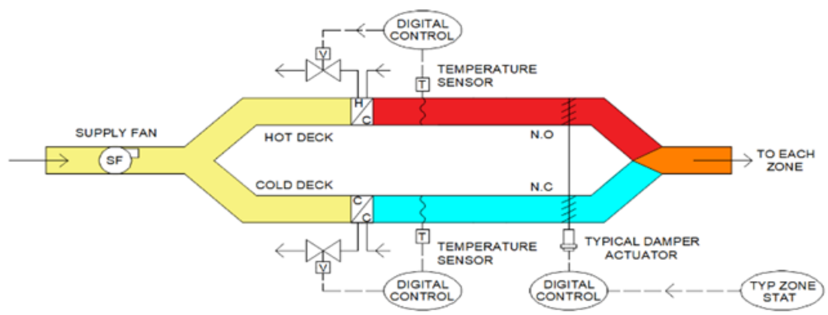
DCV Option – *This feature uses sensors in the space to detect periods of low or no occupancy and reduces ventilation during those times.*

Multizone Configurations

Multizone air handlers have three typical configurations: conventional two-deck, bypass, and neutral deck. Each of these configurations has a supply fan (and sometimes a return fan) that operates at a single speed delivering a constant volume of air and uses zone dampers to mix air streams in the desired proportions. The various types of multizone air handlers differ in the number of decks they have as well as the number and placement of coils. A summary of each configuration follows:

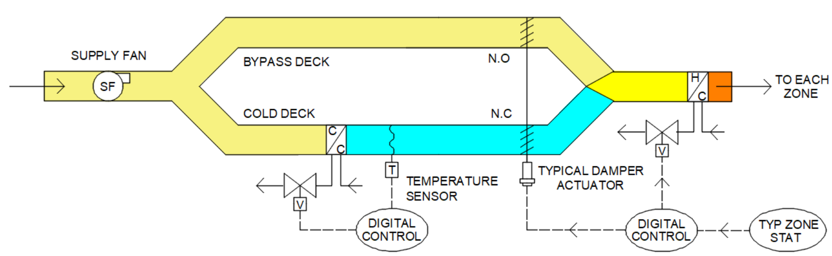
CONVENTIONAL MULTIZONE

- 2 Decks; 1 hot, 1 cold
- Heating and cooling coils in respective decks
- Both decks typically operated continuously, even when heating/cooling is not needed.
- Typical retrofit efficiency strategies include deck temperature reset, seasonal deck coil shut off, i.e. running only the hot deck coil in winter (with outside air providing needed free cooling) and only the cold deck coil in summer (but has led to mold issues and reduced comfort), and decoupling zone dampers to operate them independently (but is difficult and costly).



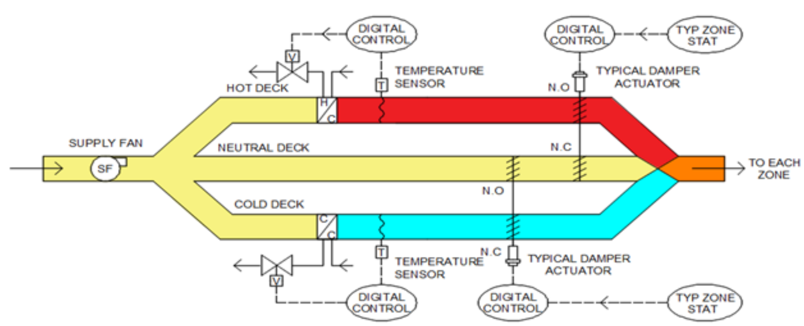
BYPASS MULTIZONE (TEXAS STYLE)

- 2 decks: Cold and Bypass
- No Coil in Bypass Deck
- Heating coil typically in <u>each</u> zone duct
- Uses mixed air (recirculated and outside air) in bypass deck for "free heating"
- More efficient than Conventional Multizone (by avoiding simultaneous heating and cooling)
- More coils to maintain



