VAV Systems Part 1: VAV Design Tips

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- Joined AMCA in February 2019
- Responsible for development of AMCA's education programs; staff liaison for the Education & Training Committee
- Projects include webinars, online education modules, presentations at trade shows, AMCA Speakers Network and other duties as assigned.

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- 40 years experience in commercial HVAC and control system design and construction
- Holds an BS in Physics and MS in Mechanical Engineering from Stanford University
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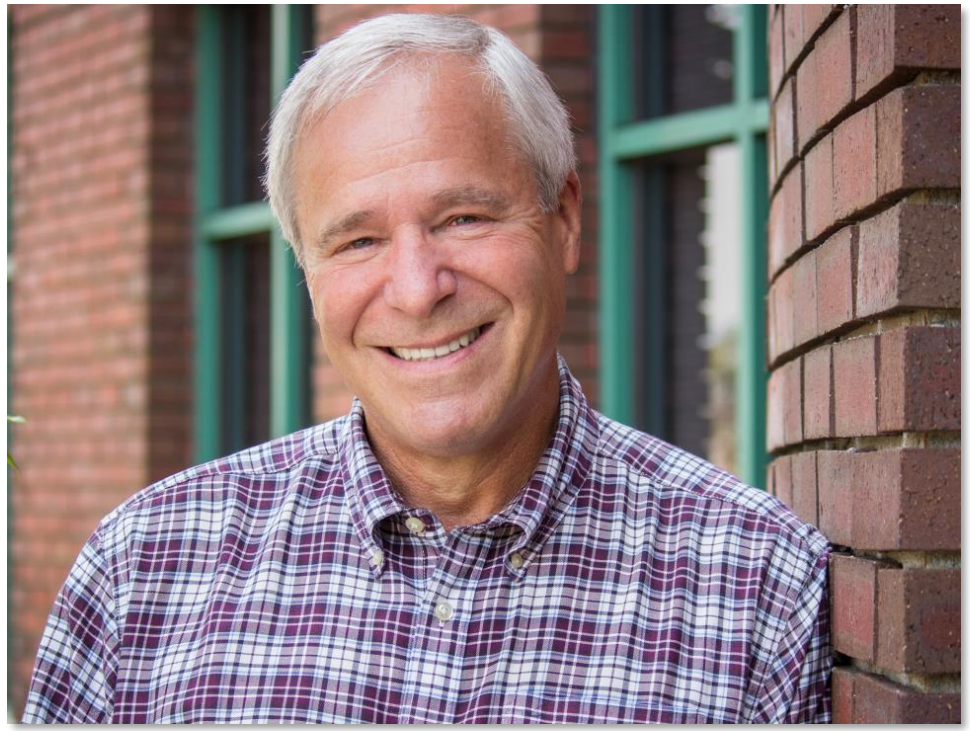


VAV Systems Part 1: VAV Design Tips

Purpose and Learning Objectives

The purpose of this presentation is to provide design tips for design and control of VAV systems and introduce ASHRAE Guideline 36 High Performance Sequences of Operation to the audience.

At the end of this presentation, you will be able to:

1. Apply tips to improve VAV system performance.
2. Identify changes to Standards 62.1 and 90.1, and how they affect minimum VAV box setpoints.
3. Explain how fan arrays can reduce costs and improve performance.
4. Describe how best to measure and control minimum outdoor airflow.

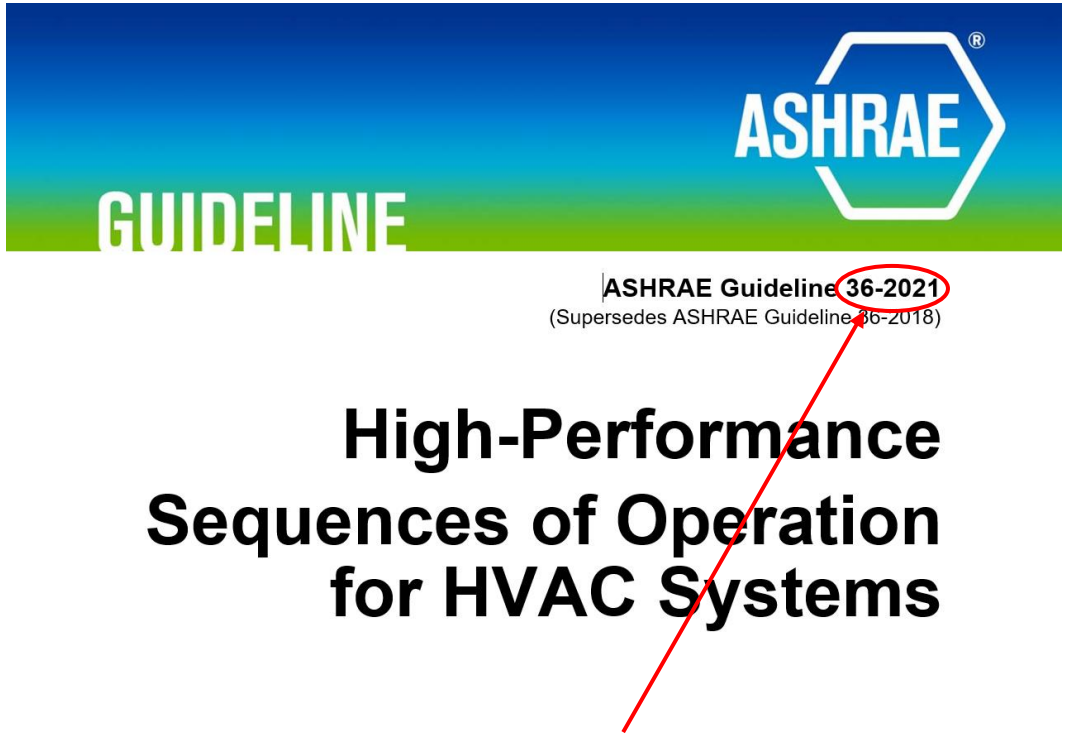
Agenda – VAV Design Tips

- Tip #1: Use ASHRAE Guideline 36 Sequences
- Tip #2: Set VAV Box minimum airflow to minimum ventilation rate
- Tip #3: Use Fan Arrays
- Tip #4: Control minimum outdoor air using DP across a fixed orifice

Tip #1: Use ASHRAE Guideline 36 Sequences

ASHRAE Guideline 36

- Guideline for best-of-class Sequences of Operation
- The Goal:
  - ASHRAE experts create and maintain advanced sequences
  - Manufacturers preprogram, test, and debug all the sequences for their dealers
  - Engineers simply spec: “Use ASHRAE Guideline 36 sequences”
  - Control contractors simply use the preprogrammed sequences from their vendor
  - Commissioning agents use the functional performance tests included (eventually) with Guideline 36

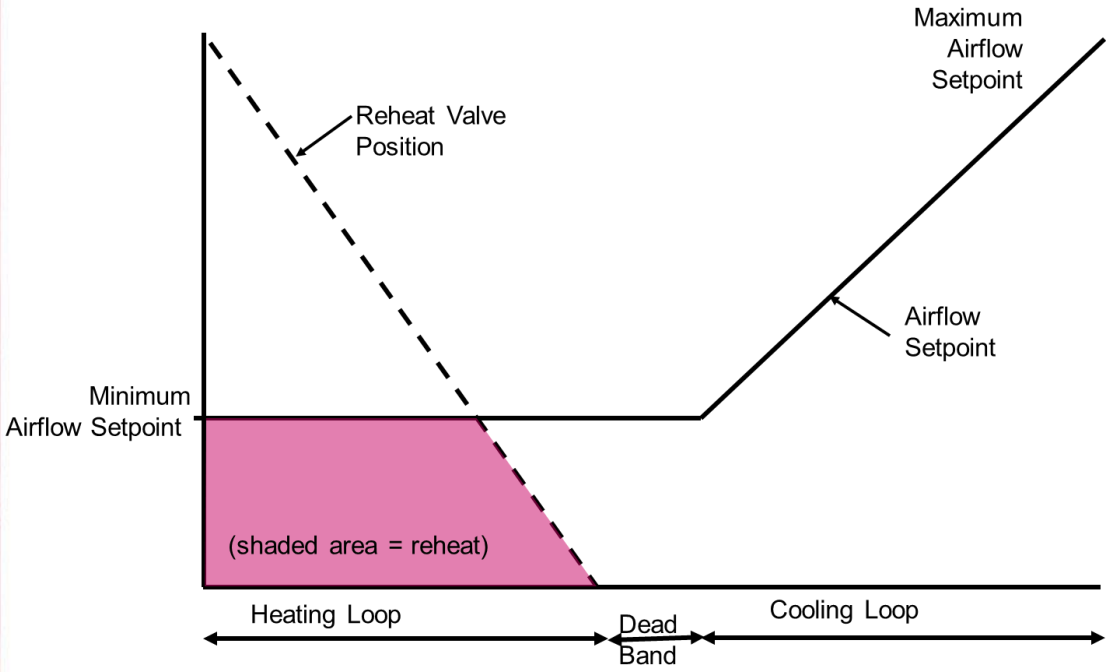


2021 version includes sequences for HW and CHW plants!

