Advanced Variable Air Volume Control Sequences

Steven T. Taylor, PE
Taylor Engineering
Alameda, CA

November 12, 2013

Agenda

- VAV Box Control Sequences
- AHU Control Sequences
  - Zone Groups
  - DP setpoint reset
  - SAT setpoint reset
- Outdoor Air Control
  - Minimum outdoor air control
  - Demand Controlled Ventilation
- Automatic Fault Detection and Diagnostics, Alarms

Highlighting Recent ASHRAE Research

- RP 1455, "Advanced Control Sequences for HVAC Systems - Phase I Air Distribution and Terminal Systems."
- RP 1515, "Thermal and Air Quality Acceptability in Buildings that Reduce Energy by Reducing Minimum Airflow from Overhead Diffusers."
- RP 1547, "CO2-based Demand Controlled Ventilation for Multiple Zone HVAC Systems."

What is RP-1455?

- **Intent**
  - Combine reliability and efficiency of “configurable” pre-programmed sequences with the benefits of advanced, high performance sequences
  - Standardized best-in-class control sequences
  - Include fault detection and alarm suppression

Why RP-1455?

- **Maximize Performance**
  - Sequences are critical to HVAC system performance but are hard to write well
    - Style: Detailed, unambiguous, complete
    - Content: minimize energy costs, maximize comfort, meet codes & standards
- **Minimize Installation and Commissioning Costs**
  - Reinventing the wheel: Most sequences do similar things, but everyone's are slightly different.
  - All jobs start almost from scratch, requiring new programming, testing, and commissioning

What does RP-1455 Cover?

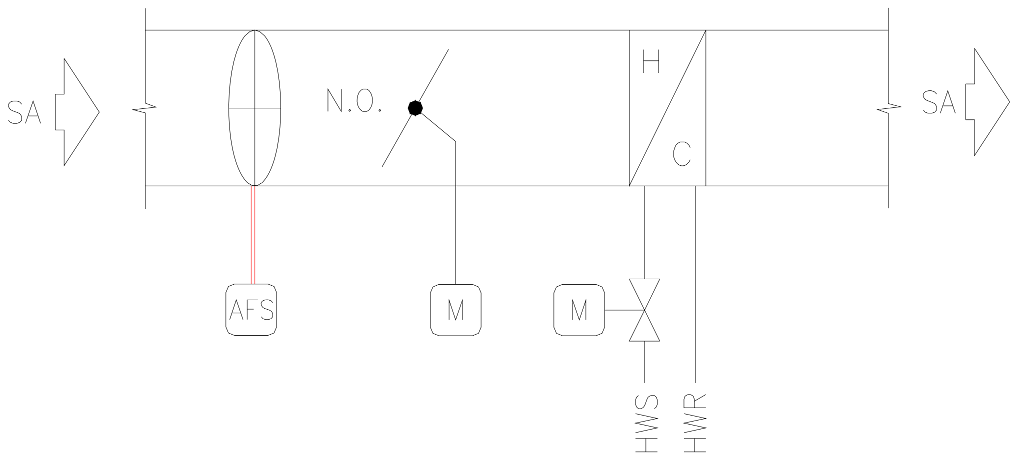
- **Variable Air Volume Systems**
  - Various configurations and options
- **VAV Terminal Units:**
  - VAV, cooling-only or reheat
  - Dual-duct, with inlet or discharge sensors
  - Series fan-powered, constant speed fan
  - Parallel fan-powered, constant or variable speed fan
- **VAV AHUs:**
  - Single or dual duct
  - Return or relief fans
  - Various methods of controlling minimum outdoor air
- **Future RPs proposed for HW and CHW plants**

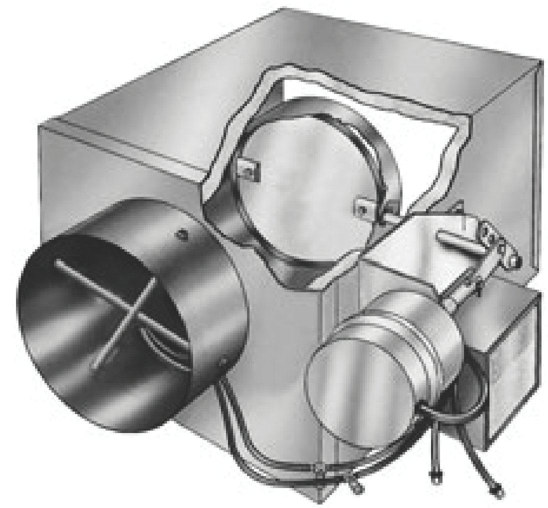
How will RP-1455 be used?

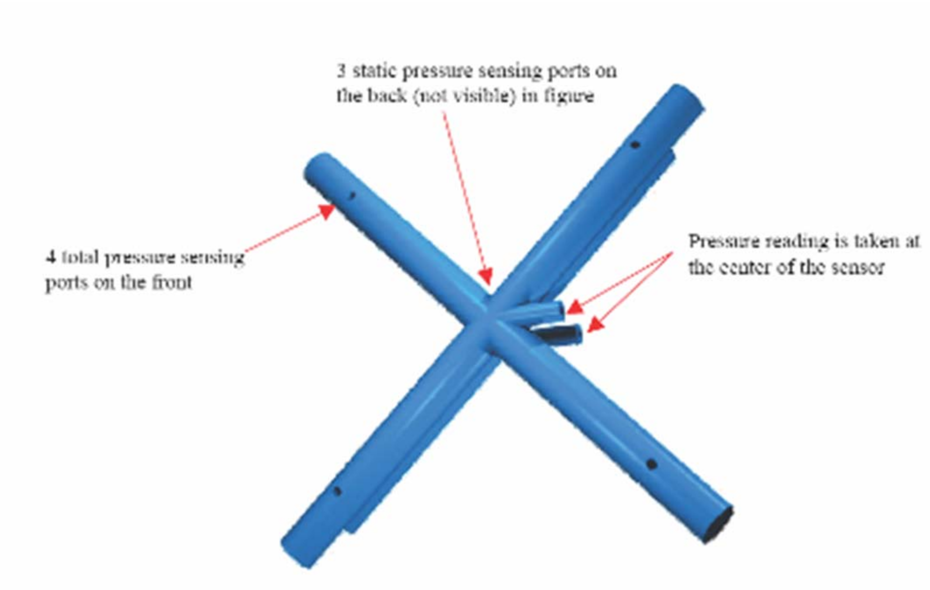
- **English-language sequences will be published as an ASHRAE Guideline, available for anyone's use**
  - GPC will also maintain sequences as improvements and bug fixes are proposed
  - Commissioning tests also TBD
  - Starting January 2014
- **Manufacturer will implement sequences for plug-and-play**
  - One manufacturer (ALC) has done so
  - Other vendors will surely follow…

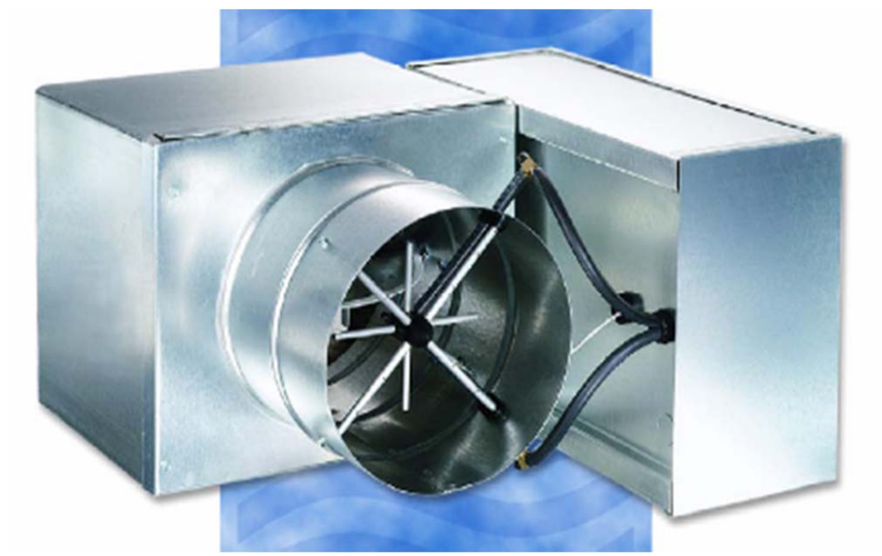
VAV Terminal Controls

VAV Reheat Box









What the lowest minimum?

- **Function of**
  - DDC Controller: What's the lowest controllable velocity pressure signal?
    - DDC velocity pressure transducer accuracy
    - A/D converter resolution (bits)
  - VAV Box:
    - Amplification factor
    - Inlet size

$$FPM_{\min} = 4005\sqrt{\frac{VP_{\min}}{Amp.}} \qquad CFM_{\min} = FPM_{\min}A$$

Why Not Just Look in the VAV Box Catalog?

Inlet Size	Total CFM Range	CFM Ranges of Minimum and Maximum Settings							
		PESV - Pneumatic TITUS II Controller		PESV - Pneumatic TITUS I Controller		AESV - Analog Electronic TA1 Controller		DESV - Digital Electronic TD1 Controller	
		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
4	0-225	45*-170	80-225	55*-170	80-225	45*-225	45-225	45*-225	45-225
5	0-350	65*-270	120-350	85*-270	120-350	65*-350	65-350	65*-350	65-350
6	0-500	80*-330	150-500	105*-330	150-500	80*-500	80-500	80*-500	80-500
7	0-650	105*-425	190-650	135*-425	190-650	105*-650	105-650	105*-650	105-650
8	0-900	145*-590	265-900	190*-590	265-900	145*-900	145-900	145*-900	145-900
9	0-1050	175*-700	315-1050	225*-700	315-1050	175*-1050	175-1050	175*-1050	175-1050
10	0-1400	230*-925	415-1400	300*-925	415-1400	230*-1400	230-1400	230*-1400	230-1400
12	0-2000	325*-1330	600-2000	425*-1330	600-2000	325*-2000	325-2000	325*-2000	325-2000
14	0-3000	450*-1800	810-3000	575*-1800	810-3000	450*-3000	450-3000	450*-3000	450-3000
16	0-4000	580*-2350	1100-4000	750*-2350	1100-4000	580*-4000	580-4000	580*-4000	580-4000
24x16	0-8000	1400*-5200	2600-8000	1800*-5200	2600-8000	1400*-7500	1400-7500	1400*-7500	1400-7500

* Factory CFM settings (except zero) will not be made below this range because control accuracy is reduced.
On pressure dependent units, minimum CFM is always zero and there is no maximum.

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

Why Not Just Look in the VAV Box Catalog?

Still too high

UNIT SIZE	400 SERIES (PNEUMATIC) STANDARD CONTROLLER		7000 SERIES ANALOG ELECTRONIC		DDC CONSIGNMENT CONTROLS (See Notes Below)				
					MIN.			MAX.	
					Min. transducer differential pressure (in. w.g.)			Max. transducer differential pressure (in. w.g.)	
	MIN.	MAX.	MIN.	MAX.	0.015	0.03	0.05	1.0	≥1.5
4	43	250	35	250	30	43	55	250	250
5	68	350	50	350	48	65	88	350	350
6	75	490	60	550	53	75	97	435	530
8	145	960	115	1000	105	145	190	840	1000
10	235	1545	185	1600	165	235	305	1355	1600
12	340	2250	285	2300	240	340	440	1975	2300
14	475	3100	390	3100	335	475	615	2750	3100
16	625	4100	520	4100	440	625	805	3595	4100
19	1180	6500	1025	6500	845	1180	1510	6375	6500
22	1730	8000	1450	8000	1260	1730	2200	8000	8000

NOTES:

1. Minimum and maximum airflow limits are dependent on the specific DDC controller supplied. Contact the control vendor to obtain the minimum and maximum differential pressure limits (inches W.G.) of the transducer utilized with the DDC controller.
2. Maximum CFM is limited to value shown in General Selection Data.

Good Advice! NEVER use Box manufacturer's minimums!

Controllable VP Range

- Some manufacturers list the range

Velocity Pressure Input

Control Range 0.004 to 1.5 in. of W.C.

Over Pressure Withstand ±20 in. of W.C.