NEUTRAL DECK MULTIZONE

- 3 Decks: Hot, Neutral, and Cold
- Neutral Deck has no coil and introduces mixed air (recirculated and outside air)
- "Free Heating" from recirculated air in a neutral deck
- More efficient than Conventional Multizone (by avoiding simultaneous heating and cooling)



Demonstration Test

A demonstration of the retrofit technique developed by ERDC-CERL researchers was carried out on five systems at two locations over the course of fourteen months. Three of the five systems were located at Fort Bragg, NC while the remaining two were located at ERDC-CERL in Champaign, IL. The CERL units were conventional multizones, while the Fort Bragg units were neutral deck multizones. As part of the demonstration, systems were evaluated on several aspects, including:

- Energy Savings
- Life Cycle Cost
- Thermal Comfort

Three operational modes were analyzed:

- Base Case: Pre-retrofit state with constant volume fan and typical energy efficiency methods including hot deck temperature reset (based on outside air temperature), air-side economizer control (free cooling using outside air), and time based equipment start/stop scheduling.
- Variable Volume with Fixed Ventilation: Variable fan speed based on the critical zone damper (i.e. the most 'open' damper). Fixed ventilation rate was maintained through measurement of outside airflow and adjusting the outside air damper position. Heating and cooling coils were enabled (*modulating to set point*) or disabled (*valve forced closed*) based on the demand for heating and cooling as indicated by the zone dampers. As with the 'Base Case', economizer control and equipment start/stop schedules were used. Binary Hot deck reset was implemented, keeping the hot deck "hot", to achieve the same load carrying capacity at a lesser airflow rate and thus a reduced fan speed.
- Variable Volume with Demand Control Ventilation: Same as 'Variable Volume with Fixed Ventilation' above, except the ventilation rate was varied based on space ventilation demand (according to CO_2 or occupancy sensors), by adjusting the outside air damper position.

Table 1: Equipment Specifications

MZ AHU	Location	Type	Age of Unit (Yr)	Retrofit Approach*	End Use	Flow Rate (CFM)	Floor Area Served (SF)	# of Zones & spaces	Total Fan HP
CERL 1	Central IL	Conventional	40	Partial	Office	15,190	8800	5 zones 18 spaces	8 (5HP SAF+ 3HP RAF)
CERL 2	Central IL	Conventional	40	Full	Conference rooms	3475	2400	3 zones 9 spaces	3
Bragg 1	Central NC	Neutral Deck	10	Partial	Classrooms	4620	2983	3 zones 3 spaces	5
Bragg 2	Central NC	Neutral Deck	10	Partial	Office	4670	4328	9 zones 20 spaces	5
Bragg 3	Central NC	Neutral Deck	10	Partial	Office	5930	4837	8 zones 19 spaces	7.5

*Notes: *Partial retrofits are variable volume additions to a pre-existing DDC system, and include the addition of a VFD, AFMA and controls programming, Full retrofits are for systems with older failed or failing controls such as pneumatic controls and includes a controls upgrade to DDC, as well as the addition of VFD, AFMA and programming. CERL units had the cold coil disabled in winter. SAF=supply air fan. RAF=return air fan*

Maintenance staff at both sites reported an acceptable level of maintenance. Maintenance staff at CERL even reported one unit as being easier to maintain after retrofit.

Table 2 shows the savings derived from the demonstration. The systems tested attained savings of 24% to 60% reduction in energy usage at the air handler.