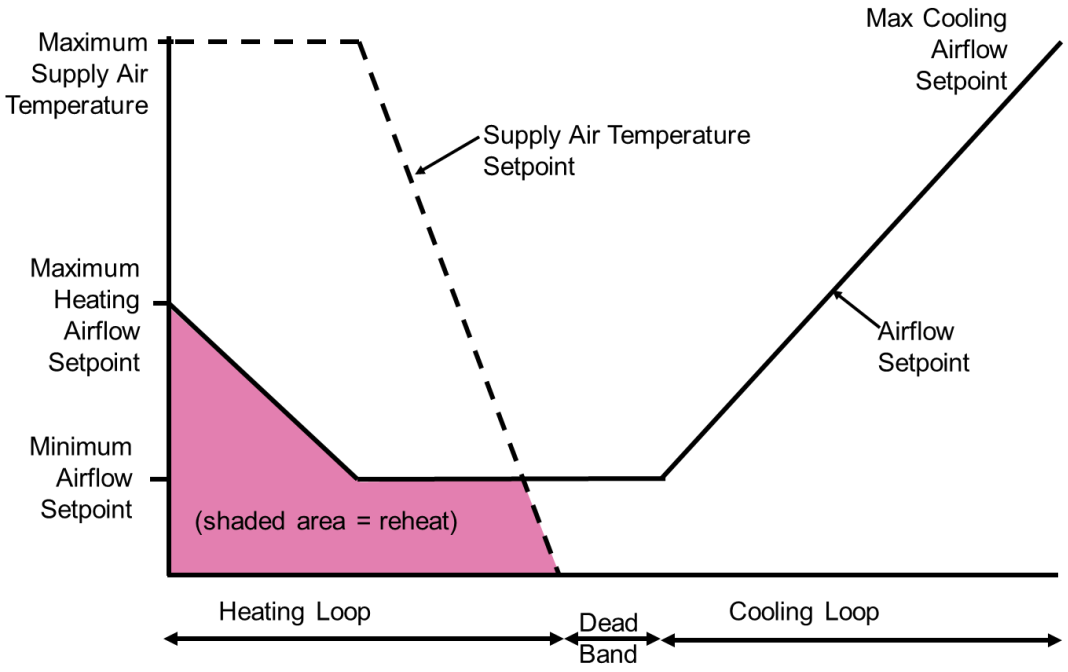
Example: “Dual Max” VAV Control

VAV Boxes with Reheat

Conventional VAV Control

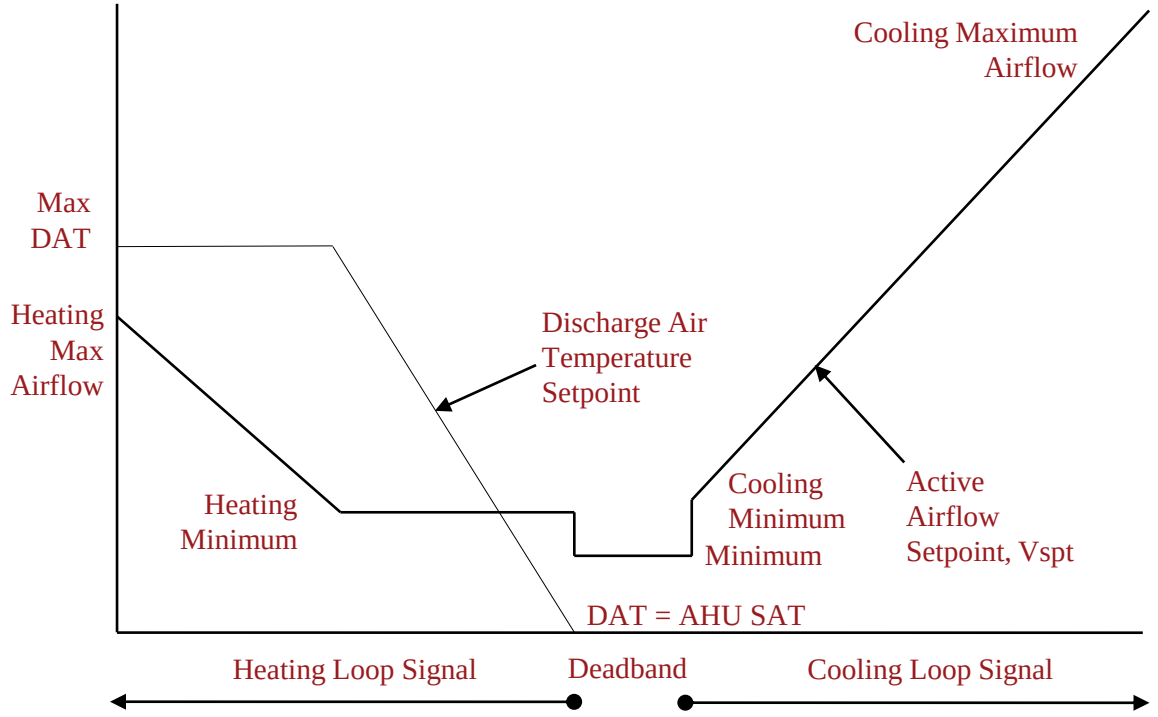


Dual Maximum VAV Box Logic

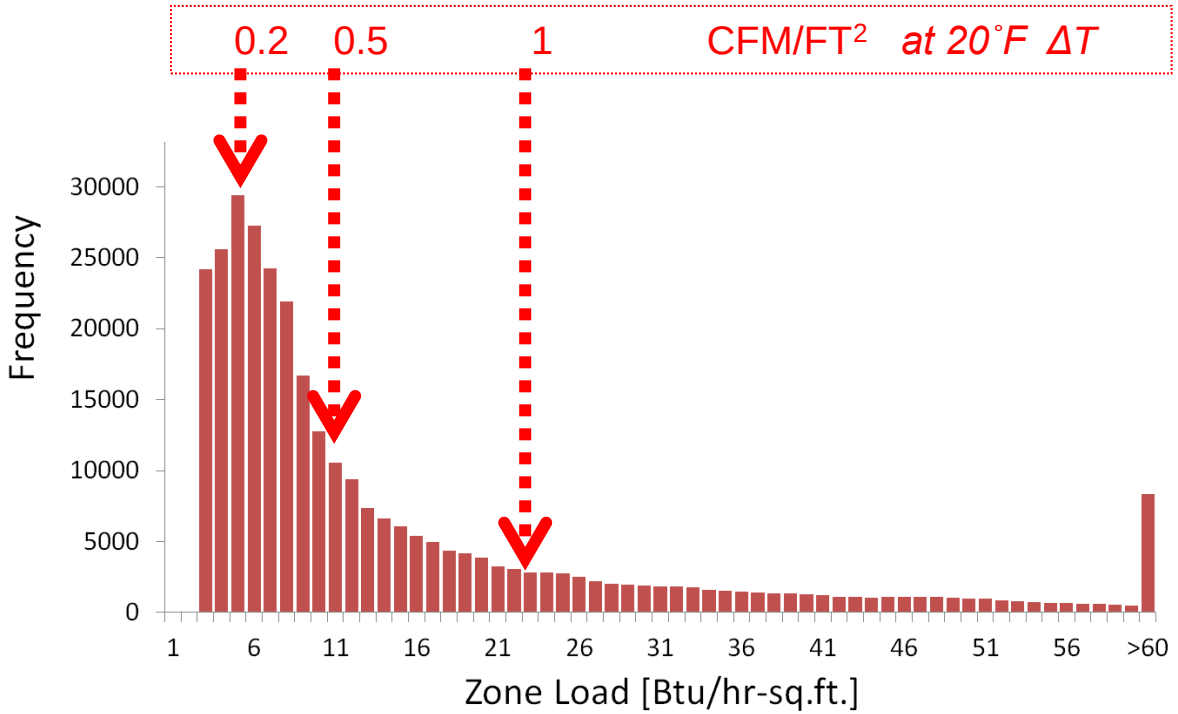


Dual Max in Guideline 36

Endpoint	Occupied	Cooldown	Setup	Warm-Up	Setback	Unoccupied
Cooling maximum	Vcool-max	Vcool-max	Vcool-max	0	0	0
Cooling minimum	Vmin*	0	0	0	0	0
Minimum	Vmin*	0	0	0	0	0
Heating minimum	Max (Vheat-min, Vmin*)	Vheat-min	0	Vheat-max	Vheat-max	0
Heating maximum	Max (Vheat-max, Vmin*)	Vheat-max	0	Vcool-max	Vcool-max	0

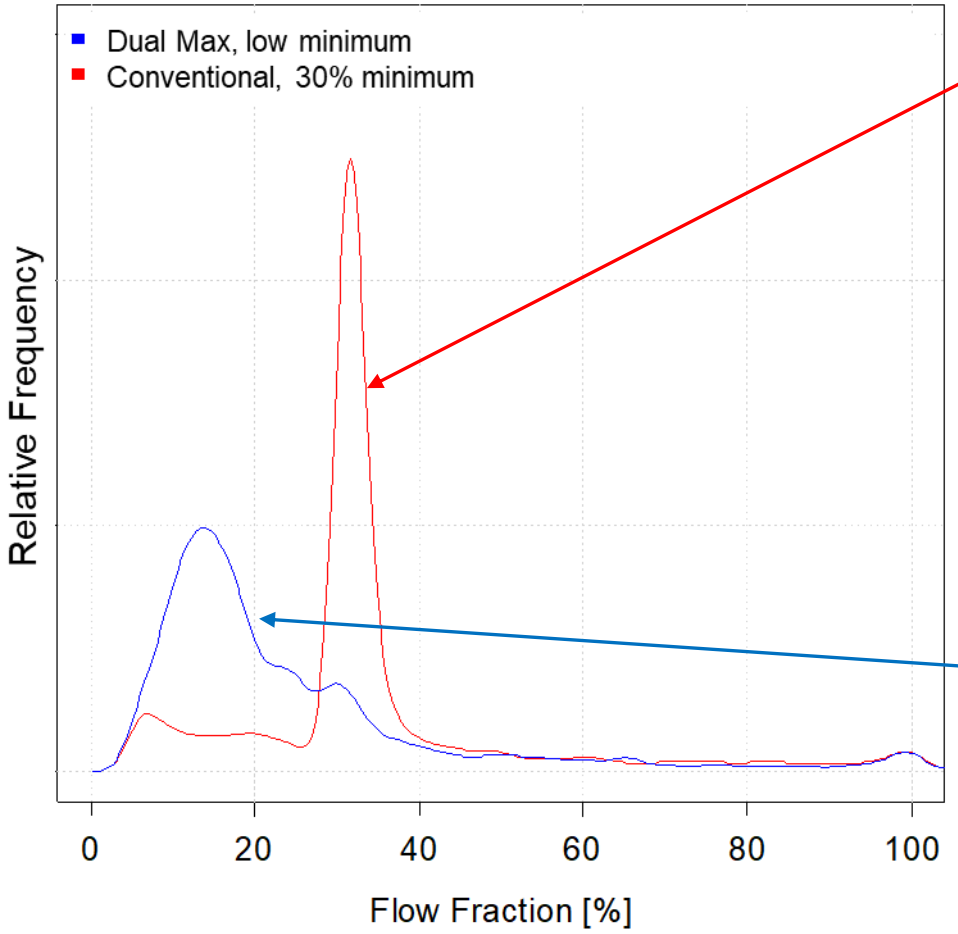


RP-1515: Loads are very low!