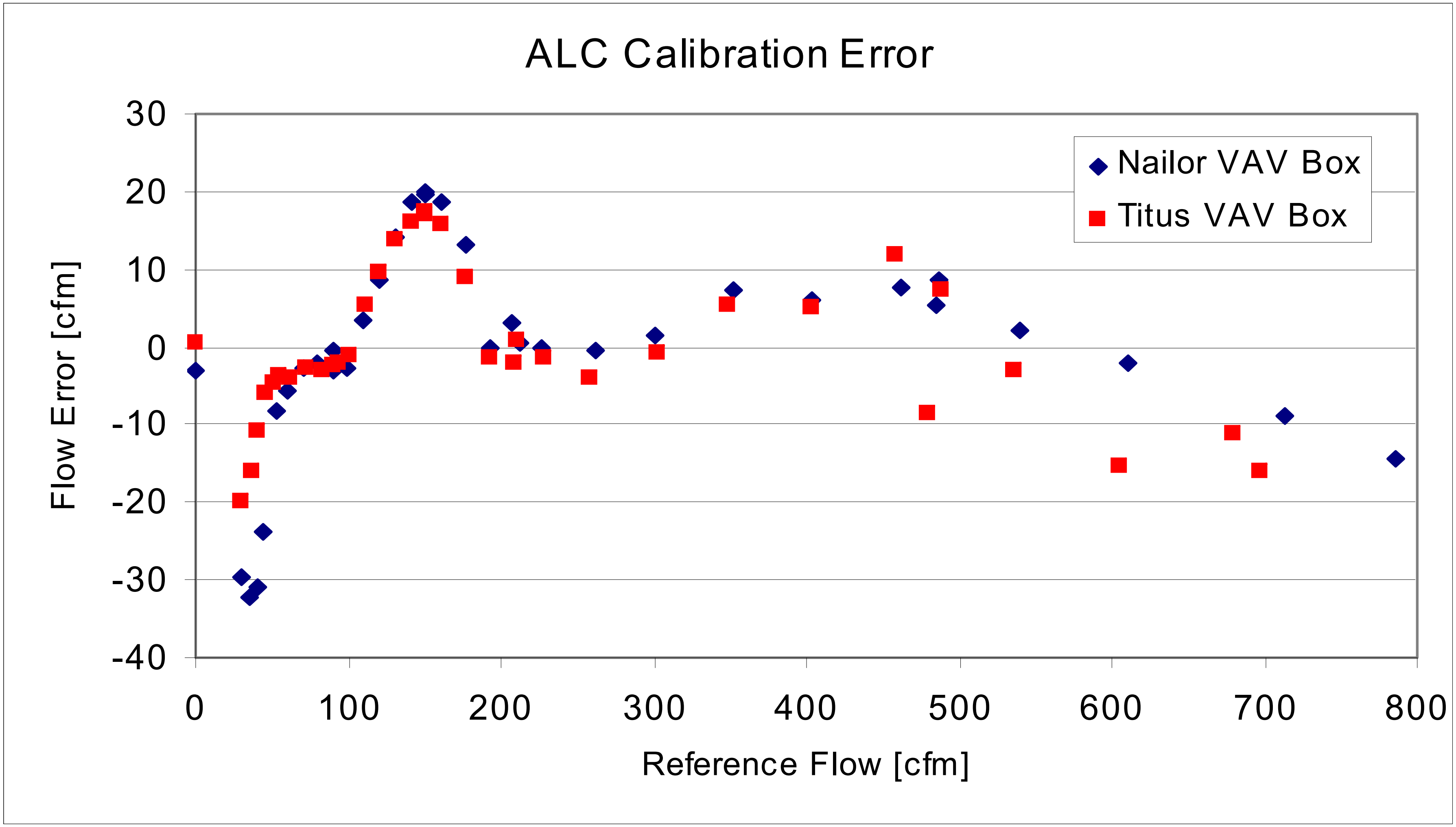
Accuracy ±5% at 1.00 in. of W.C. with laminar flow at 77 °F (25 °C) and suitable flow station.

Sensor Type Self-calibrating flow sensor (differential pressure).

- Some you have to ask
- Most available from ASHRAE RP 1353 and PG&E research projects (see references)
  - All controllers ± 10% at 0.003”
- Specify allowable setpoint ≤ 0.004”

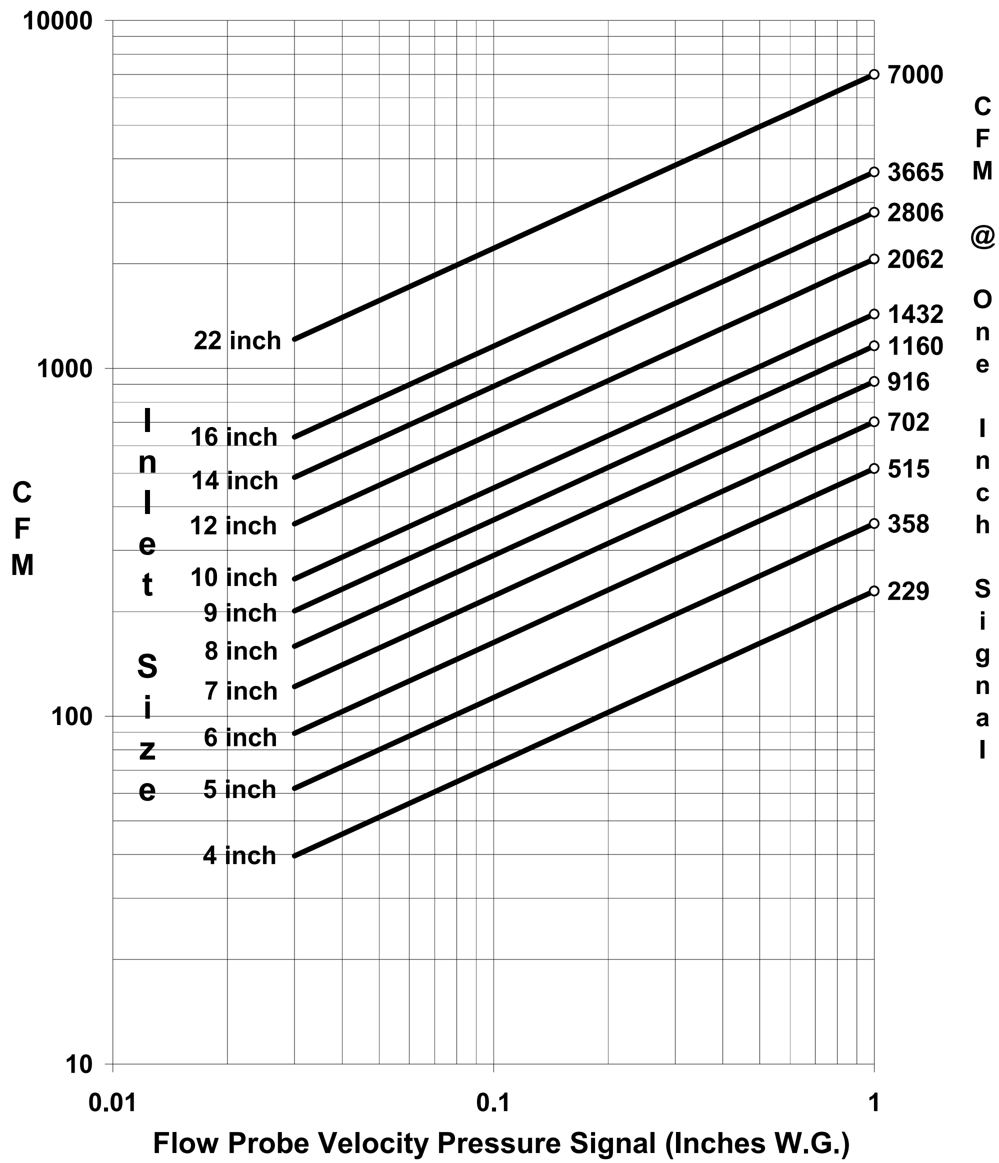
13

Typical DDC Performance



Highly accurate down to about 50 CFM (0.003")

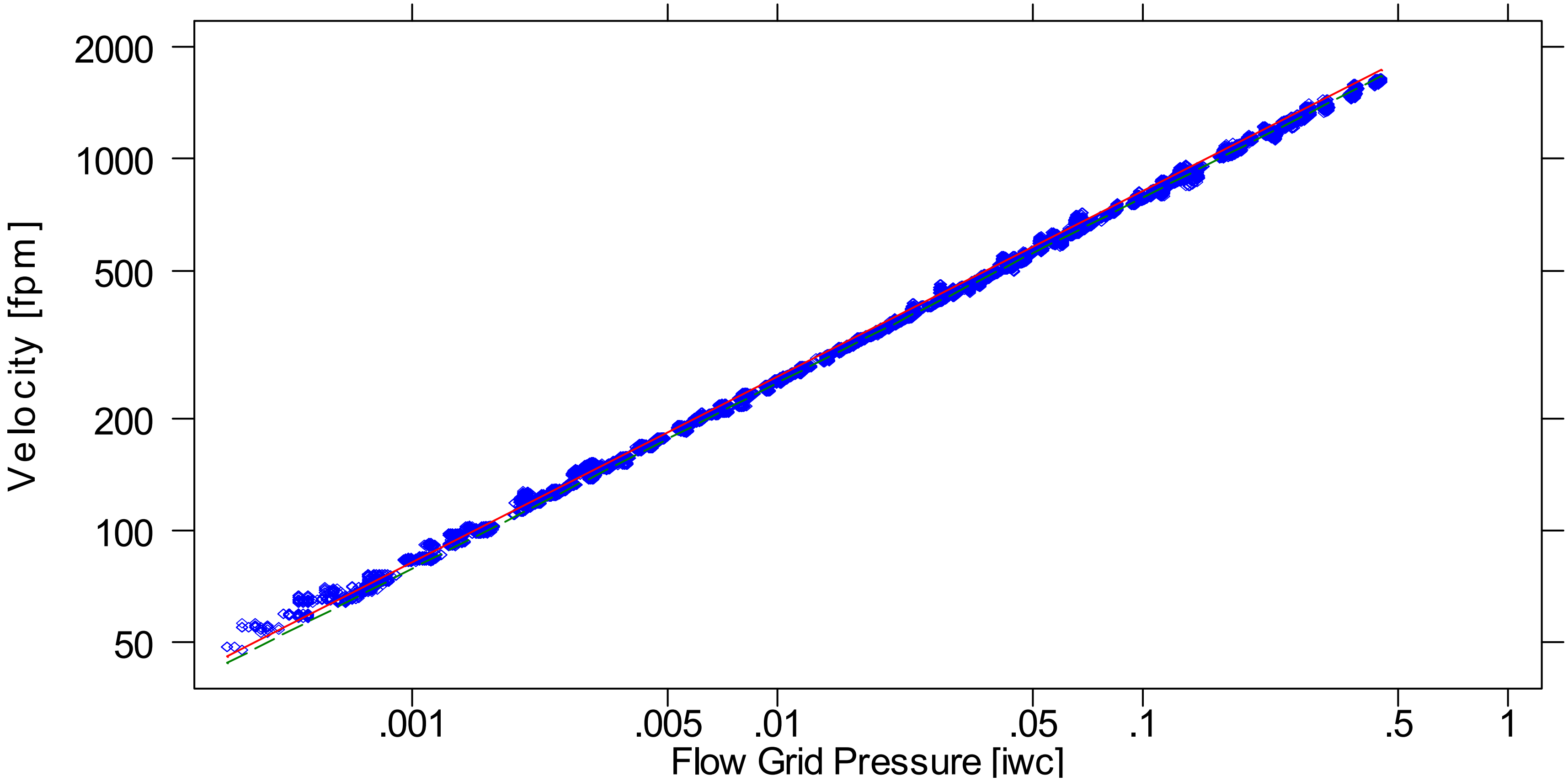
Flow Probe Amplification



$$F = \left(\frac{4005A}{K}\right)^2$$

F = amplification factor
K = actual flow in CFM at flow probe output of 1.0" w.c.
A = is the nominal inlet area in ft^2

Typical Flow Probe Performance



$$F = \left(\frac{4005 * A}{K} \right)^2 = 2.6$$

Spec ≥2.0

Sample Controllable Minimum

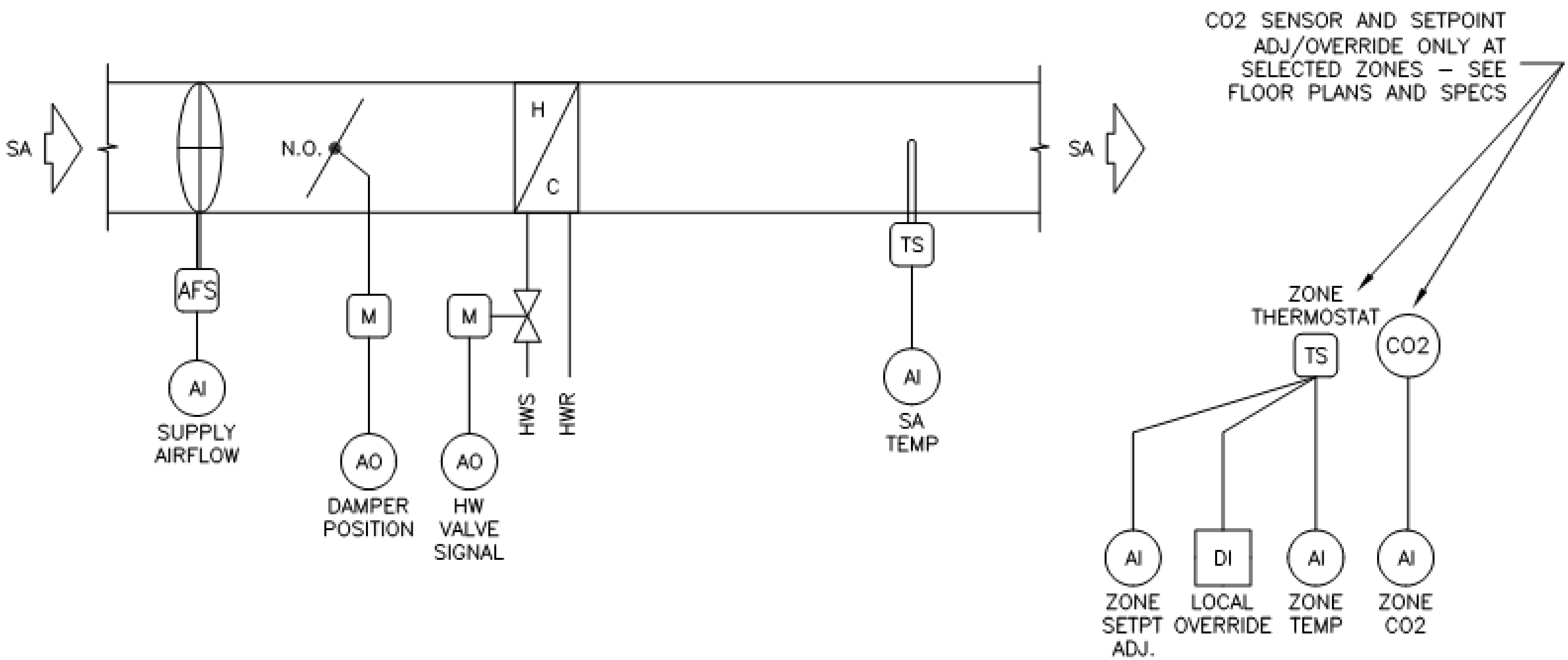
$$FPM_{\min} = 4005\sqrt{\frac{VP_{\min}}{Amp.}}$$