Table 2: Energy Savings for the Historic Weather-Normalized Data Set

MZ AHU	Base Case CV	VV w/ Fixed Ventilation		VV w/ Demand Control Ventilation	
	Energy Use (kBtu)	Energy Use (kBtu)	Energy Savings v. Base Case	Energy Use (kBtu)	Energy Savings v. Base Case
CERL 1	514,434	391,676	24%	367,642	29%
CERL 2	581,926	257,910	56%	233,881	60%
Bragg 1	123,991	66,135	47%	61,084	51%
Bragg 2	118,266	88,423	25%	NA	NA
Bragg 3	138,899	94,775	32%	94,086	32%

Notes: CV=Constant Volume, VV=variable volume

Implementation Approaches

There are several approaches for implementing the retrofit which impact the scope and cost of the change and subsequent return on investment:

- Incremental Retrofit: Consists of a variable volume *add-on* to a DDC upgrade project that is underway. Cost analysis only accounts for the addition of a VFD, an airflow measurement array and controls programming. (This approach piggy-backs off the existing DDC project that already covers many administrative/quality assurance costs such as contract set-up, submittals, documentation, training, warranty, travel, and commissioning. This is the least expensive and assumed most likely approach for implementation.)
- Partial Retrofit: Is the same as an incremental retrofit except it is executed as a brand new project on a pre-existing DDC system. (Here all administrative/quality assurance costs are included in the cost of the retrofit package for economic analysis.)
- Full Retrofit: Converts an entire older HVAC control system (e.g., old pneumatic control system) to DDC and incorporates the variable volume technology. (This is the costliest approach and includes hardware material and installation costs as well as administrative/quality assurance costs.)

Benefits of Retrofit

- Improves energy resilience at a fraction of the cost of full system replacement. See Table 5.
- Substantial energy savings (24-60%) at AHU. Savings on older units, like CERL AHU2, can be even greater if the original unit does not have economizer, occupancy schedules, or hot deck reset.
- Quick economic returns (3-5yrs) expected on typical applications for incremental retrofits. See Table 4. Simple Pay Back (SPB) of first costs can be improved in older units with pneumatic controls, or lacking equipment scheduling or economizer. Fits in tight budgets.
- Low impact to occupants — little or no construction in occupied spaces
- Reduced carbon emissions
- Maintains comparable space conditioning and comfort with no observed O&M impact
- Interim measure that allows accruing savings now while deferring major construction

Cost Drivers

- Implementation approach, whether incremental, partial or full will impact cost
- Older systems present additional savings opportunities such as incorporating an airside economizer, time-based scheduled start/stop, or high efficiency motor
- Cost of retrofit remains relatively static regardless of system size, so care should be taken when considering smaller systems for retrofit
- Additional cost related to training will be required to familiarize staff with new sequences
- Cost may be reduced depending on incremental upgrades already made to the units over the course of their lifetimes (such as sensor/ actuator replacements, DDC control upgrades)

Energy and Cost Impact

Table 3: Field Units - Economic Impact of Incremental Retrofit (most with DCV) (See Table 4 for typical applications)

AHU Unit	Incremental Retrofit Cost ($)	Unit Electric Cost ($/kWh)	Unit Gas Cost ($/therm)	Baseline Utility Cost Pre Retrofit ($)	Energy Savings ($/Yr)	Net Present Value, NPV ($)	Simple Pay Back, SPB (Yr)	Savings to Investment Ratio, SIR
CERL 1	$13.8K	0.0636	0.84	$4,561	$1,684	$7K	8	1.5
CERL 2	$9.7K	0.0636	0.84	$6,906	$4,357	$45K	2	5.7
Bragg 1	$7.6K	0.0733	0.62	$1,113	$734	$1K	10	1.2
Bragg 2**	$7.2K	0.0733	0.62	$1,069	$420	($2K)	n/a	0.7
Bragg 3	$7.3K	0.0733	0.62	$1,160	$574	(0.5K)	13	0.9

*Notes: 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: 0.71kW/ton. Real discount rate = 3%, life of retrofit=15yrs, blended energy costs used. Use of occupancy sensors for DCV. ** The Bragg 2 unit has No DCV.*

The demonstration units did not have typical thermal loading because the Conventional units at CERL served entirely interior zones (did not have building shell effects of outside walls, etc.) and the Neutral Deck units at Ft. Bragg had conservative room temperature setpoints (68°F heating, 74°F cooling) that limited the heating and cooling provided. CBECS was used as a source of typical heating/cooling/ventilation requirements by building activity and climate zones. Adjustments were made for the simultaneous heating and cooling of the conventional units. The typical impact presented below represent averages of mixed /humid and cold/very cold climates with US average construction and fuel costs. Typical conditions include a 10 yr. life cycle, a campus of less than 10 buildings served by the central plant, and air cooled chillers.