140 Zones, 2 buildings, 1 warm month (Sept)

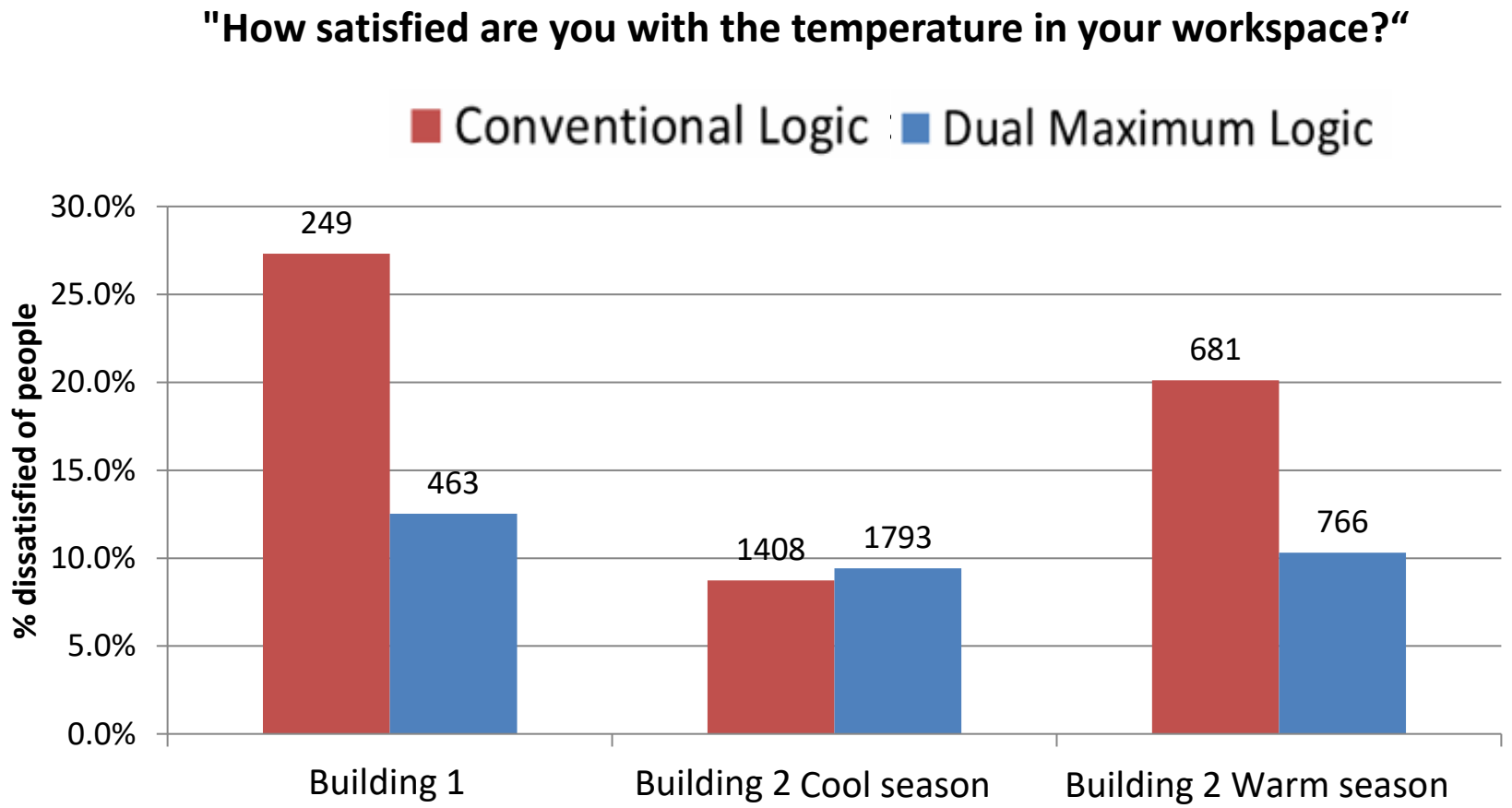
RP-1515: Measured flow fractions



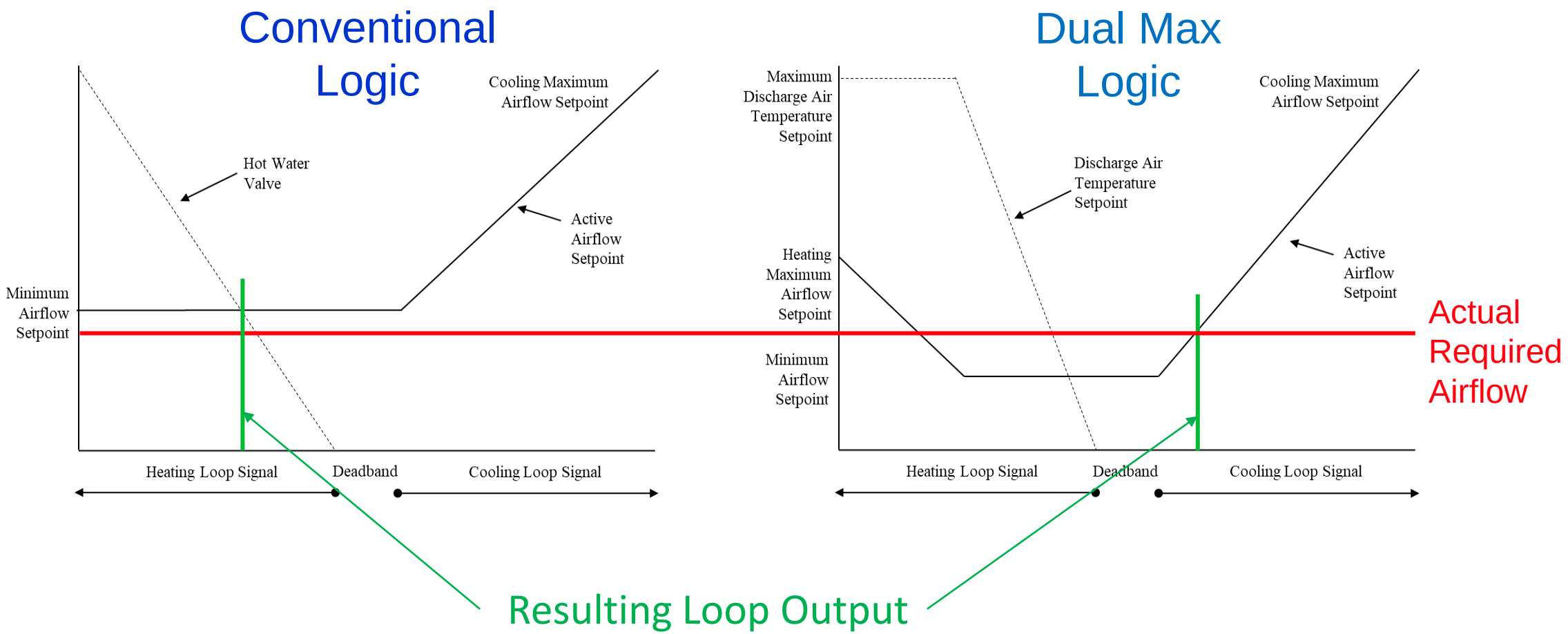
VAV Boxes are ~3 times larger than they need to be

Even 20% minimums would waste energy – no longer allowed under 90.1-2019

RP-1515 Comfort Survey



What Happens When Load is Less than Airflow Minimum?



How to specify Guideline 36?

First: Limit the bid to manufacturers who have already programmed G36 sequences:

2.1 Primary BAS Manufacturer

A. To qualify for this project, the primary BAS manufacturer shall agree to fully program and test all ASHRAE Guideline 36 sequences that are referenced herein for their dealers bidding this project at no direct cost to these dealers. The cost of Guideline 36 programming and testing shall not be a direct cost to this project.

Next: Use this reference instead of the SOOs already in your specs

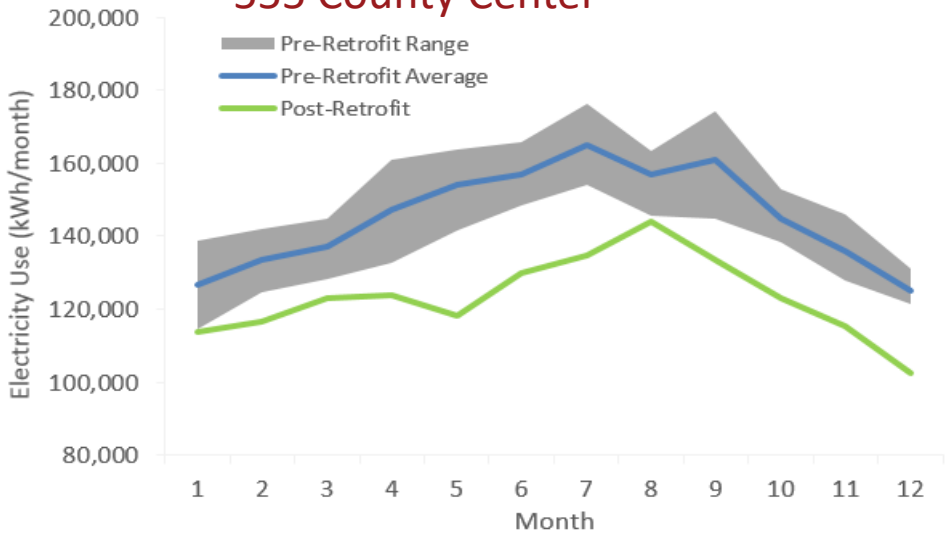
3.1 Sequences of Operation

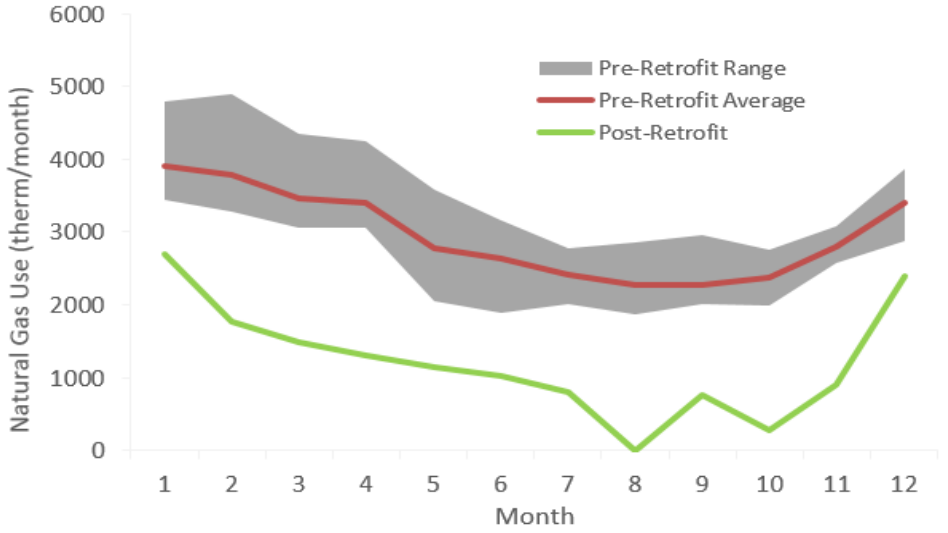
A. Control sequences shall fully implement and be in accordance with ASHRAE Guideline 36

Then: Supplement with SOOs not (yet) covered by Guideline 36.

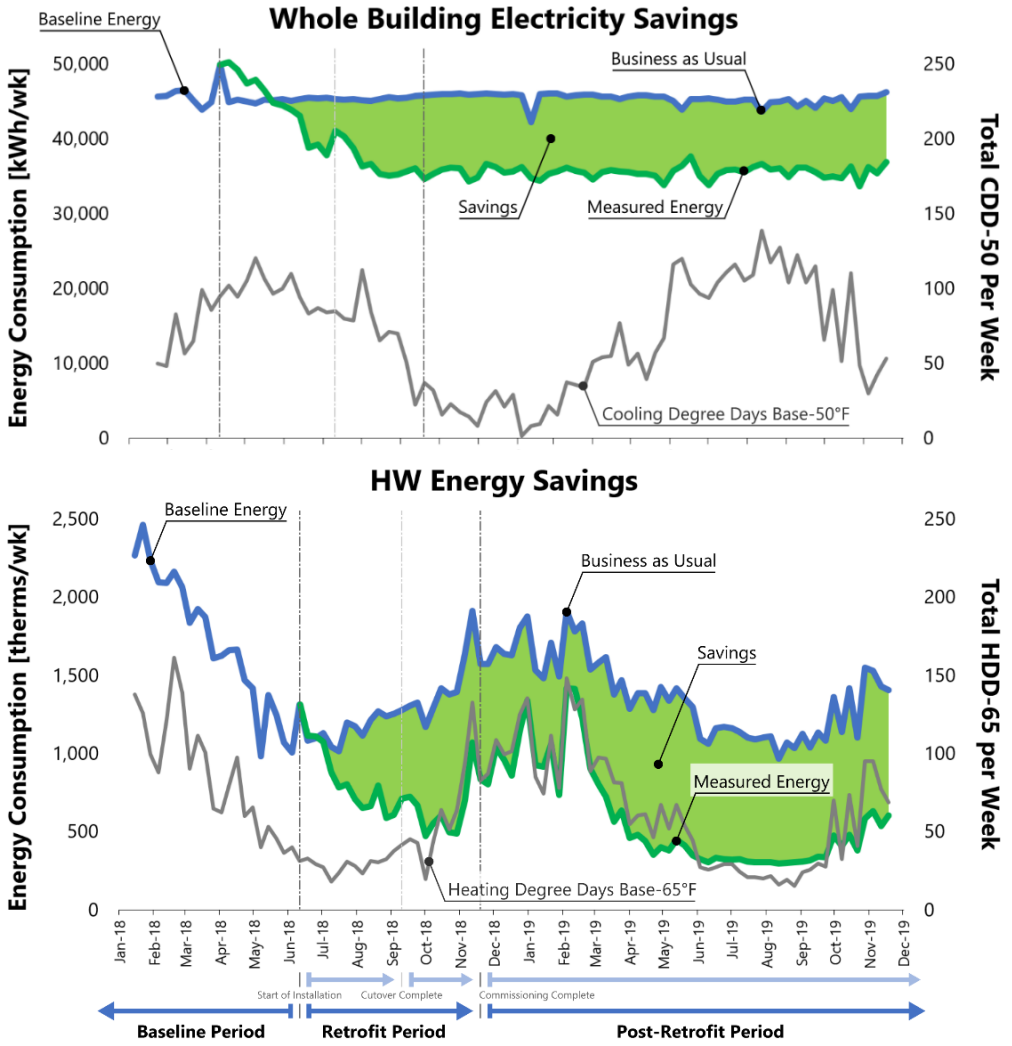
Some ASHRAE Guideline 36 Implementation Results