$$170 = 4005\sqrt{\frac{0.004}{2.3}}$$

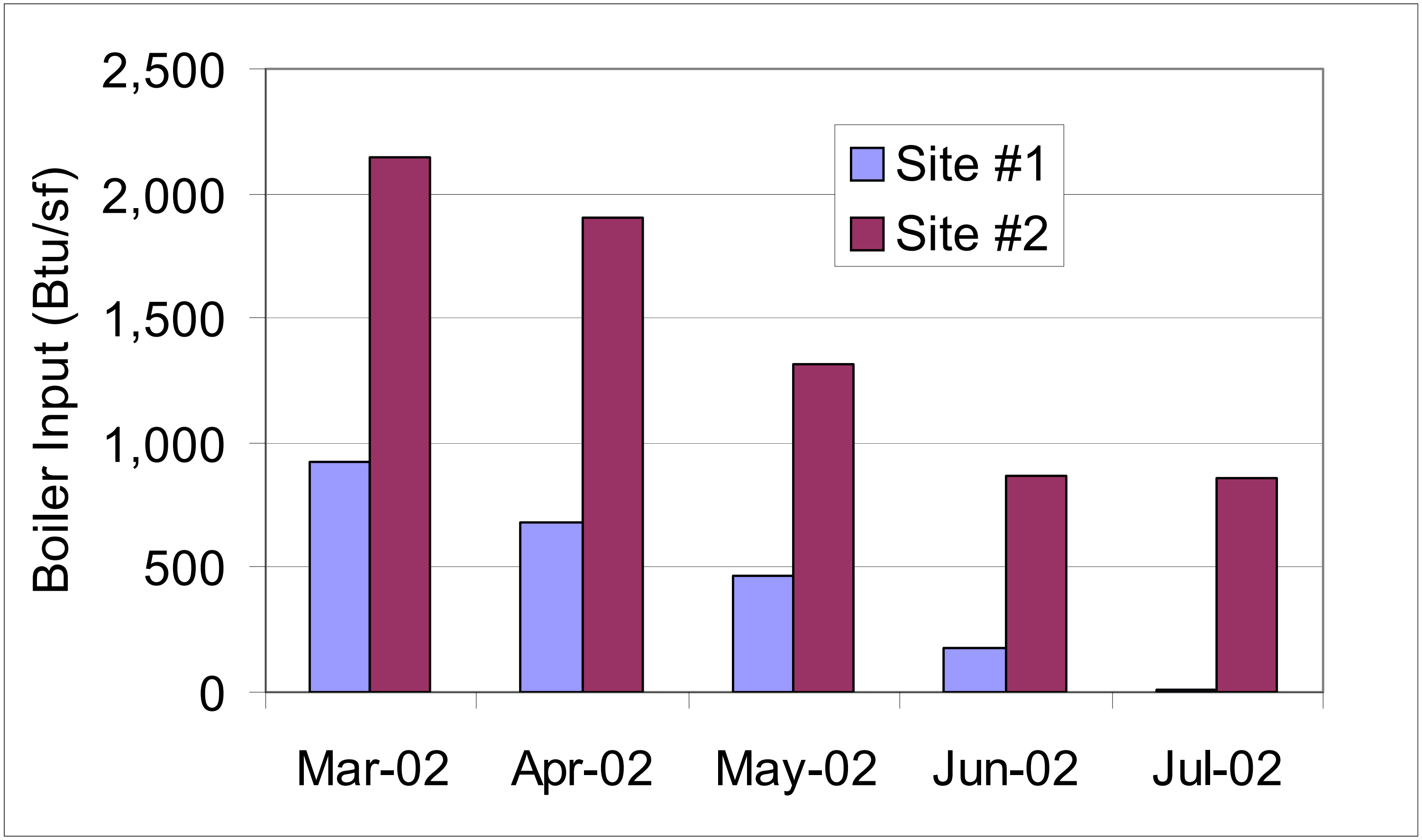
$$CFM_{\min} = FPM_{\min} A$$

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%

VAV Reheat Control

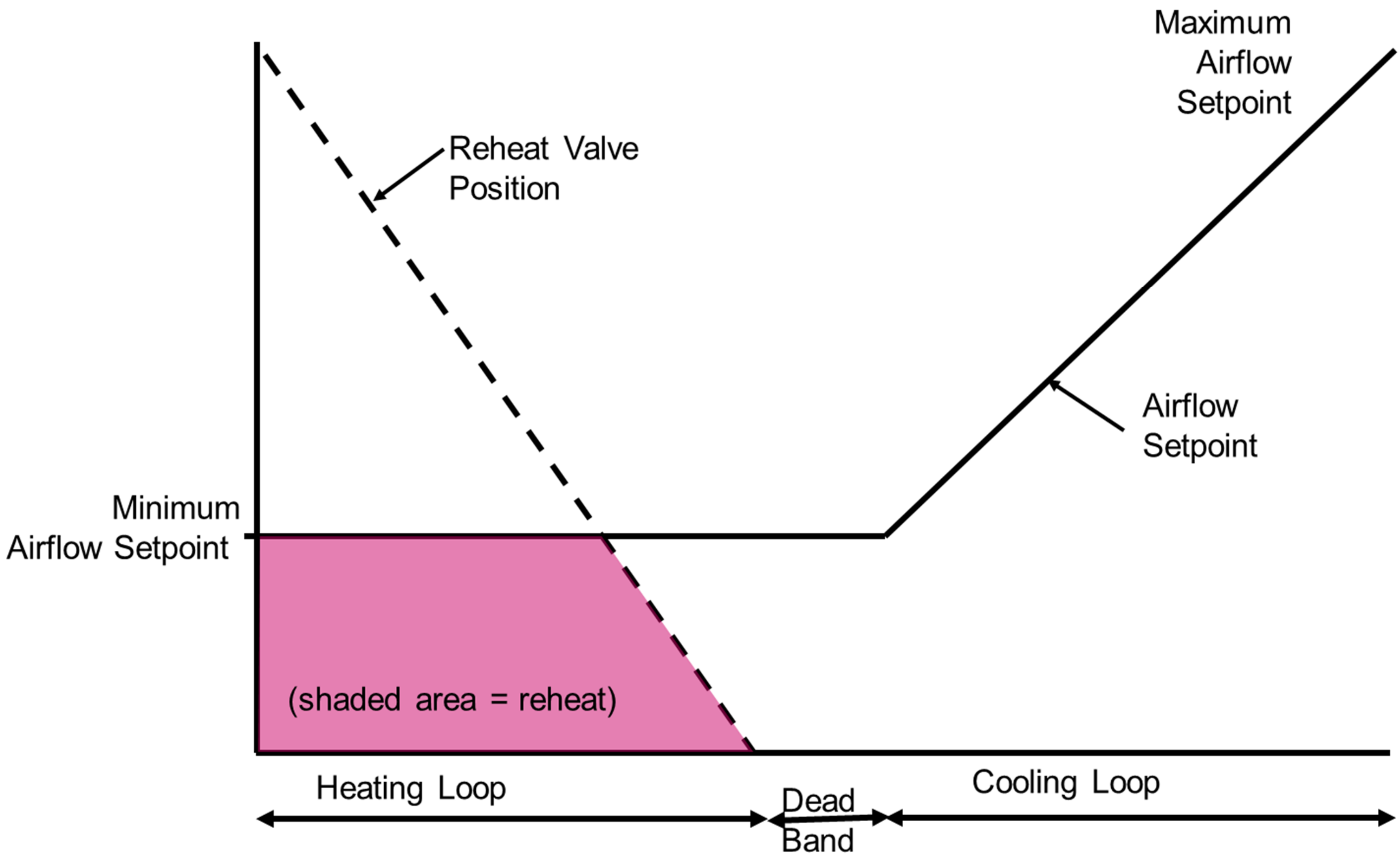


Q: Why do some buildings use 3 -5 times as much energy as others?



A: Reheat

Conventional VAV Control



Conventional VAV Box Minimum Setpoint

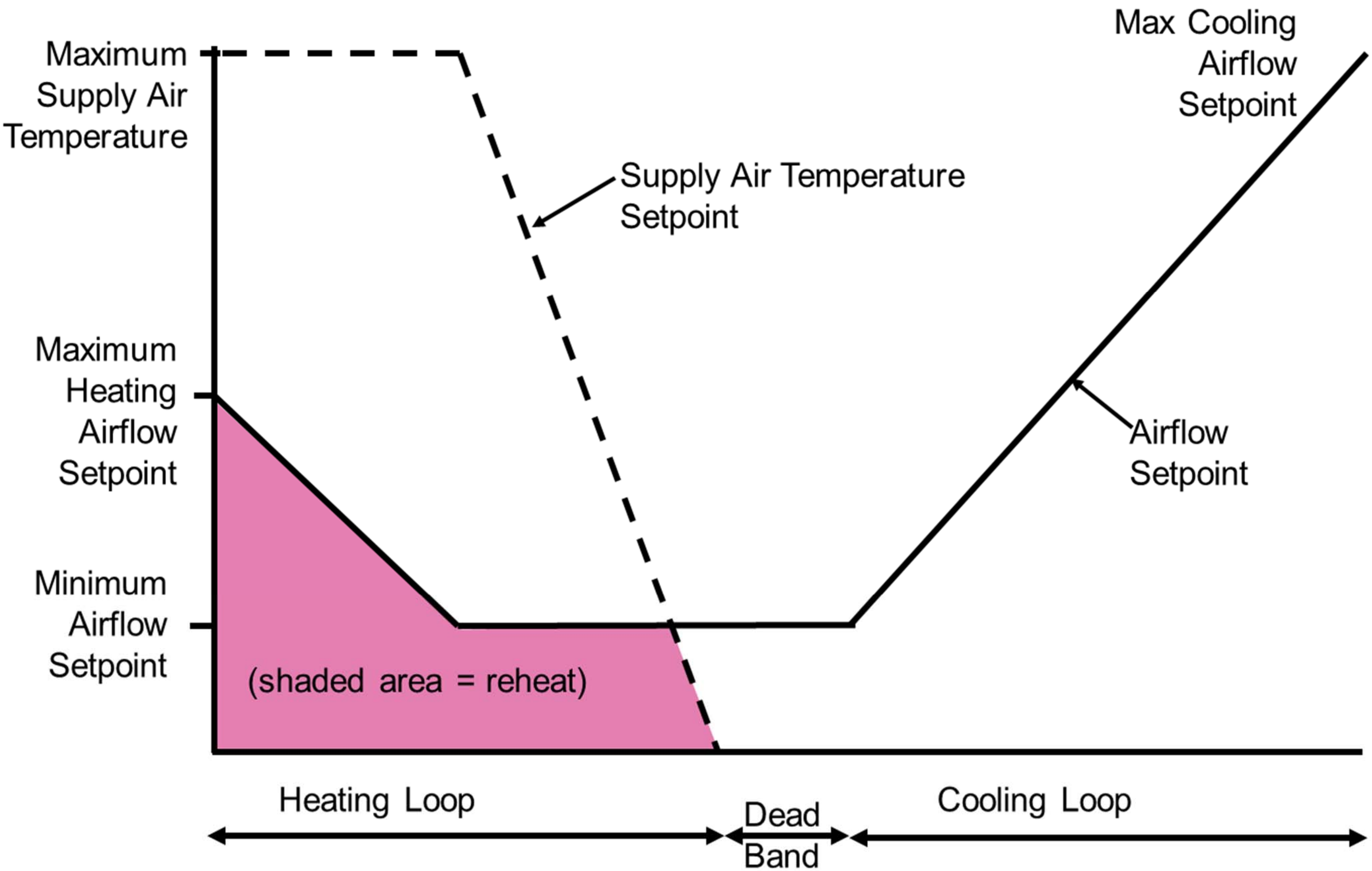
- **No less than larger of:**
  - Minimum ventilation rate
    - Per Standard 62.1
  - Controller minimum
    - Not usually an issue – see discussion above
  - Limit “dumping”
    - Not a real issue – see RP-1515 results
  - Limit stratification
    - No more than 20°F above space temperature (~≤95°F) per Standard 90.1
- **No more than larger of:**
  - 30% of cooling maximum
  - Minimum ventilation rate