Table 4: Typical Multizone Retrofits with DCV - Economic Impact

AHU Unit	Incremental Retrofit Cost ($)	Baseline Utility Cost Pre Retrofit ($)	Energy Savings ($/Yr)	NPV ($)	SPB (Years)	SIR
Typical Conventional MZ in good shape (had equipment schedules)	$10K	$7,100	$2,900	$16K	3.4	2.6
Typical Conventional w/ RCx (had no equipment schedules)	$14K	$10,000	$4,900	$29K	2.8	2.6
Typical Neutral Deck MZ in good shape (had equipment schedules)	$10K	$2,800	$1,900	$6K	5.3	1.6
Typical Neutral Deck MZ w/ RCx (had no equipment schedules)	$14K	$4,200	$3,100	$12K	4.5	1.9

Notes: Office space. Building size=3600sf. Supply fan size = 5HP. Production efficiency corrections for hot water load: distribution losses = 2%, boiler efficiency = 80%. Production efficiency for chilled water load: 1.2kW/ton air cooled. Real discount rate = 3%, life of retrofit=10yrs, Blended energy costs used. Electric unit cost =$0.1054/kwh. Natural Gas unit cost =$0.7213/therm.

Table 5: Sample Retrofit Costs and Complete System Replacement Cost

Retrofit Type	Cost
Incremental	$7.2K-$13K
Partial	$20-24K
Full	$48K
Complete HVAC System Replacement w/ VAV AHU and Terminal Units	$550K-750K

Table 6 presents the breakout of energy savings. For the conventional units at CERL, boiler plant savings accounted for most of the savings. For the neutral deck units at Ft. Bragg, reductions in fan energy predominated.

Table 6: Breakout of annual energy and cost savings (most w/ DCV)

AHU Unit	Total Cost Savings	Svgs, % Tot Baseline Utility Cost *	Fan Energy Savings			Chiller Plant Savings			Boiler Plant Savings		
			kWh	$	% Tot Baseline Utility $	kWh	$	% Tot Baseline Utility $	Therm	$	% Tot Baseline Utility $
CERL 1	$ 1,684	37%	4,506	$287	6%	2,084	$133	3%	1,506	$1,265	28%
CERL 2	$ 4,357	63%	1,613	$103	1%	563	$36	1%	5,022	$4,218	61%
Typical Conventional Unit	$ 2,900	41%	6,658	$702	10%	2,699	$284	4%	2704	$1948	27%
Bragg 1	$ 734	66%	6,845	$502	45%	2,088	$153	14%	128	$80	7%
Bragg 2	$ 412	39%	4,811	$353	33%	1,042	$76	7%	(28)	($17)	(2%)
Bragg 3	$ 574	49%	5,755	$422	36%	1,295	$95	8%	92	$57	5%
Typical Neutral Deck Unit	$1,900	67%	12,833	$1,350	48%	2,635	$278	10%	337	$245	9%

*Notes: Svgs=Savings, Tot=Total. *Baseline Utility Cost provided in Table 3, Equipment types in Table 1*

Considerations of Unit Suitability for Retrofit

- Is the unit in reasonably good working order?
- Do the controls work/function properly?
- Is the unit rusting and can it be remedied?
- What is the condition of the ductwork?
- Are the control valves leaking when closed?
- Are dampers loose or linkages slipped?
- What repairs may be required to continue to use the system for another 10-15 years?
- What does the maintenance staff think about an upgrade and what repairs/improvements do they recommend?