555 County Center





EPIC Best in Class - MOB



CEC EPIC Best in Class; RP-1515

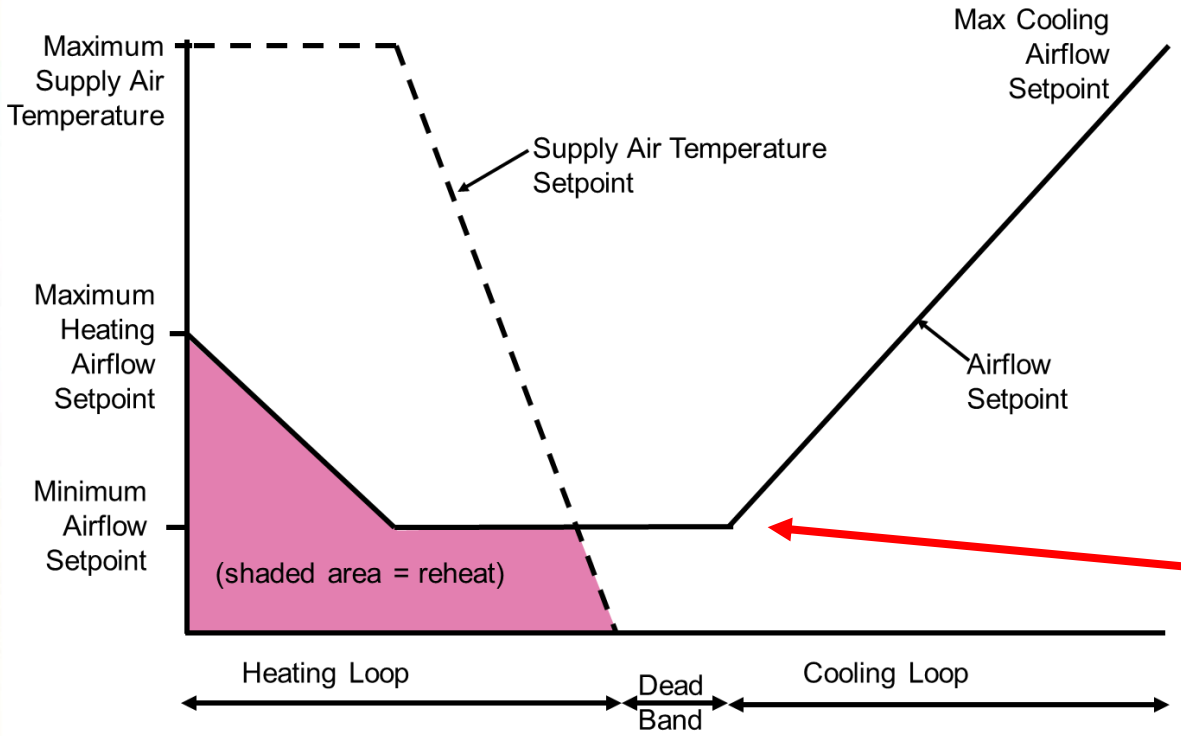
Building	Project Parameters / Retrofit Scope									Site Energy Savings							Energy Cost Savings ($/ft2)			Economics
Site	Size (ft^2)	ASHRAE CZ	Cooling Type	Heating Type	District CUP	HVAC Equip	BAS Equip	BAS AHU Logic	BAS Zone Logic	Fan	Cooling	Heating	Total HVAC	Whole Building Electric	Gas	Whole Building	Whole Building Electricity	Gas	Total	Overall Payback (yr)
Vallejo MOB	**200,000**	**3B**	**CHW**	**HW**	**X**	**X**	**X**	**X**	**X**	**78%**	**40%**	**61%**	**53%**	**26%**	**61%**	**45%**	**$0.62**	**$0.44**	**$1.06**	**8**
Whittier MOB	**34,000**	**3B**	**DX**	**HW**		**X**	**X**	**X**	**X**	**71%**	**71%**	**34%**	**57%**	**30%**	**34%**	**32%**	**$1.32**	**$0.30**	**$1.62**	**6**
555 County Center	142,000	3C	DX	HW			X	X	X	41%	41%	60%	45%	15%	60%	32%	$0.22	$0.14	$0.37	6
UCD Social Sciences	140,000	3B	CHW	HW	X			X	X	60%	26%	18%	25%	23%	18%	20%	$0.42	$0.09	$0.51	
CCC SAB	**50,000**	**3B**	**CHW**	**HW**				**X**	**X**	**38%**	**35%**	**4%**	**21%**	**11%**	**4%**	**8%**	**$0.11**	**$0.01**	**$0.12**	**7**
KPPDC	**23,700**	**3C**	**CHW**	**HW**				**X**	**X**	**65%**	**27%**	**15%**	**26%**	**17%**	**15%**	**16%**	**$0.50**	**$0.12**	**$0.62**	**2**
Yahoo A (RP-1515)	180,700	3C		HW					X	8%	8%	16%	13%	3%	16%	9%	$0.04	$0.03	$0.07	
Yahoo B (RP-1515)	180,700	3C		HW					X	20%	20%	19%	20%	7%	19%	11%	$0.07	$0.02	$0.09	
Yahoo E (RP-1515)	212,600	3C		HW					X	17%	17%	9%	13%	6%	9%	7%	$0.09	$0.02	$0.10	
Yahoo G (RP-1515)	79,700	3C		HW					X	9%	9%	4%	5%	3%	4%	4%	$0.02	$0.01	$0.03	
800 Ferry (RP-1515)	20,000	3B		HW					X	43%	29%	6%	22%	14%	6%	11%	$0.18	$0.01	$0.19	

Tip #1: Use ASHRAE Guideline 36 Sequences

- ASHRAE Guideline 36 combines the best of both the configurable and programmable worlds:
  - Plug and play
  - Advanced sequences and diagnostics
- Desired implementation
  - Engineers no longer write sequences
    - Just specify “Control sequences shall fully implement and be in accordance with ASHRAE Guideline 36”
    - You can do this right now!
  - Sequences all preprogrammed and debugged by control system manufacturer
    - At least five manufacturers have already done so!
  - Controls contractors no longer program sequences
  - Commissioning agents no longer test sequences
- Everyone wins
  - Lower first costs for entire design/construction team
  - Lower maintenance costs and easier to maintain
  - Lower energy costs and improved performance

Tip #2: Set VAV Box minimum setpoint to minimum ventilation rate

Tip #2: Set VAV Box minimum setpoint to minimum ventilation rate



TAG	INLET SIZE	DESIGN CFM		
		COOL	MIN	HEAT
VR-101	10	755	50	300
VR-102	10	700	50	350
VR-103	12	950	105	290

Set to Minimum Ventilation Rate

Supposed Issues

- What about Standard 62.1 and complying with the Multiple Spaces Equation?
- Minimum controllable setpoint is much higher according to VAV box manufacturers

ASHRAE Standards on VAV minimums

- ASHRAE Standard 62.1-2019 includes the Simplified Procedure

6.2.5.3 Simplified Procedure

6.2.5.3.1 System Ventilation Efficiency. System Ventilation Efficiency (Ev) shall be determined in accordance with Equation 6.2.5.3.1A or B as a function of occupant diversity, D.

$$Ev = 0.88*D + 0.22 \text{ for } D<0.60 \qquad (6.2.5.3.1A)$$

$$Ev = 0.75 \text{ for } D\geq 0.60 \qquad (6.2.5.3.1B)$$

6.2.5.3.2 Zone Minimum Primary Airflow. For each zone, the minimum primary airflow ($V_{pz\text{-}min}$) shall be determined in accordance with equation 6.2.5.3.2 based on zone minimum outdoor airflow rate, V_{oz}.

$$V_{pz\text{-}min} = V_{oz}*1.5 \qquad (6.2.5.3.2)$$

- ASHRAE Standard 90.1-2019 mandates that the primary airflow minimum must be equal to the ventilation minimum per the Simplified Procedure
- ASHRAE Guideline 36-2021 automatically calculates Vmin dynamically
  - Adjusts for dynamic changes to ventilation rate and if AHU is 100% outdoor air

Example Standard 62.1 Simplified Procedure

Minimum Ventilation Rate Cfm/ft2

Occupancy Category	$V_{pz\text{-}min}$ without DCV		$V_{pz\text{-}min}$ with DCV	
	Overhead Heating Ez=0.8	Other Ez=1.0	Overhead Heating Ez=0.8	Other Ez=1.0
Auditorium seating area	1.52	1.22	0.11	0.09
Classrooms (age 9 plus)	0.88	0.71	0.23	0.18
Conference/meeting	0.58	0.47	0.11	0.09
Corridors	0.11	0.09	0.11	0.09
Office space	0.16	0.13	0.11	0.09
Sales	0.44	0.35	0.23	0.18

G36 compliant VAV box schedule

TAG	INLET SIZE	DESIGN CFM			MIN OA CFM		ZONE Ez		CO2 PPM SETPOINT	OCC. STANDBY	WINDOW SWITCH
		COOL	MIN	HEAT	AREA	PEOP	COOL	HEAT			
VR-101	6	300	AUTO	150	18	50	1.0	0.8	1000	Y	Y
VR-102	8	540	AUTO	210	16	44	1.0	0.8	1000	Y	-
VR-103	12	1200	AUTO	320	120	50	1.0	0.8	-	Y	-

G36-2021: Just put "AUTO" in this minimum column and G36 sequences will dynamically determine minimum

Can minimum setpoints really be that Low?

- Minimum controllable setpoints are much higher according to VAV box manufacturers

NOT "typical" at all. Way too conservative!