New for Standard 90.1-2013

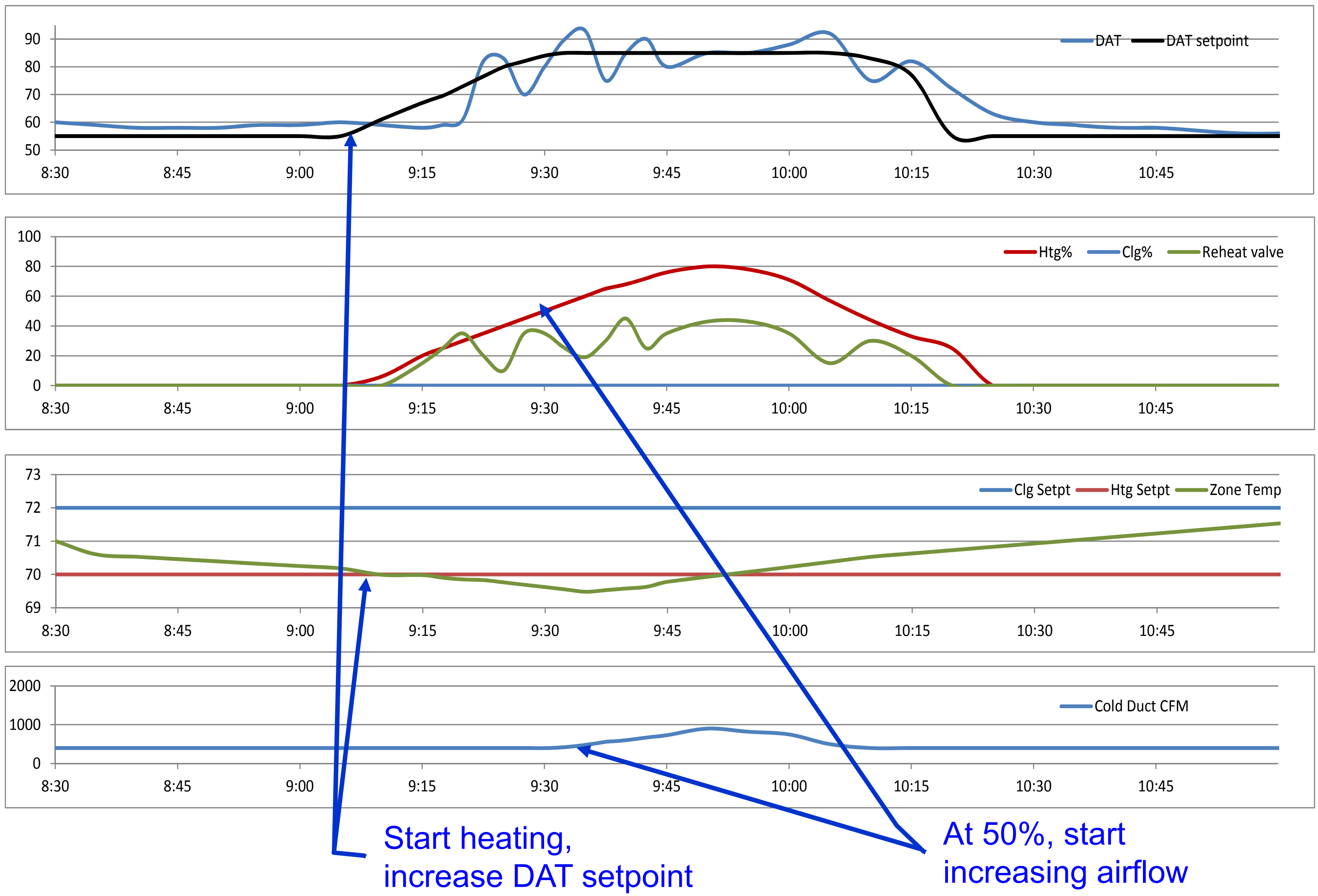
b. *Zones* **with *DDC*** that comply with all of the following:

1. The air flow rate in dead band between heating and cooling does not exceed the largest of the following:
    i. 20% of the zone design peak supply rate;
    ii. The outdoor air flow rate required to meet the ventilation requirements of ASHRAE Standard 62.1 for the zone;
2. The air flow rate that is reheated, recooled, or mixed shall be less than 50% of the zone design peak supply rate.
3. The first stage of heating consists of modulating the zone supply air temperature setpoint up to a maximum setpoint while the airflow is maintained at the dead band flow rate.
4. The second stage of heating consists of modulating the airflow rate from the dead band flow rate up to the heating maximum flow rate.

"Dual Maximum" Control
(Per Standard 90.1 and RP-1455)

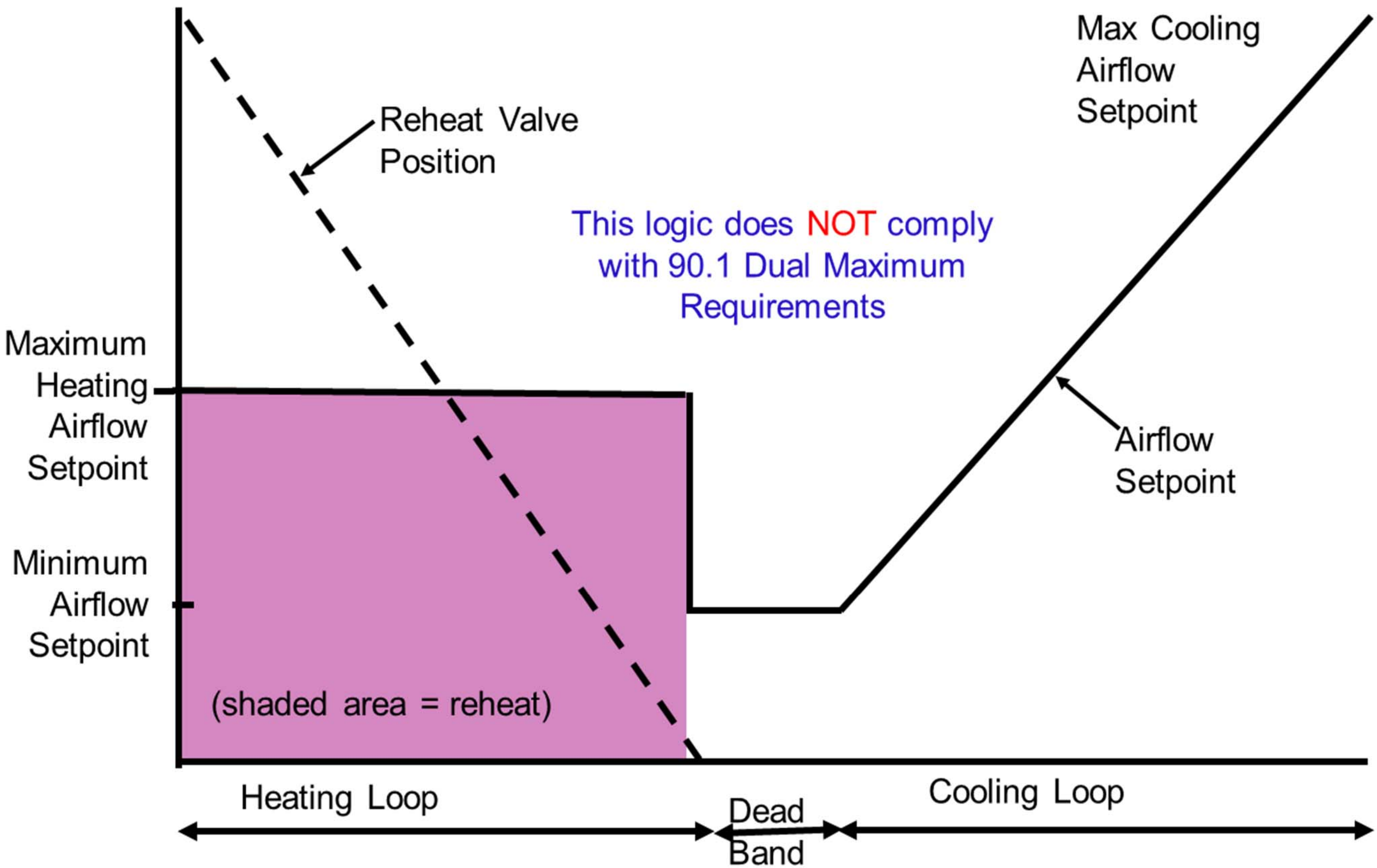


Dual Maximum Logic in Action



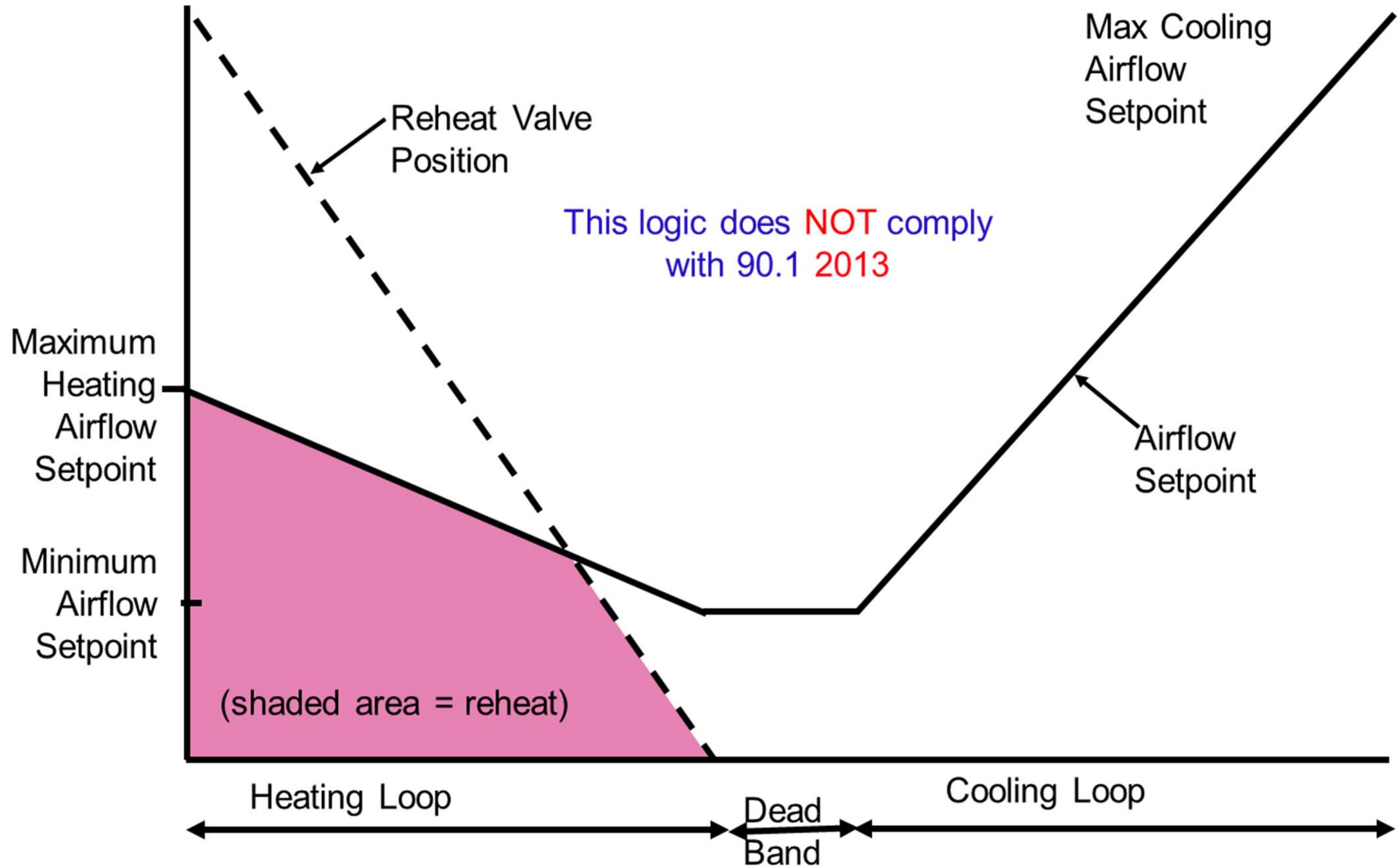
Sort of Dual Maximum Control

(Found in some configurable controllers)



Sort of Dual Maximum Control

(Found in some configurable controllers)



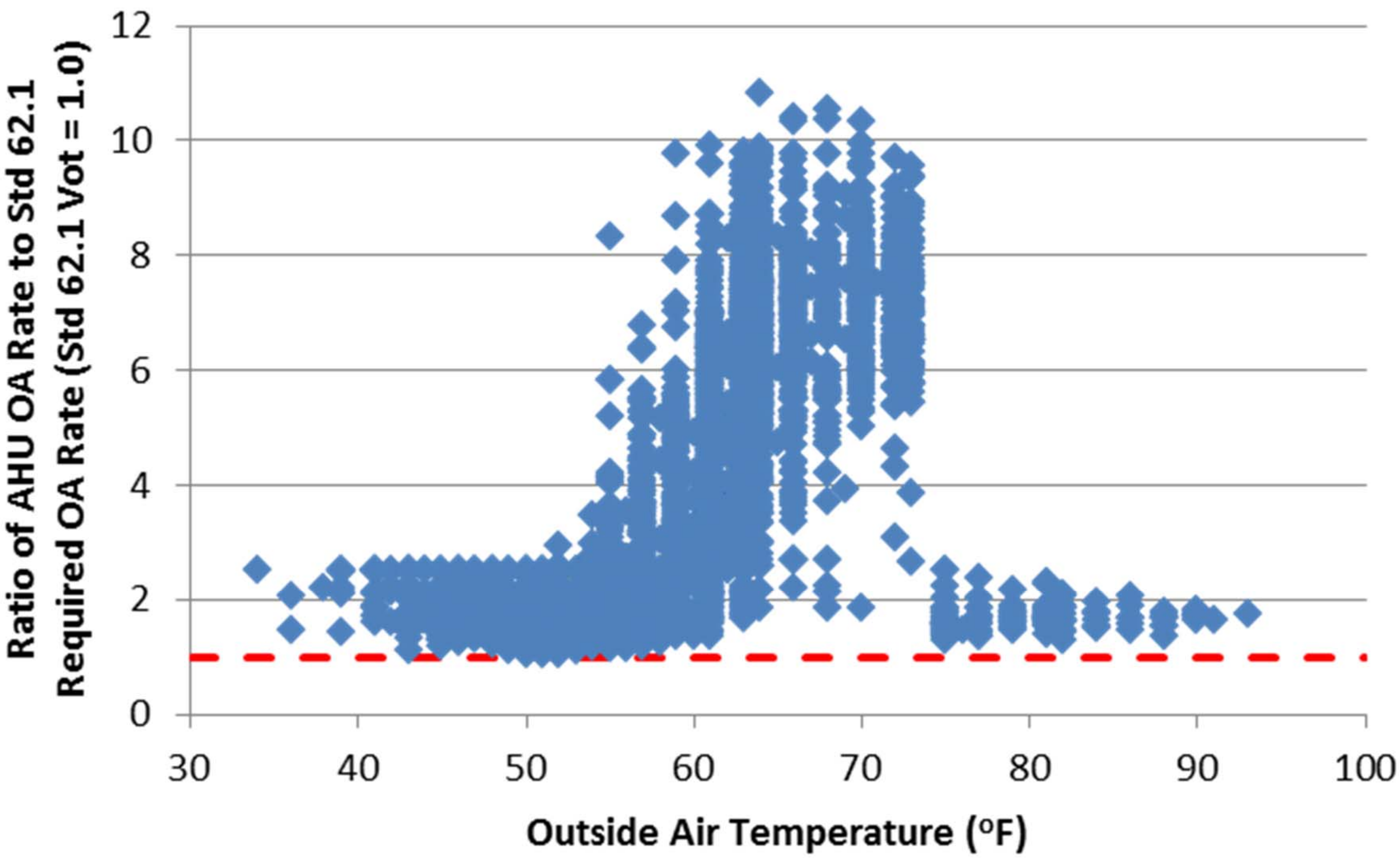
VAV Box Dual Maximum Control Setpoints per Standard 90.1-2013