Rusty damper blades still work in 40-year-old unit.

Typical Good Candidates

- Conventional (hot deck / cold deck) multizones with inefficient simultaneous heating and cooling
- Older units that are not slated for replacement in the foreseeable future, and have hardware that is still functional (e.g., valves, dampers, fans) or can be replaced at reasonable cost
- Larger units with sizable heating/cooling loads
- Units that serve variable occupancy spaces such as conference rooms
- A unit that needs or is slated for a controls replacement since the additional work to perform the conversion would be an incremental cost, and the retrofit will boost overall savings.
- A DDC upgrade is planned/underway, or the system is already DDC, where the latter case may require a smaller capital investment if the DDC sensors, and actuators can be reused.
- Units with older control hardware such as pneumatic controls hardware that is likely failed or failing, or units that have old-style mechanical time clocks that have been disabled.
- High energy costs (i.e., high electric or gas rates), an annual utility bill of at least $2k/yr.

- Units scheduled for retrocommissioning that incorporates this retrofit as part of that process
- Units already remotely monitored via the building automation system
- Units with a large potential for savings: larger units (e.g. 5 HP fan motor or larger or serving 5000 sf or more of floor space), or running 24/7.
- Multiple units included in a retrofit allows for economies of scale for package development, submittal documents, and operator training.

Complementary Retrofit Needs *are system changes which are appropriately conducted along with the retrofit and are dependent on the as-found condition of the unit:*

- DDC Upgrade/Conversion: If the existing controls are pneumatic (or otherwise failed or failing), upgrade of DDC or conversion to DDC is needed. Integration into the controls front end is advantageous.
- Airside Economizer and Start/Stop Scheduling: are cost saving control function additions that might not have been present in the pre-existing system.
- Demand Controlled Ventilation: is a beneficial added controls function where the installation of occupancy sensors or CO_2 sensors in the space(s) relay ventilation requirements to the control system.
- Fan Motor Replacement: In some cases, it may be appropriate to replace the fan motor with a premium efficiency motor. This can provide additional energy savings.
- Controls Upgrade: Installation of new actuators and sensors to support conversion. It is recommended that pneumatic actuators be replaced with electric. Zone thermostats with occupancy mode override buttons or occupancy sensors would afford occupants needed conditioning during unscheduled visits. Zone thermostats with a relative humidity sensor can help monitor occupant comfort.
- Mechanical Repairs: Repair or replace malfunctioning equipment. Examples include dampers/valves in disrepair (loose linkages, water leaks, etc.), leaky ductwork/piping, rusting floors of air handlers that might be able to be repaired (e.g., epoxy), friable insulation, and broken motor mounts.

Implementation Support Tools help user through entire process of evaluating, implementing, and using the technology successfully.

Evaluate Technology: *Determine if the retrofit technology is the right fit for your circumstances:*

- Fact Sheet, Technical Note: Provide distilled technology, demonstration, and application insights
- Field Scoping Guide: Steps user through strategic installation-wide screening as well as assessment of an individual unit's operational status and suitability for retrofit
- Savings Estimator: Gauges the expected energy and cost impact of retrofit with life cycle cost analysis
- Pitch Briefing: Supports discussion with decision makers through a slide with script
- Training: Free on-demand training on the technology is available at: https://slipstreaminc.org/estcp

Streamline procurement:

- Design Guide: Lays out a roadmap for implementation
- Templates for: Drawings, Specifications, Sequences of Operation, Points Schedules, and Performance Work Statement: Detail the technical requirements for success, allows user to pick and choose needed graphics and text.

Establish and verify proper operation of the system:

- Commissioning Guidance: Provides checklists, performance verification test, and deficiency log.

See www.wbdg.org/ffc/army-coe/design-guides for implementation support tools. *For additional information contact:*
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