Inlet Size	Total cfm Range	cfm Ranges of Minimum and Maximum Settings							
		[redacted] Pneumatic [redacted] Controller		[redacted] Pneumatic [redacted] Controller		[redacted] Analog Electronic [redacted] Controller		[redacted] Digital Typical Controller	
		Minimum	Maximum	Minimum	Maximum	MINIMUM	MAXIMUM	MINIMUM	MAXIMUM
4	0-225	45*-170	80-225	55*-170	80-225	45*-225	45-225	30*-225	30-225
5	0-350	65*-270	120-350	85*-270	120-350	65*-350	65-350	40*-350	40-350
6	0-500	80*-330	150-500	105*-330	150-500	80*-500	80-500	45*-500	45-500
7	0-650	105*-425	190-650	135*-425	190-650	105*-650	105-650	70*-650	70-650
8	0-900	145*-590	265-900	190*-590	265-900	145*-900	145-900	90*-900	90-900
9	0-1050	175*-700	315-1050	225*-700	315-1050	175*-1050	175-1050	120*-1050	120-1050
10	0-1400	230*-925	415-1400	300*-925	415-1400	230*-1400	230-1400	145*-1400	145-1400
12	0-2000	325*-1330	600-2000	425*-1330	600-2000	325*-2000	325-2000	190*-2000	190-2000
14	0-3000	450*-1800	810-3000	575*-1800	810-3000	450*-3000	450-3000	300*-3000	300-3000
16	0-4000	580*-2350	1100-4000	750*-2350	1100-4000	580*-4000	580-4000	385*-4000	385-4000
24 x 16	0-8000	1400*-5200	2600-8000	1800*-5200	2600-8000	1400*-7500	1400-7500	720*-7500	720-7500

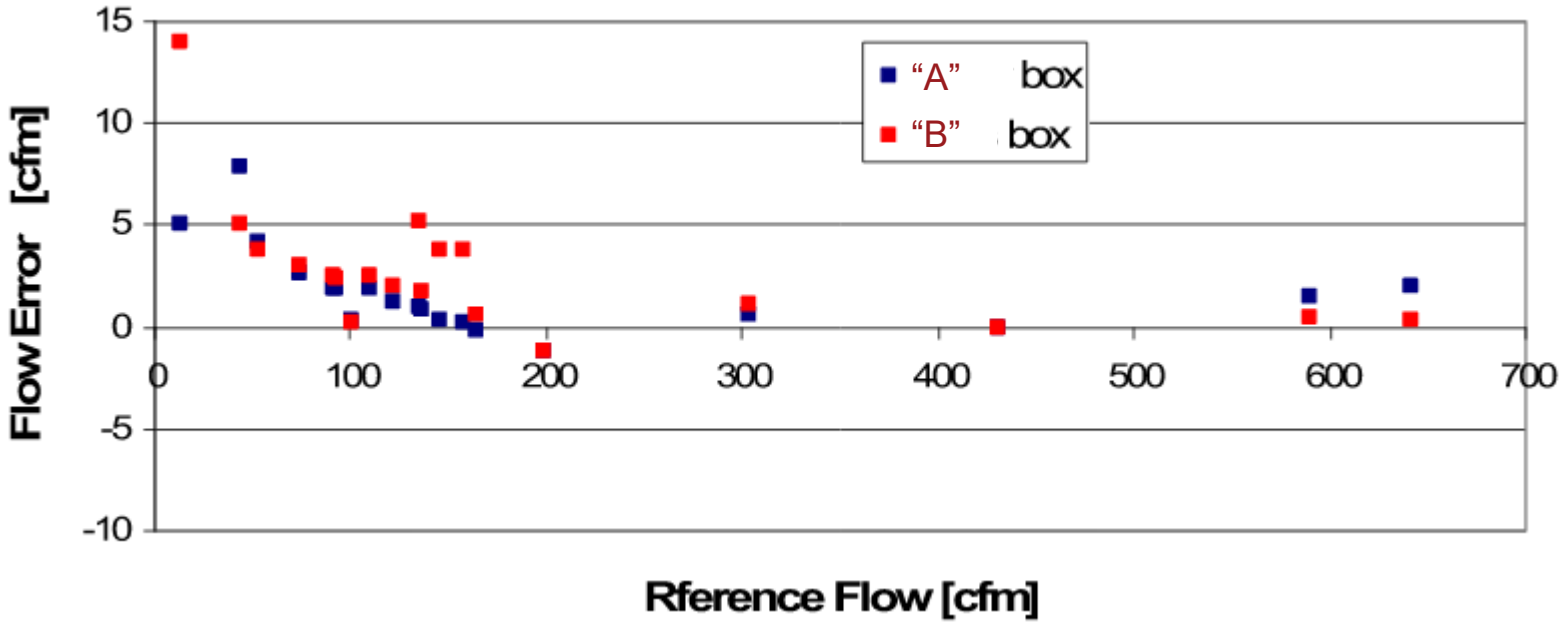
Equates to ~0.03" minimum VP and about 30% of design CFM for typical box selections

Can minimum setpoints really be that Low?

YES!

PG&E RP and ASHRAE RP-1353

8” VAV Box



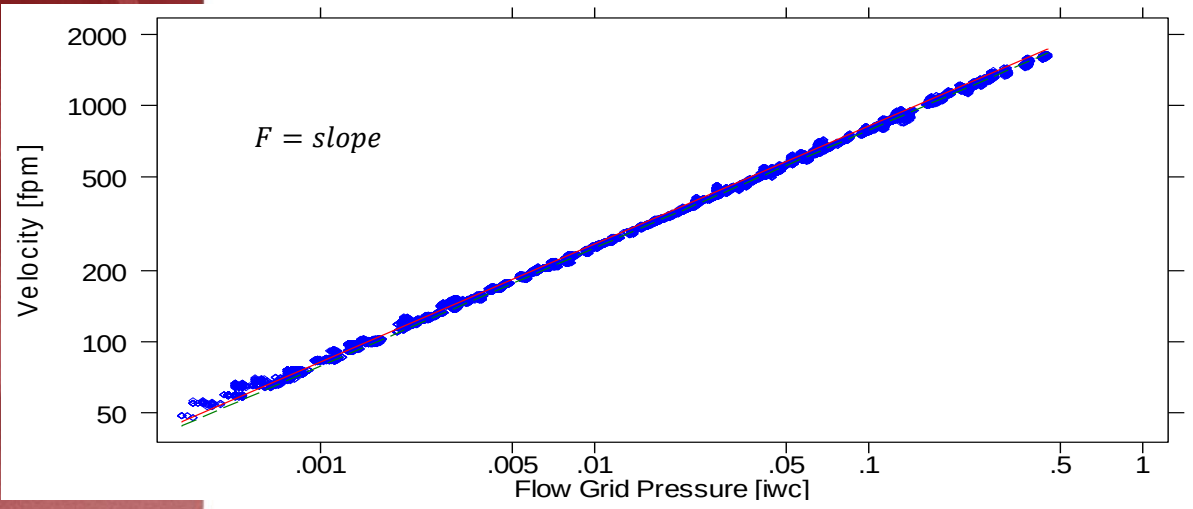
Most VAV controllers are highly accurate down to about 0.003”VP.
Controllable setpoints can be ~0.004”VP

Typical Controllable Minimum

$$FPM_{min} = 4005\sqrt{\frac{VP_{min}}{F}} \qquad 170 = 4005\sqrt{\frac{0.004}{2.3}}$$

$$CFM_{min} = FPM_{min}\left(\frac{\pi D^2}{4}\right)$$

VAV Flow Cross/Ring Amplification Factor

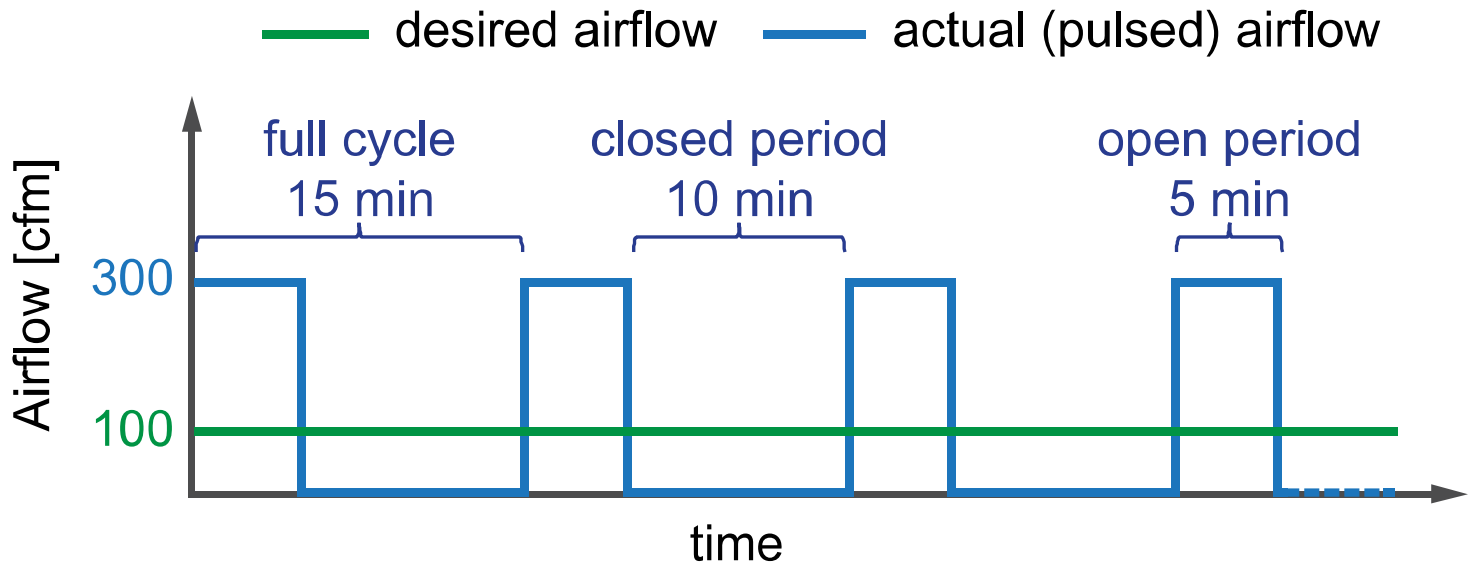


F varies from ~2 to 3.
Most VAV boxes >2
for box sizes 6” to 16”

Box Inlet Diameter	Maximum CFM at 0.5 in.w.g. pressure drop	Minimum CFM at 0.004 in.w.g. sensor reading	Minimum Ratio at Highest Maximum, %	Minimum Ratio at lowest Maximum, %
6	425	33	7.8%	-
8	715	58	8.1%	13.6%
10	1,100	91	8.3%	12.7%
12	1,560	130	8.3%	11.8%
14	2,130	177	8.3%	11.3%
16	2,730	232	8.5%	10.9%

Time-Averaged Ventilation (TAV)

- What happens if ventilation minimum is less than controllable minimum?
- ASHRAE Standard 62.1 allows time averaging over the room time constant (typically 1 to 6 hours)
- G36 TAV pulses the minimum from zero to the controllable minimum to ensure average minimum is maintained over a 15-minute window



Tip #2: Set VAV Box minimum setpoint to minimum ventilation rate

- Designers need not consider controllable minimum
  - VAV manufacturer data are usually wrong and can be ignored
  - Per Guideline 36, minimum is determined by the BAS contractor based on their controller's capability and VAV box flow probe amplification factor
  - Do specify BAS VAV controller minimum VP≤0.004"
  - Do specify VAV flow probe amplification factor F≥2
- Simply set box minimum to S62.1 Simplified Procedure rate
  - Better yet, set minimum to "AUTO" and let G36 SOOs dynamically reset
  - If the controllable minimum is higher, G36 SOOs will use TAV