- **Minimum:**
  1. No less than larger of:
     - Minimum ventilation rate for the zone
     - Controller minimum
  2. No more than 20% of cooling maximum

MARK	INLET SIZE	DESIGN CFM		
		COOL	MIN	HEAT
VR-101	12	1035	135	260
VR-102	10	810	90	230
VR-103	6	210	50	50

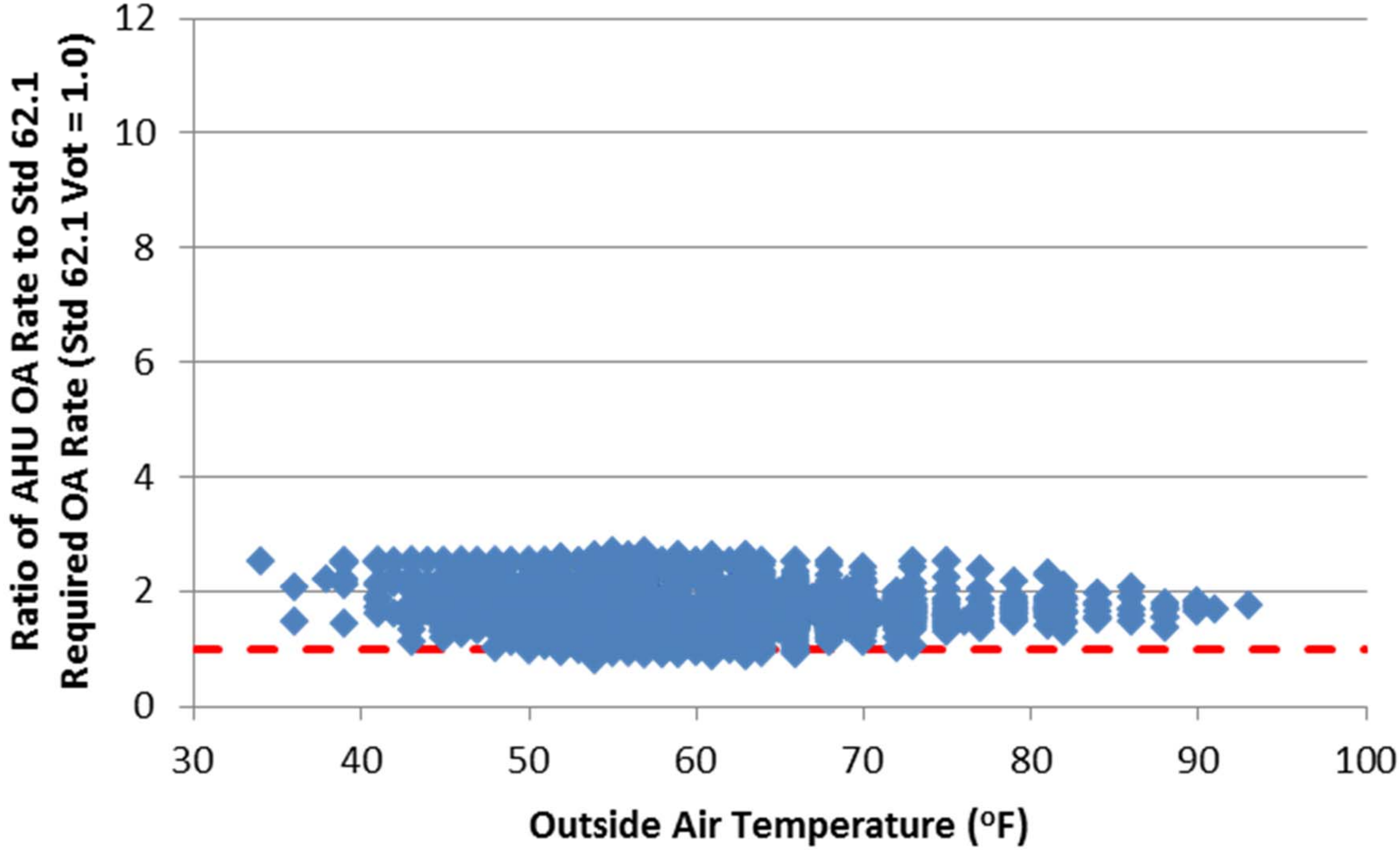
- **Heating Maximum:**
  1. No less than larger of:
     - Minimum
     - Limit stratification - ≤20°F SAT above space temperature (≤~90°F to 95°F)
  2. No more than 50% of cooling maximum
- **Always use Option 1 above**
  - **Do not use code maximum just because it's legal!**
  - **Avoid using %-of-cooling-maximum setpoints – boxes are usually oversized!**

What about Standard 62.1 Multiple Spaces compliance?



System with Outdoor Air Economizer

What about Standard 62.1 Multiple Spaces compliance?



System without Outdoor Air Economizer

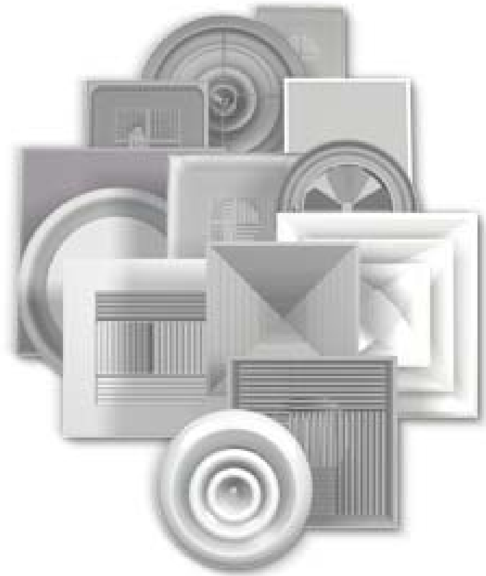
Ways to meet
Standard 62.1 with Dual Max Logic

- **Simple approach**
  - Minimum zone airflow rates should be no lower than ~0.15 cfm/ft^2
    - Or use simulations to determine minimums
    - Do not use 62.1 spreadsheet with conservative assumptions
  - CO_2 DCV should be used on all densely occupied spaces
    - Allows occupant OA component to be determined dynamically
    - Required by 90.1 and LEED anyway
  - Use outdoor air economizers
    - Increases ventilation in mild weather
- **Complex approach**
  - Use dynamic reset of zone minimums
  - To be discussed under Demand Controlled Ventilation later

How Well Does "Dual Max" Logic Work?

RP-1515 results…

RP 1515, "Thermal and Air Quality Acceptability in Buildings that Reduce Energy by Reducing Minimum Airflow from Overhead Diffusers"

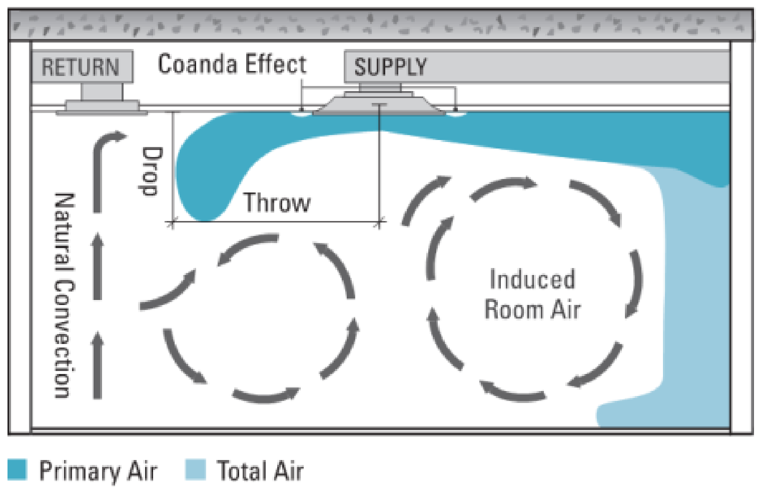


Objectives
- Measure energy savings & validate simulations
- Identify comfort issues that may occur at low flow

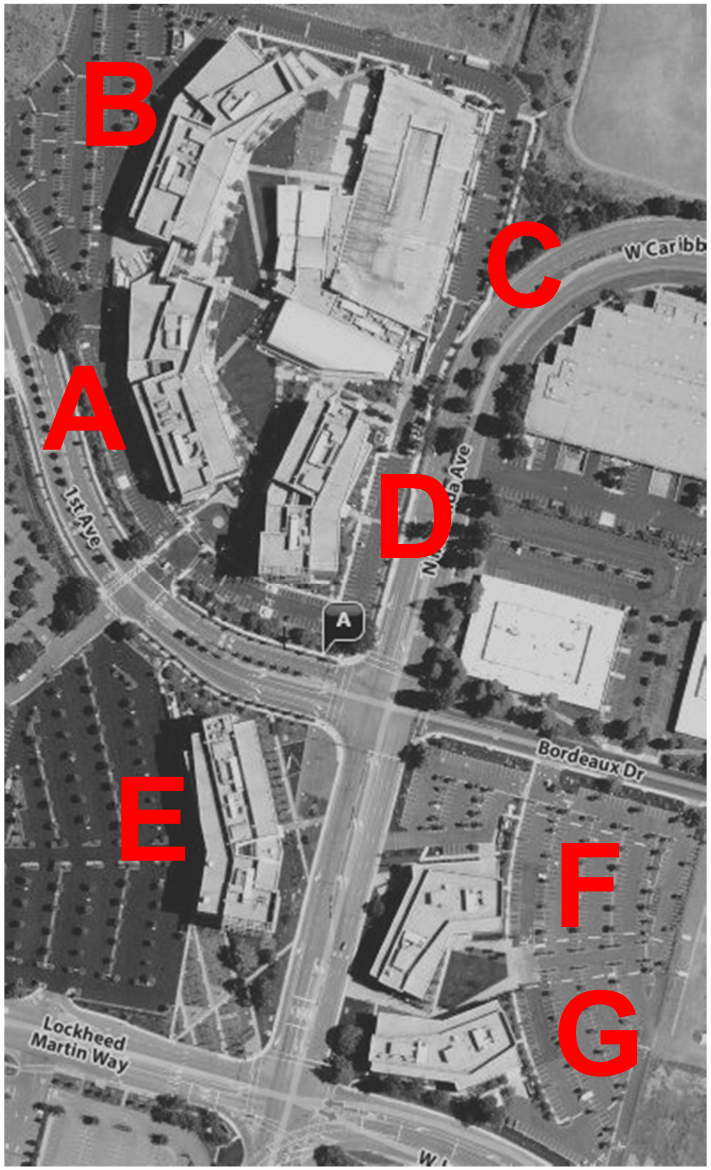
Funding
- California Energy Commission - PIER
- ASHRAE
- UC Berkeley - Center for the Built Environment

Research Team
- UC Berkeley
- Taylor Engineering
- Price Industries

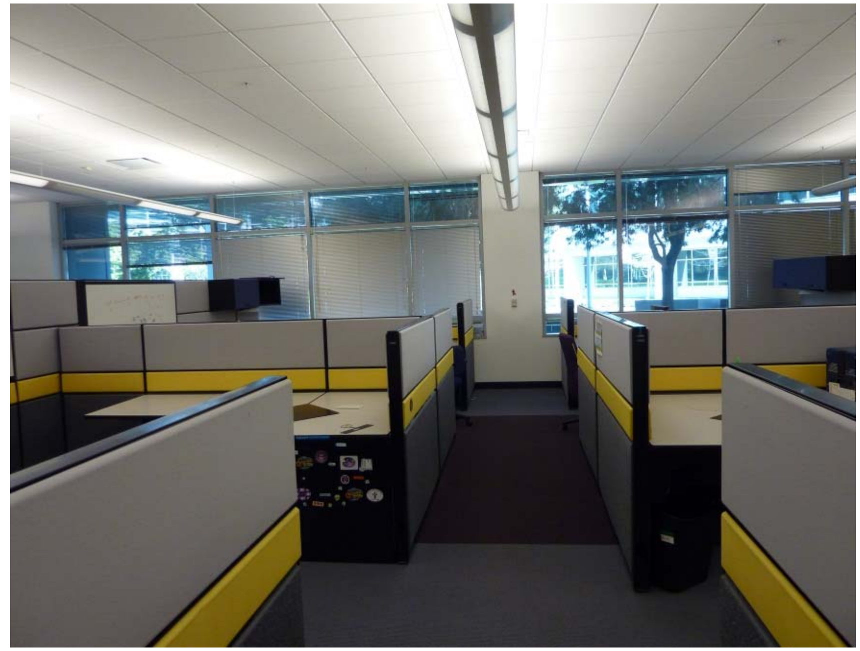
Method
- Field Study in 7 buildings
  - Background survey
  - "Right now" survey matched to zone trends
  - Energy monitoring
- Laboratory Study
  - Air distribution for various diffuser types

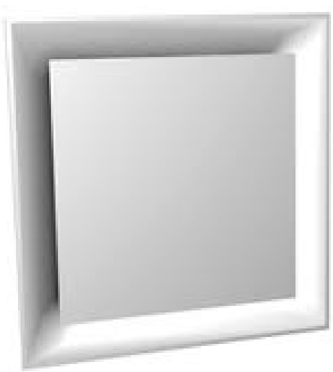


Yahoo! Sunnyvale Campus



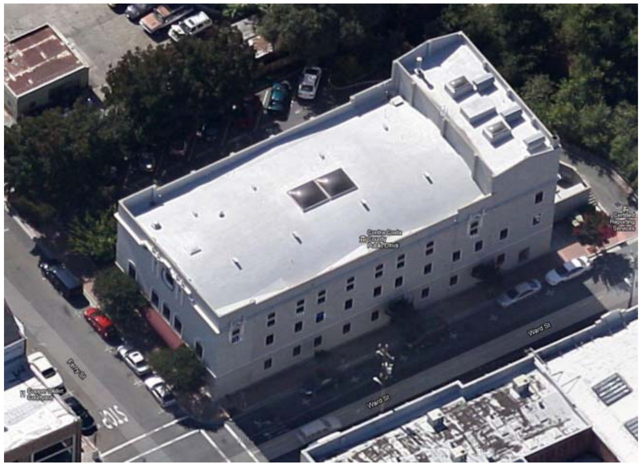
Yahoo! Sunnyvale Campus

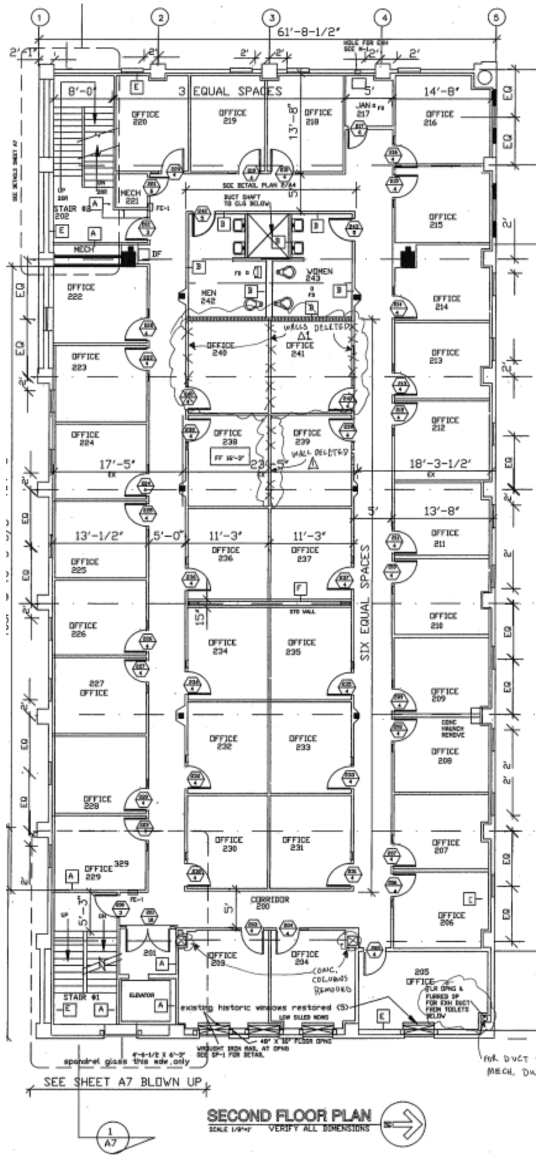


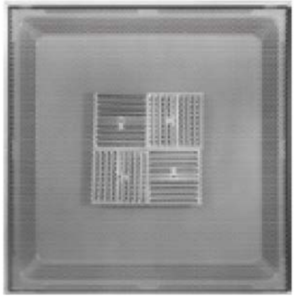


- 1073 Zones
- 3700 Occupants
- Plaque face diffusers

800 Ferry Building

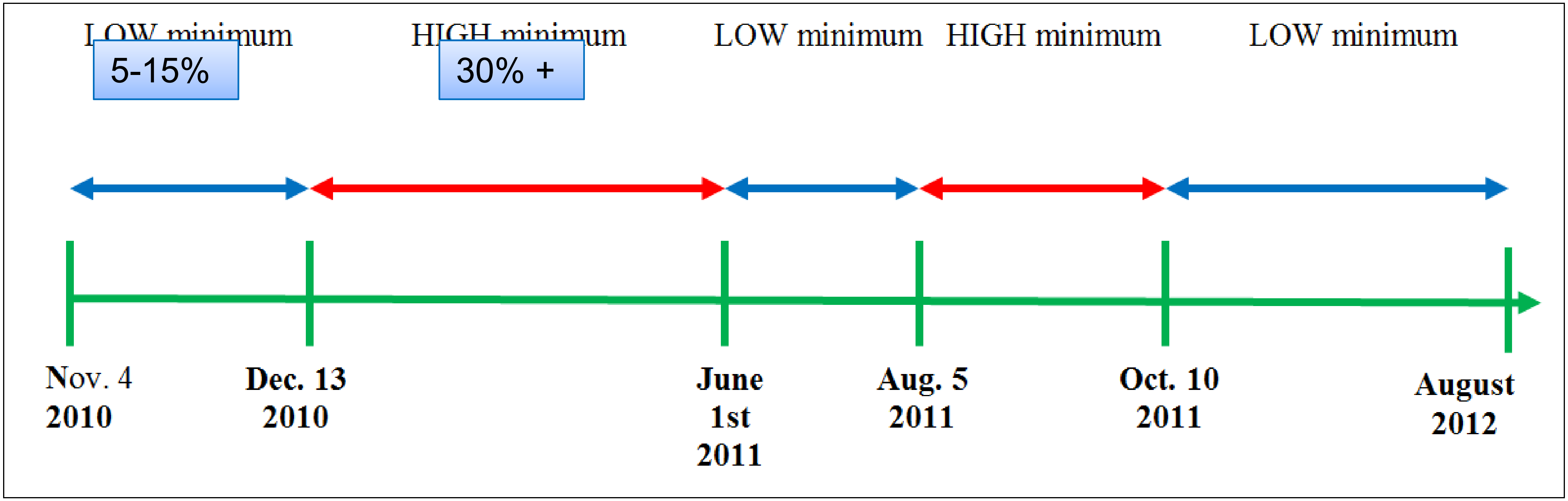






- 22 Zones
- Perforated Diffuser with blades in face

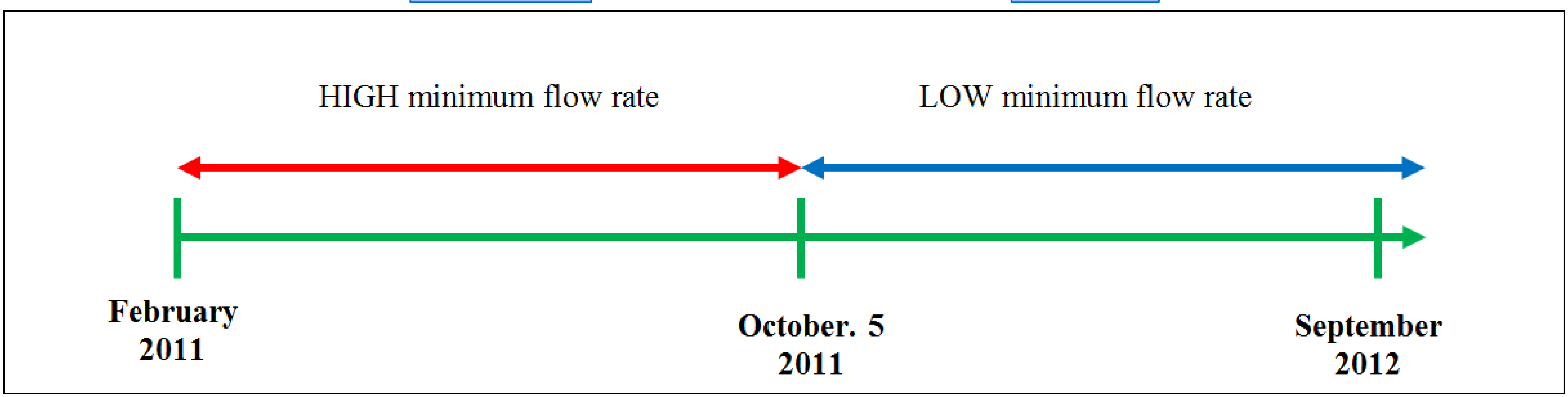
Yahoo! Building



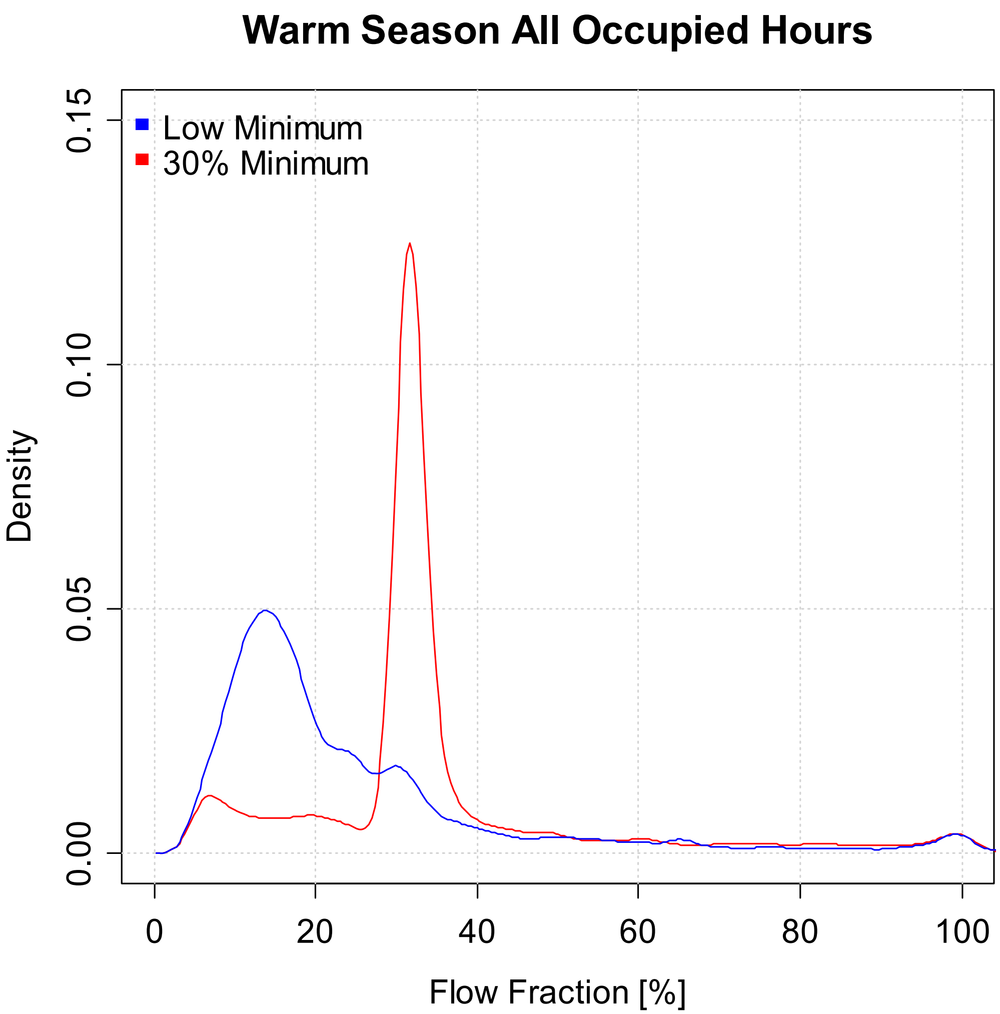
35-50%