Tip #3: Use Fan Arrays

Fan Arrays

Array of small single-width, single inlet direct-drive plenum fans

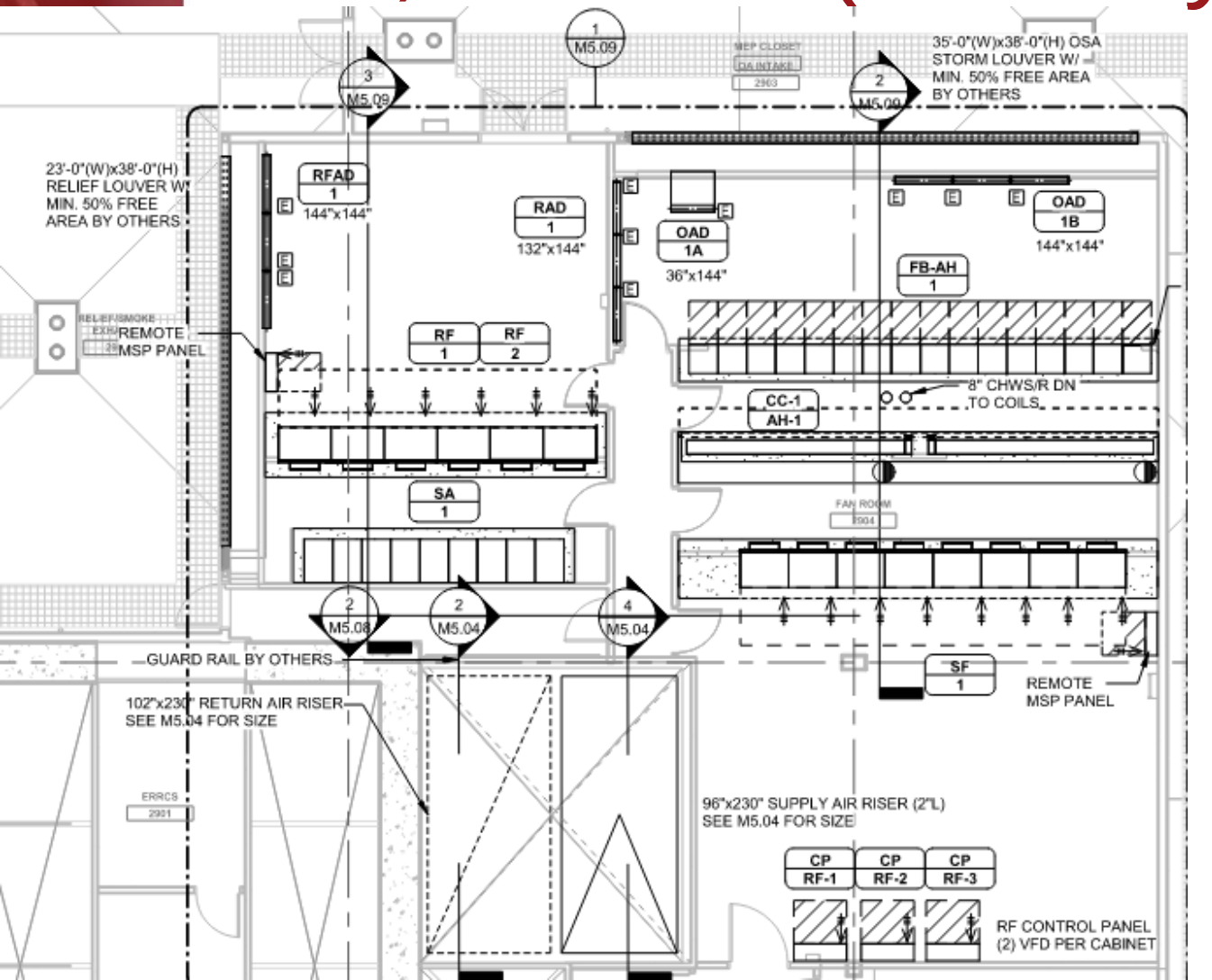
Advantages of Fan Arrays

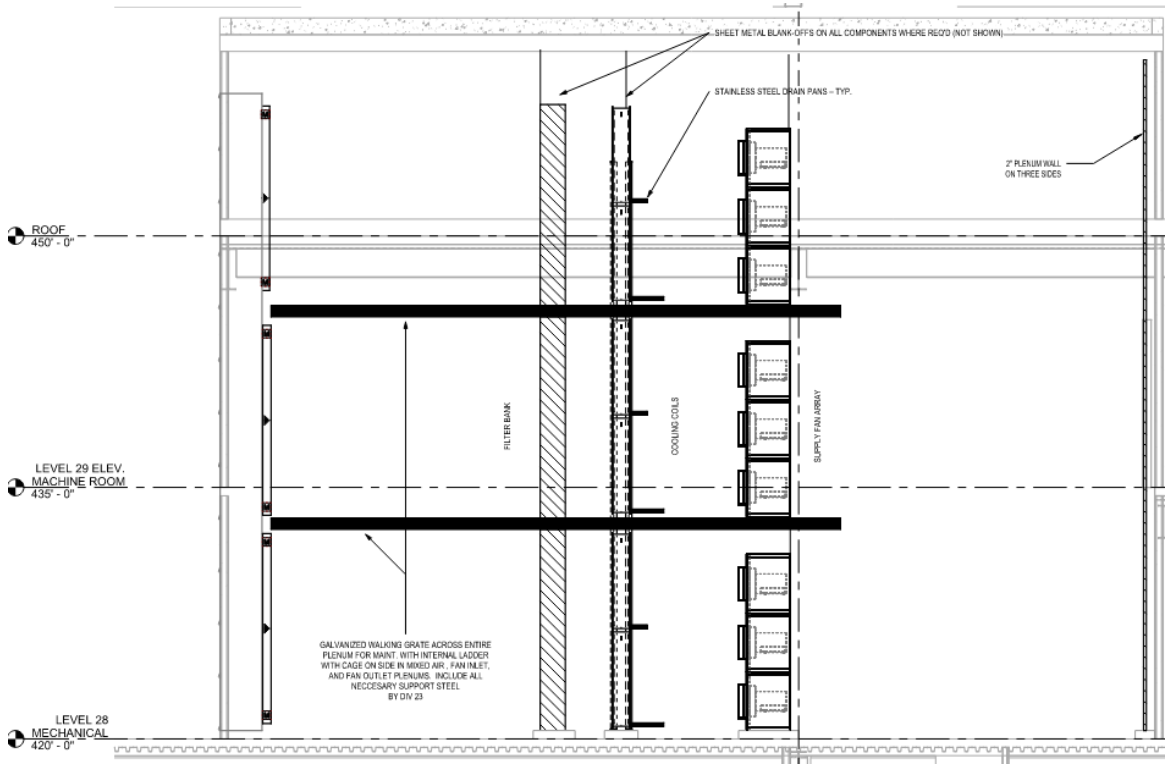
- Reduced AHU length
- Reduced sound power, especially on the discharge side
- Improved redundancy
  - Better still if multiple VFDs or ECMs are provided
- Reduced fan energy if sound attenuators or system effect are eliminated
- Easier motor and fan replacement
  - Best to limit MHP to ≤7.5 for reduced weight
- Easier to install in retrofit applications

Fan Arrays allow very large (Mega) AHUs

- ~200,000 cfm custom AHUs; >500,000 cfm field-built AHUs
- Mega AHUs vs. multiple small AHUs for large buildings
  - Much lower first costs
  - Less space required
  - Outdoor air economizer more readily possible
  - More energy efficient
- Potential Issues
  - “Rogue Zones” affecting supply air temperature and static pressure reset
    - Use Guideline 36 SOOs to identify these zones and fix them!
  - Incomplete mixing in economizer section
    - May need mixing fans in plenum for cold climates
  - Control of minimum outdoor air due to AFMS limitations
    - See next Design Tip for how to address this

500,000 cfm (28 story, 700,000 ft2 office)



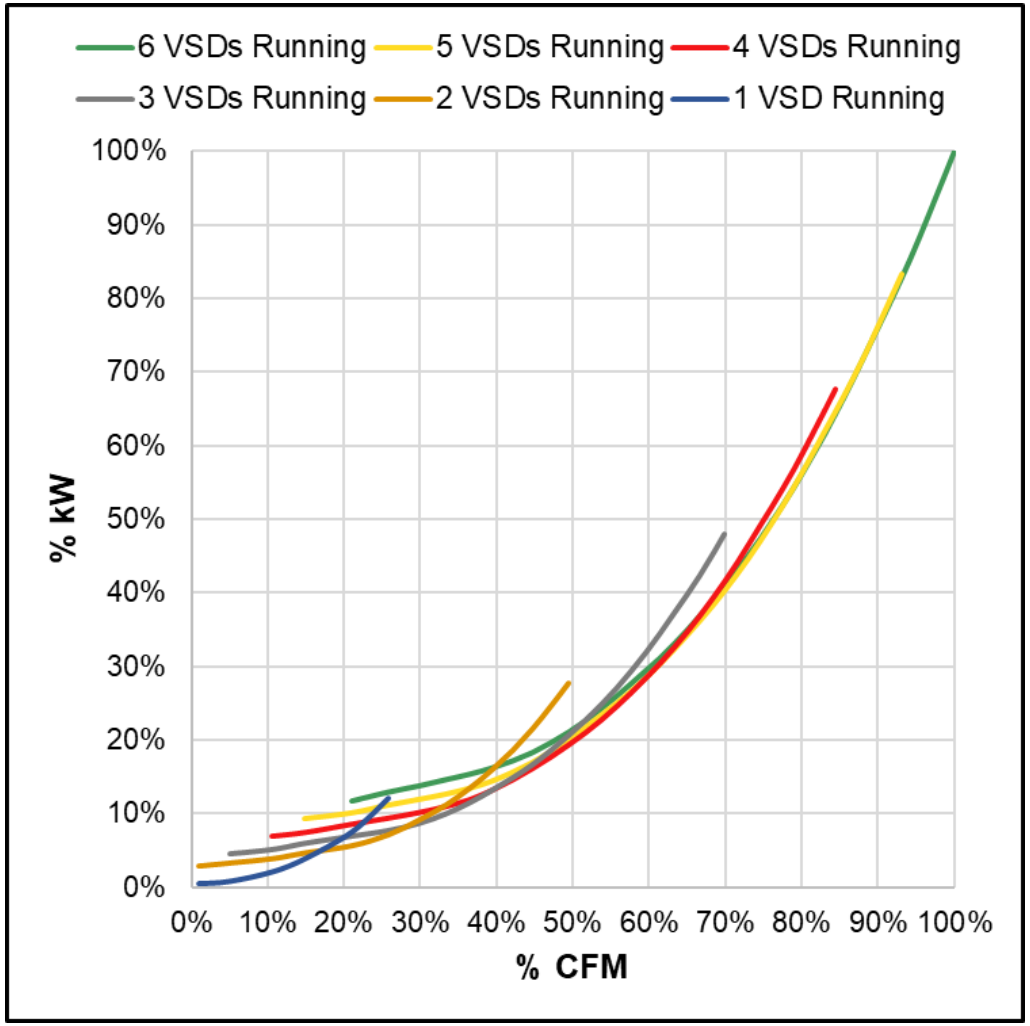


Large Fan Array Fan/VSD Staging

Requires:

- Multiple VSDs or ECMs
- Backdraft dampers

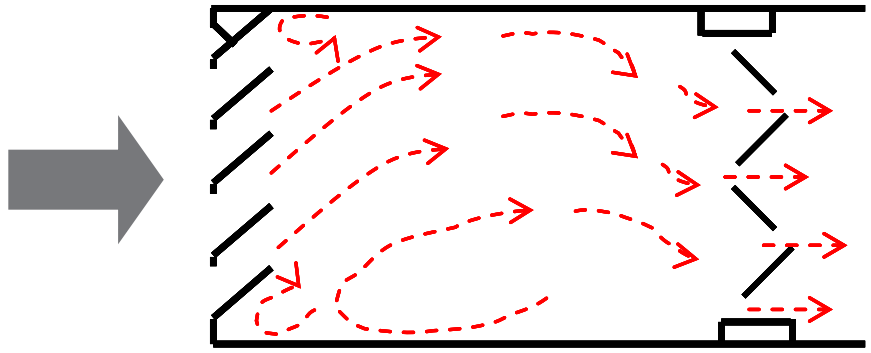
Only of value if airflow expected to be less than ~30% of design airflow e.g. if there are small Zone Groups

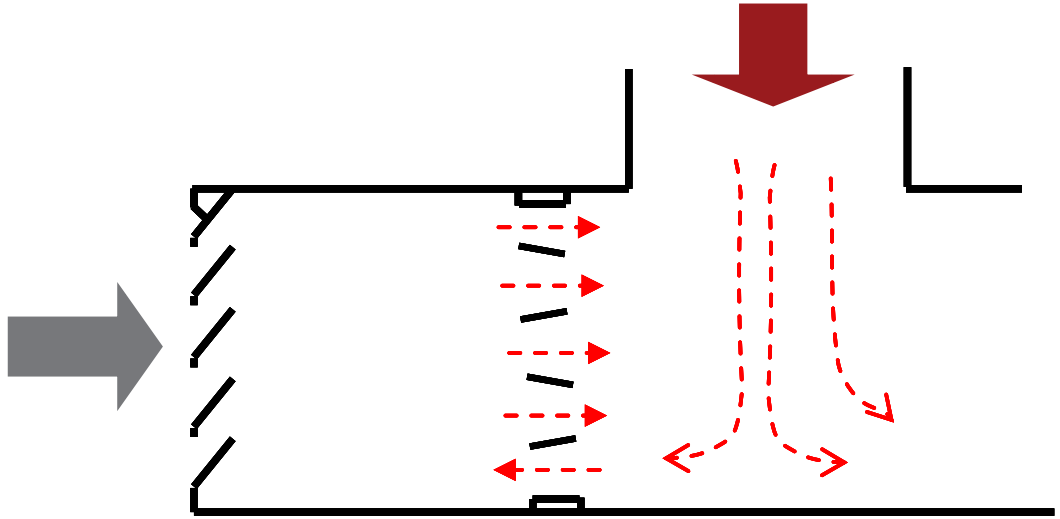


Tip #4: Control minimum outdoor air using DP across a fixed orifice

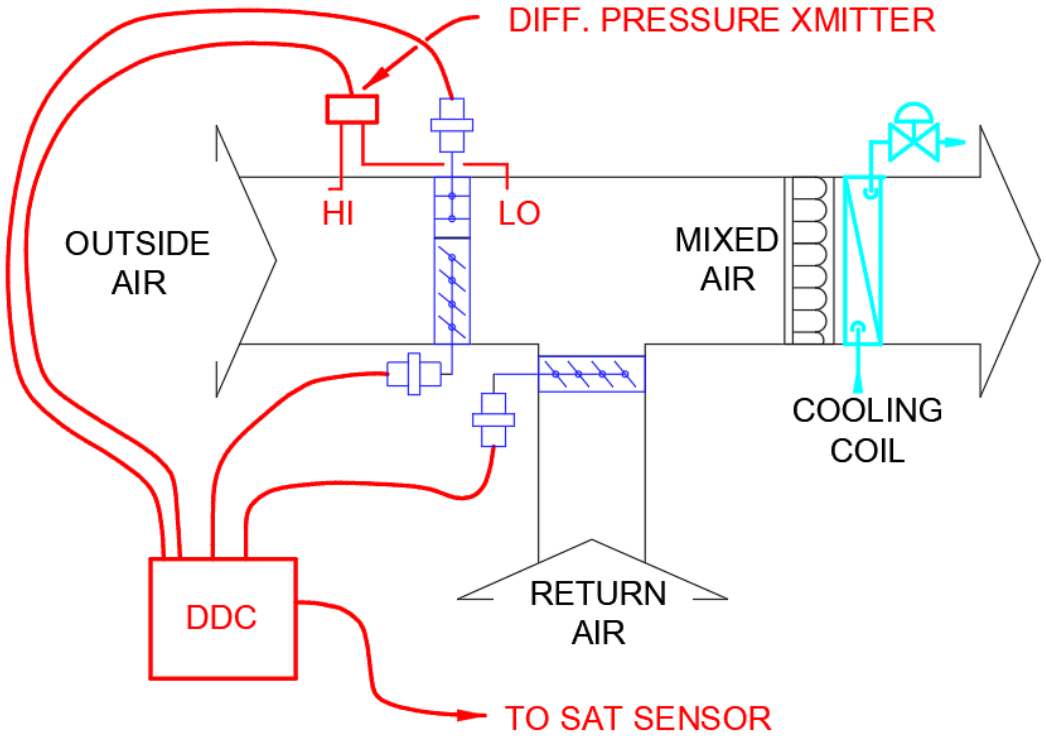
Outdoor airflow measurement is inaccurate!

- Many causes of error
  - Low air speeds, near detection limits of many sensors
    - Especially at minimum outdoor air rates
  - Non-uniform direction of air flow & turbulence
    - Partly due to limited space in AHUs
  - OA temperature and density vary
  - Sensors may be fouled due to moisture and dust
  - Effects of wind
- Controlling airflow within 10% and 15% per some codes and LEED is seldom actually possible
  - Our secret – don't tell GBCI or AHJs ☺

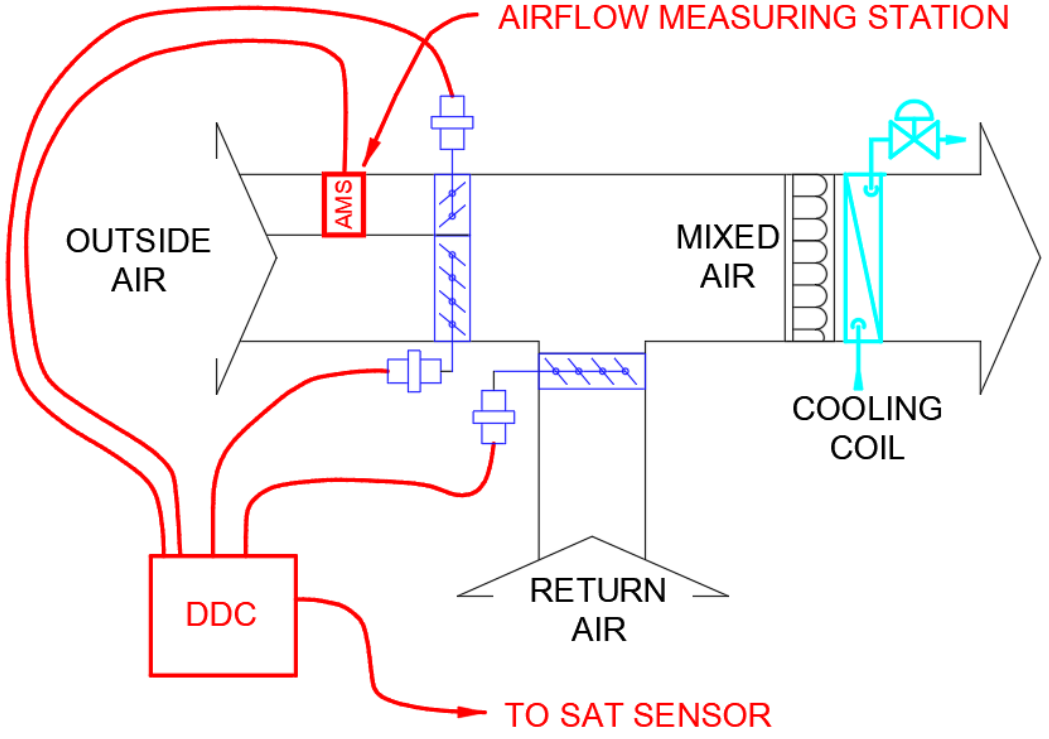




Separate outdoor air section difficult to control in cold weather

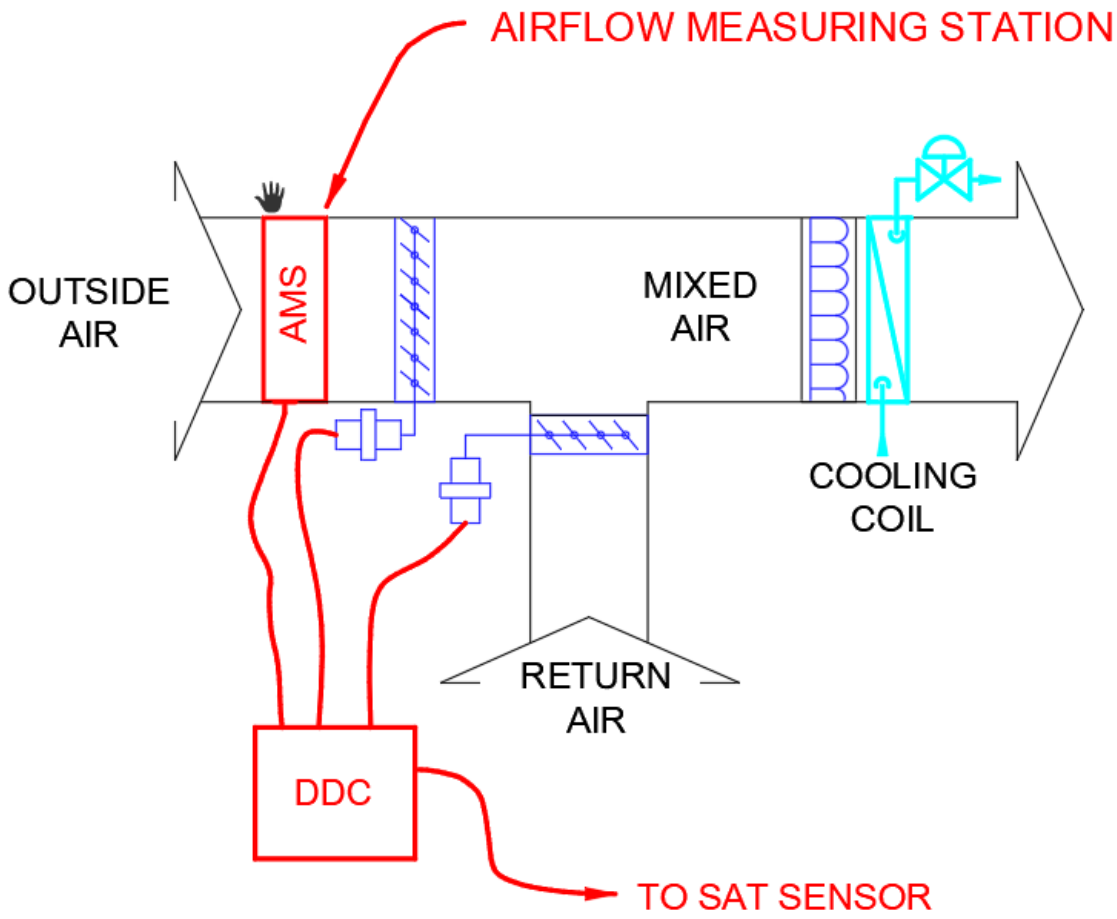


Since outdoor airflow through economizer section is unknown, not clear when return air damper control gets enabled.



Also does not work with RP-1747 DCV logic – need to know entire outdoor airflow rate.