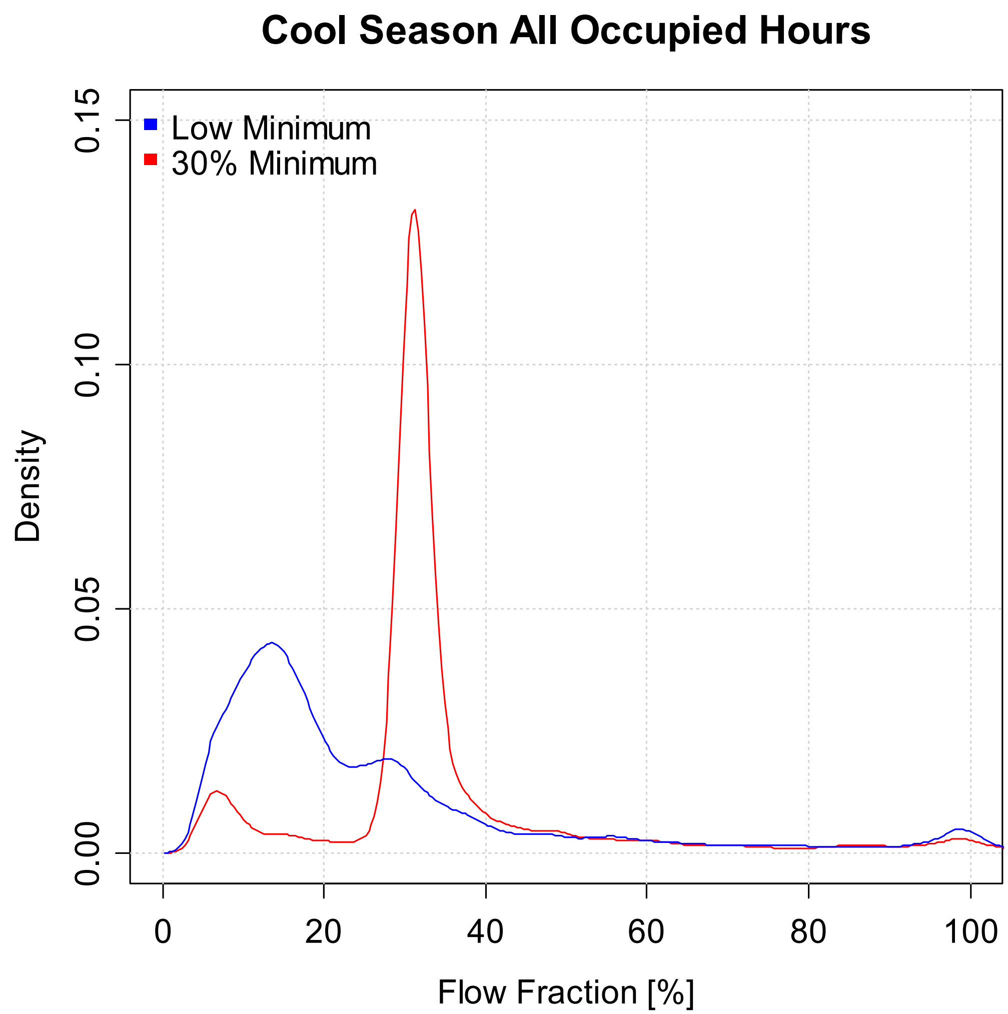
800 Ferry building

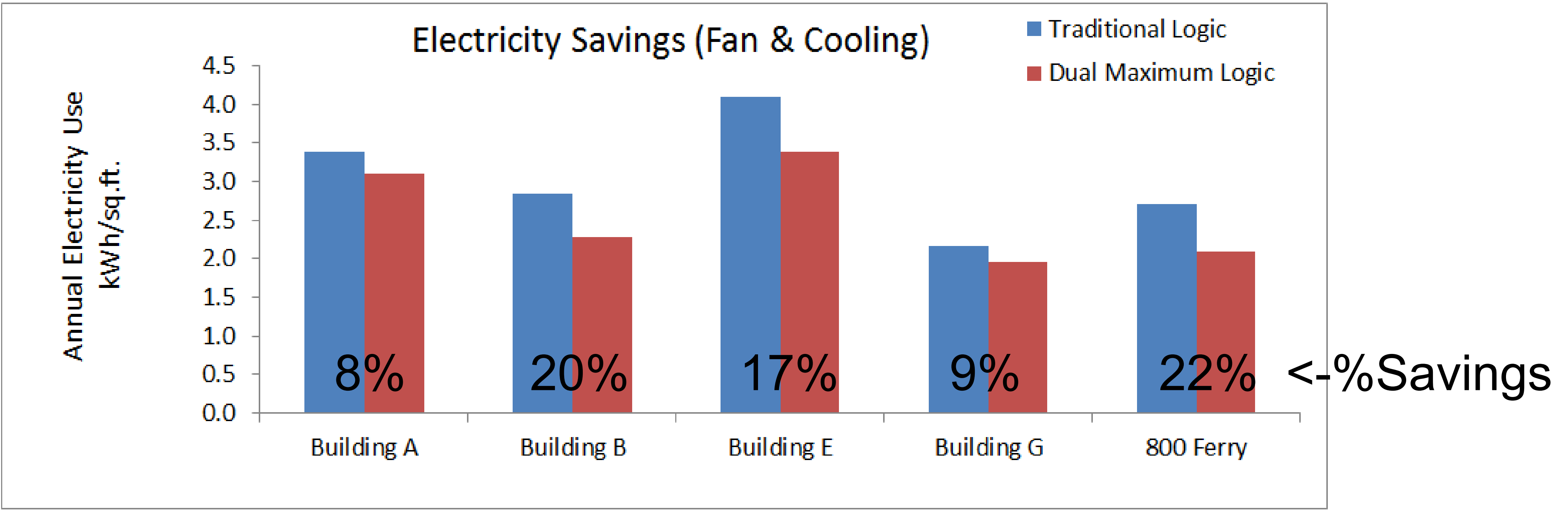
5-15%

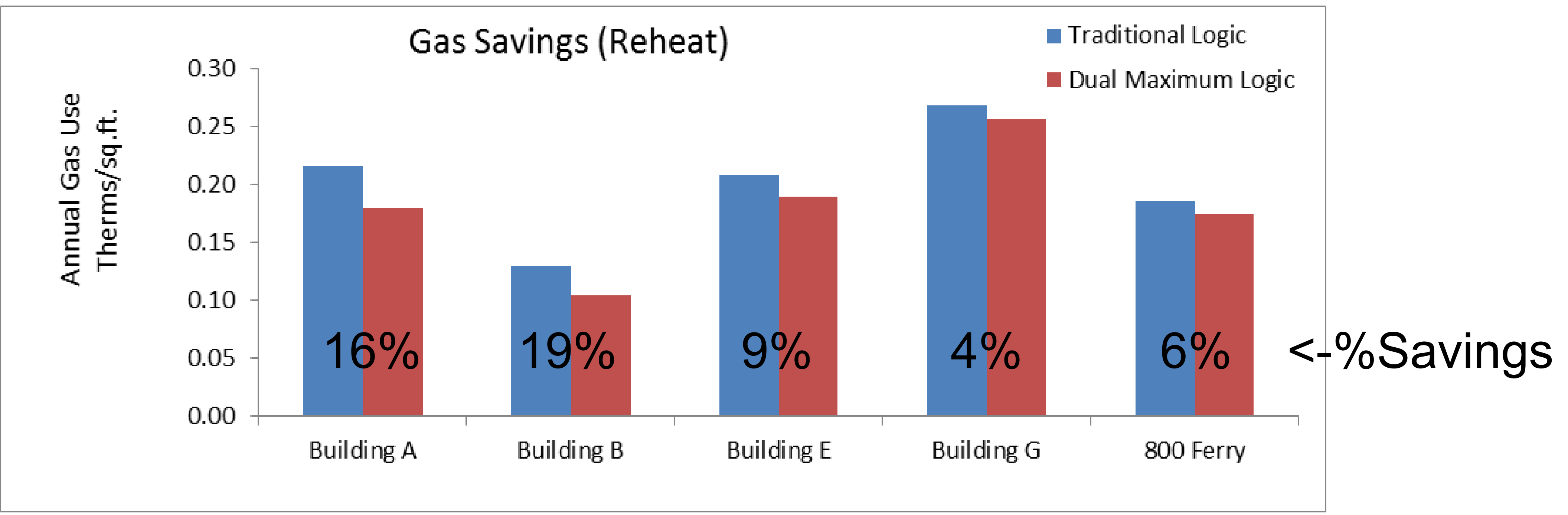


Measured flow fractions: Yahoo campus

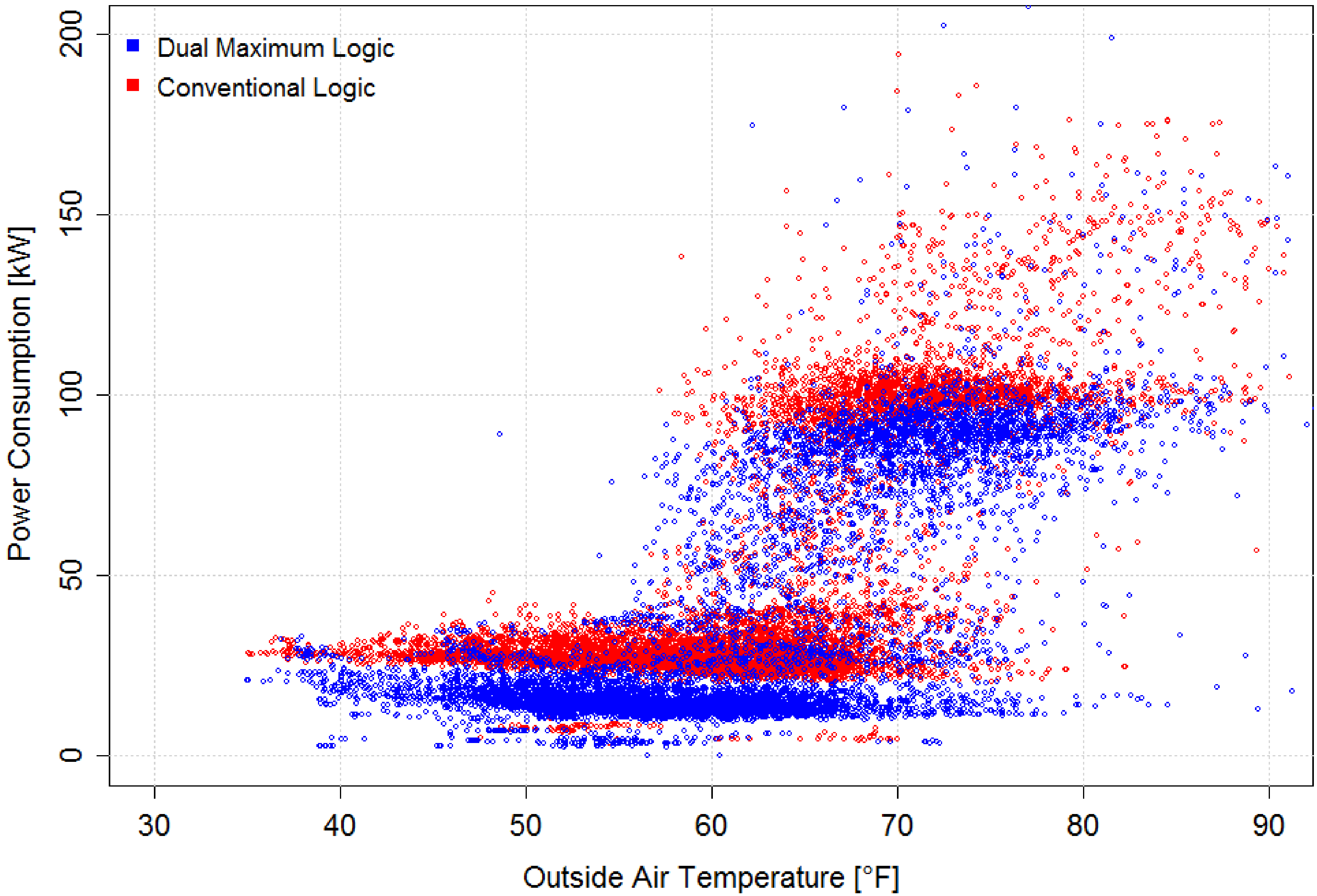




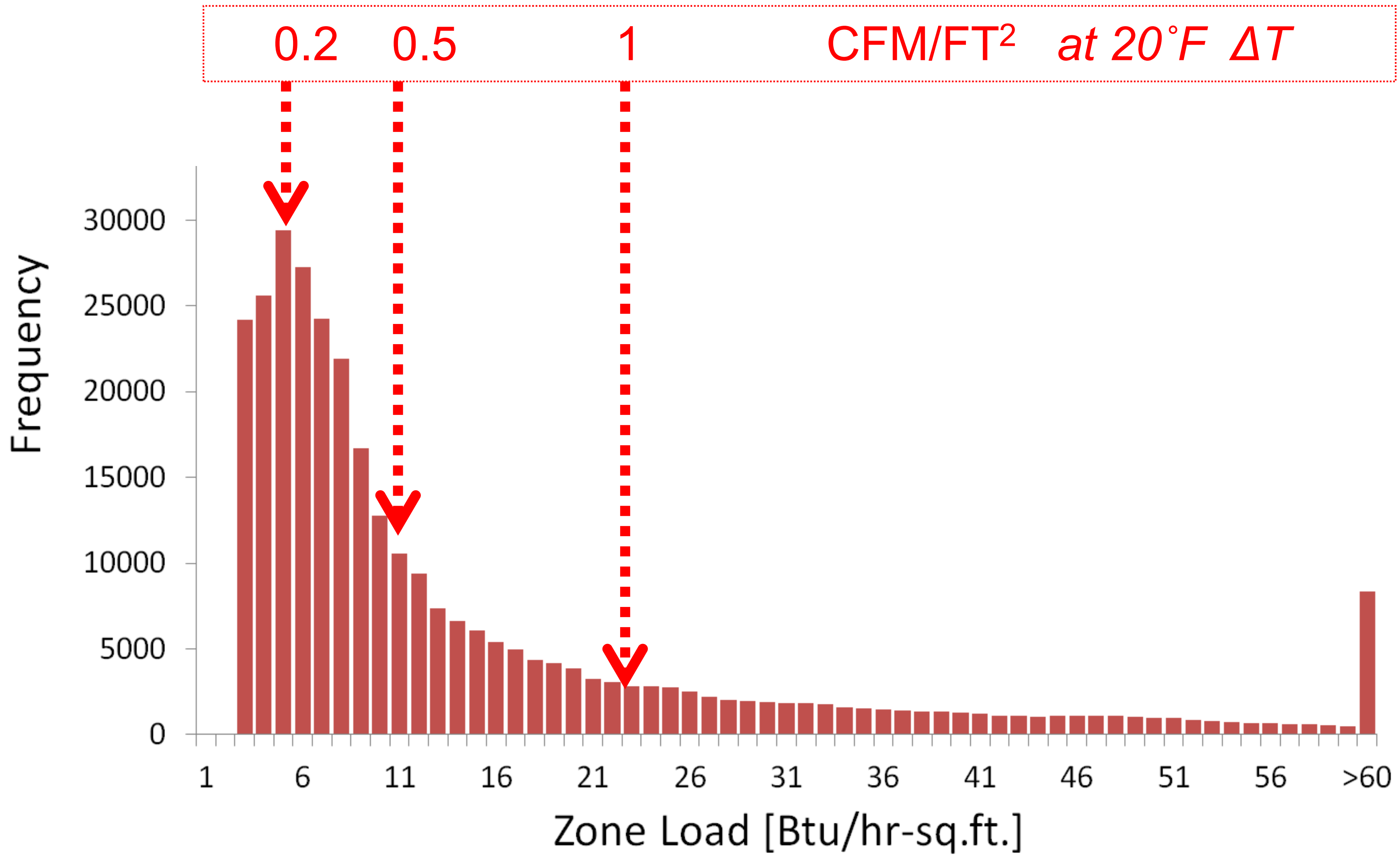

Electricity Savings (Fan & Cooling)
Traditional Logic
Dual Maximum Logic
Annual Electricity Use
kWh/sq.ft.
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
8%
20%
17%
9%
22%
<-%Savings
Building A
Building B
Building E
Building G
800 Ferry