Better to measure all outdoor airflow



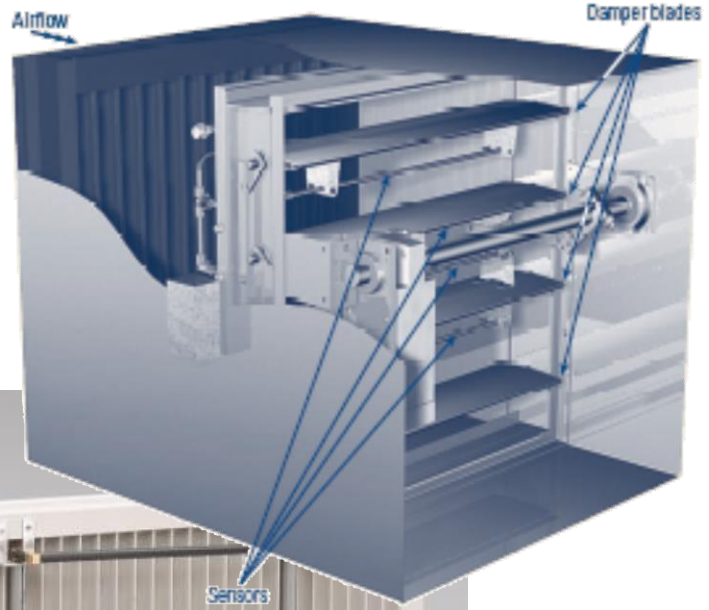
Continuous control loop maintains outdoor air at minimum with output that simply limits return air damper position. Very simple

Also works with RP-1747 DCV sequences

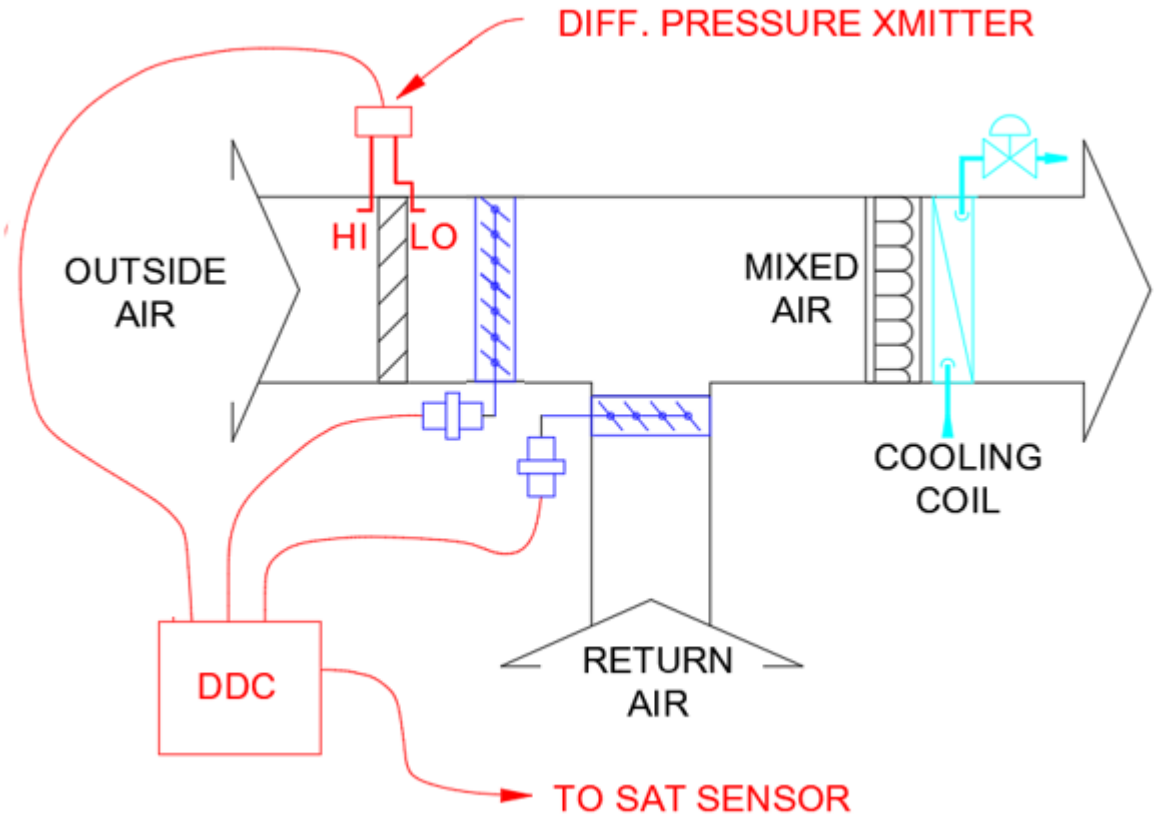
But what sensor can be used to measure airflow over such a wide range down to ~150 fpm?

Most AFMS do not work very well in typical applications

- Unable to read low velocities
- Affected by asymmetric velocity profile
- Affected by dirt, rainwater, snow
- Extra space needed



DP across a fixed orifice



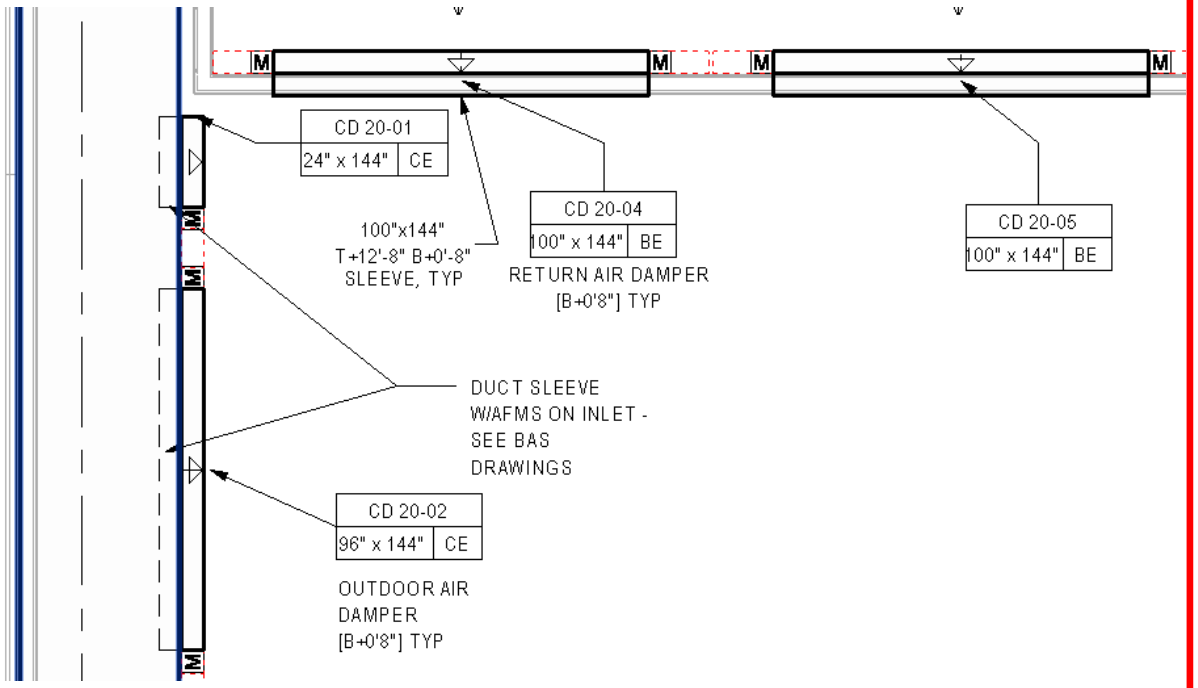
Requires:

- DP transmitter: ±0.25% in 0 to 0.1” range
- Optional temperature/density correction
- Fixed orifice (e.g. louver, mesh screen) that creates ~0.06” DP at design velocity

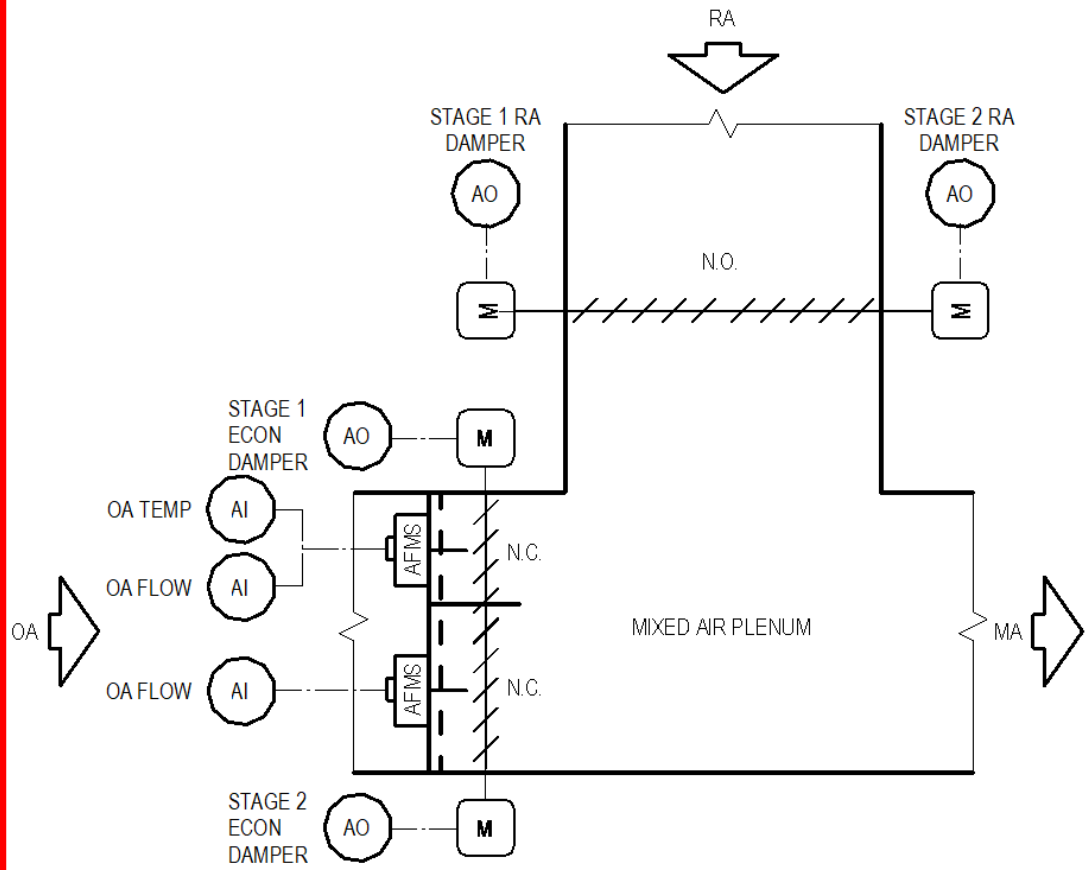
DP across a fixed orifice

- Using the louver DP as the signal mitigates effects of non-uniform velocity and wind
- Provides a 2x to 3x higher signal than a velocity or velocity pressure sensor – measures accurately down to ~150 fpm
- Avoids field calibration if fixed orifice DP is accurately known
- Less prone to fouling or damage from dirt, rain, or snow
  - Very reliable and low maintenance costs
- No added AHU length required

Staged OADs and RADs for large AHUs



Plan



Control Schematic

Summary – VAV Design Tips

- Tip #1: Use Guideline 36 Sequences
  - This is the most important tip!
- Tip #2: Set VAV Box minimum airflow to minimum ventilation rate
  - Recent changes to Standard 62 make this simple
- Tip #3: Use Fan Arrays
  - No downside, allows very large AHUs
- Tip #4: Control minimum outdoor air using DP across fixed orifice
  - Finally, a decent AFMS!

Bibliography

- ASHRAE Guideline 36-2021 High Performance Sequences of Operation for HVAC Systems
- ASHRAE Standard 62.1-2019 Ventilation and Indoor Air Quality
- ASHRAE Standard 90.1-2019 Energy Conservation for Commercial Buildings
- Dickerhoff D., Stein J.; “Stability and Accuracy of VAV Terminal Units at Low Flow”, PG&E 0514
- Lui R., Wen J.; Stability and Accuracy of VAV Box Control at Low Flows”, ASHRAE 1353-RP
- Taylor S. “Dual Maximum VAV Box Logic”, ASHRAE Journal, December 2012
- Arens et al; RP 1515, Thermal and Air Quality Acceptability in Buildings that Reduce Energy by Reducing Minimum Airflow from Overhead Diffusers, ASHRAE 1515-RP
- Taylor S. “Mega-Air Handling Units, ASHRAE Journal, March 2018

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