Gas Savings (Reheat)
Traditional Logic
Dual Maximum Logic
Annual Gas Use
Therms/sq.ft.
0.30
0.25
0.20
0.15
0.10
0.05
0.00
16%
19%
9%
4%
6%
<-%Savings
Building A
Building B
Building E
Building G
800 Ferry

Total Electricity Usage

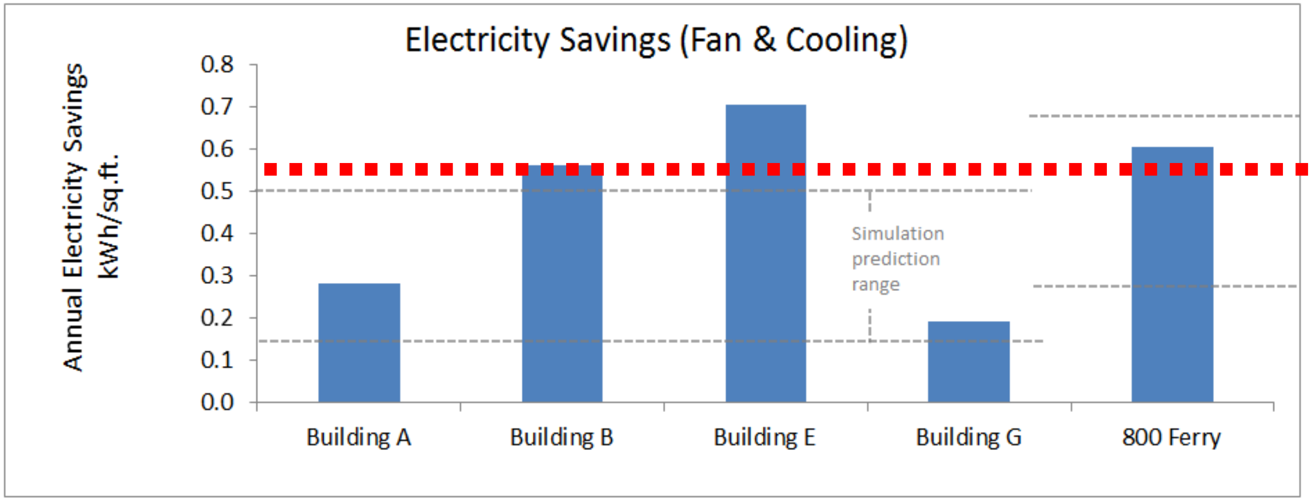


Loads are surprisingly low



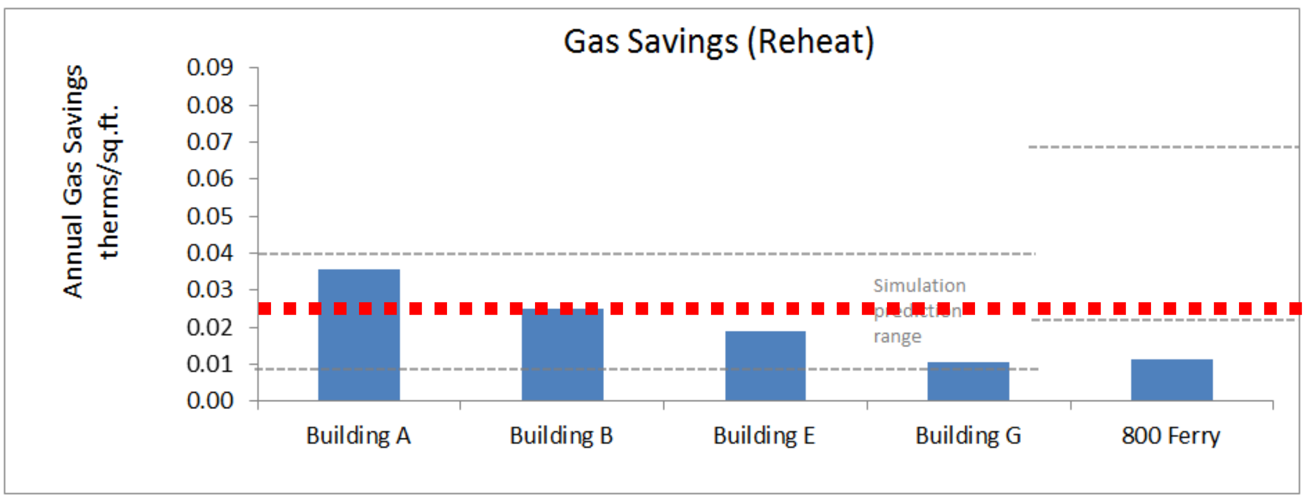
140 Zones, 2 buildings, 1 warm month (Sept)

What about your building?



$$0.55 \frac{kWh}{ft^2} \times \frac{\$0.12}{kWh} = \$0.066/ft^2$$

Total gas + elec savings $\approx \frac{\$0.10}{ft^2}$



$$0.025 \frac{therm}{ft^2} \times \frac{\$1.00}{therm} = \$0.025/ft^2$$

Occupant Comfort Survey

- **Questions**
  - When the low minimum flow rate is reduced from high to low:
  - Did occupants become less comfortable?
  - Was their sense of air movement stronger due to “dumping”?
- **Approach**
  - Surveyed 6 Yahoo! buildings and a county legal office (800 Ferry building)
  - 3 surveys: Yahoo warm and cool seasons, 800 Ferry building warm season
  - 3 – 4 weeks of surveying each season
  - Switched between high and low minimum operation in the middle of each survey period
  - Surveys administered 3 times/day
- **About 10,000 responses received**

Thermal comfort questions

Your thermal environment perception

---

1. How satisfied are you with your thermal comfort in your workspace right now?

Very satisfied ○ ○ ○ ○ ○ ○ ○ Very dissatisfied

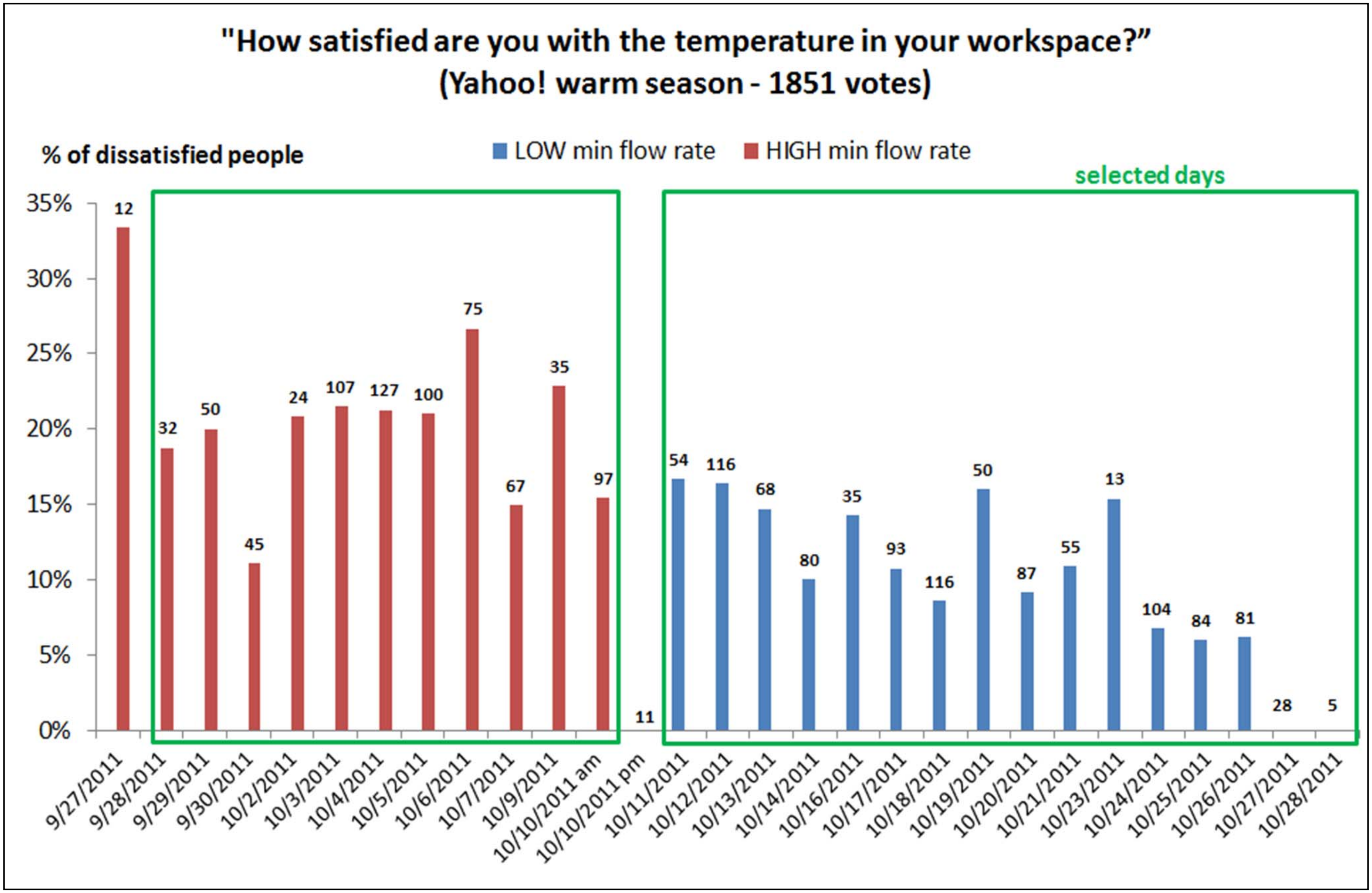
---

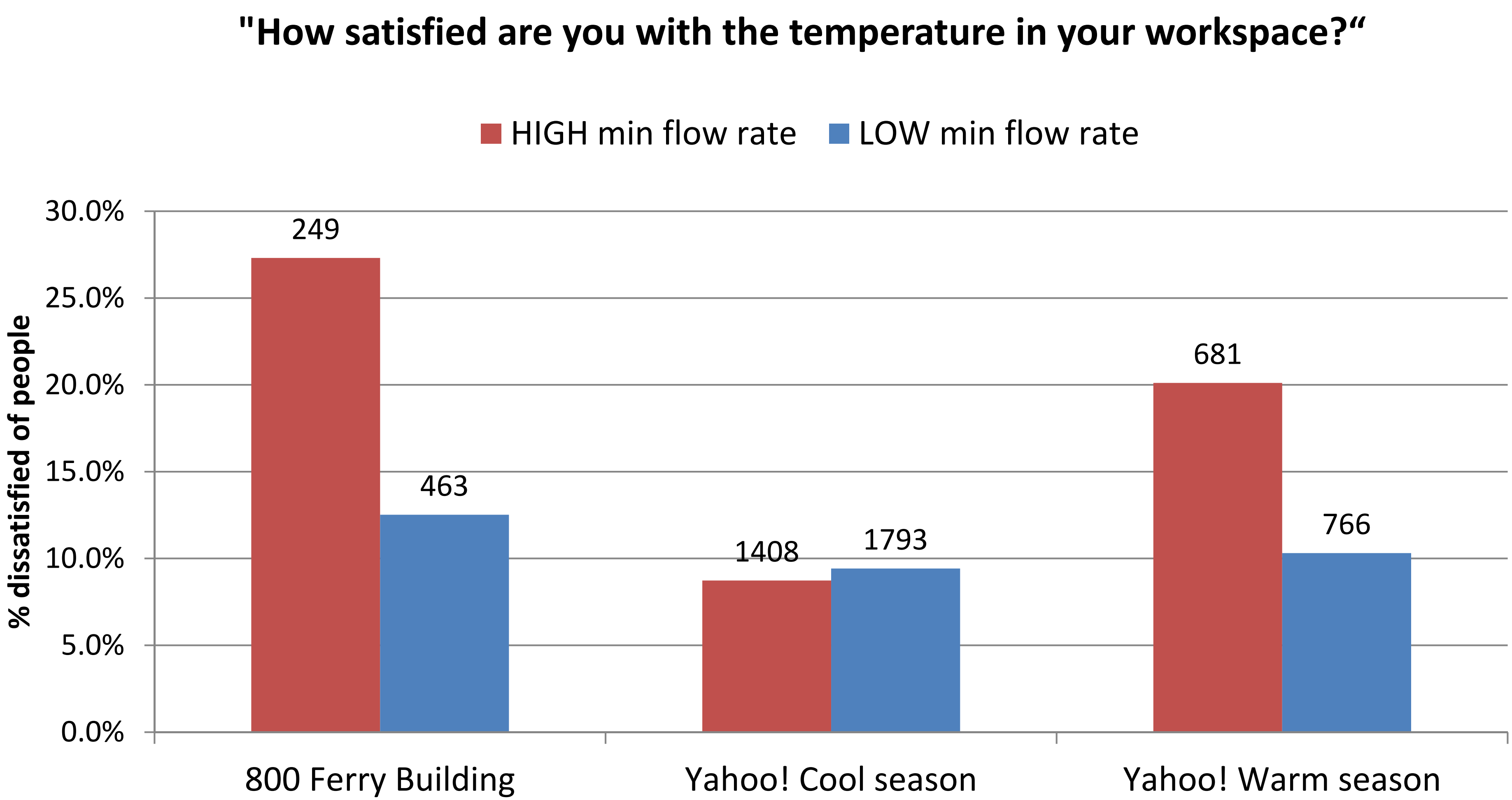
2. Overall, how would you rate your thermal sensation during the last few minutes?

- ○ Hot
- ○ Warm
- ○ Slightly warm
- ○ Neutral
- ○ Slightly cool
- ○ Cool
- ○ Cold

Continue >>

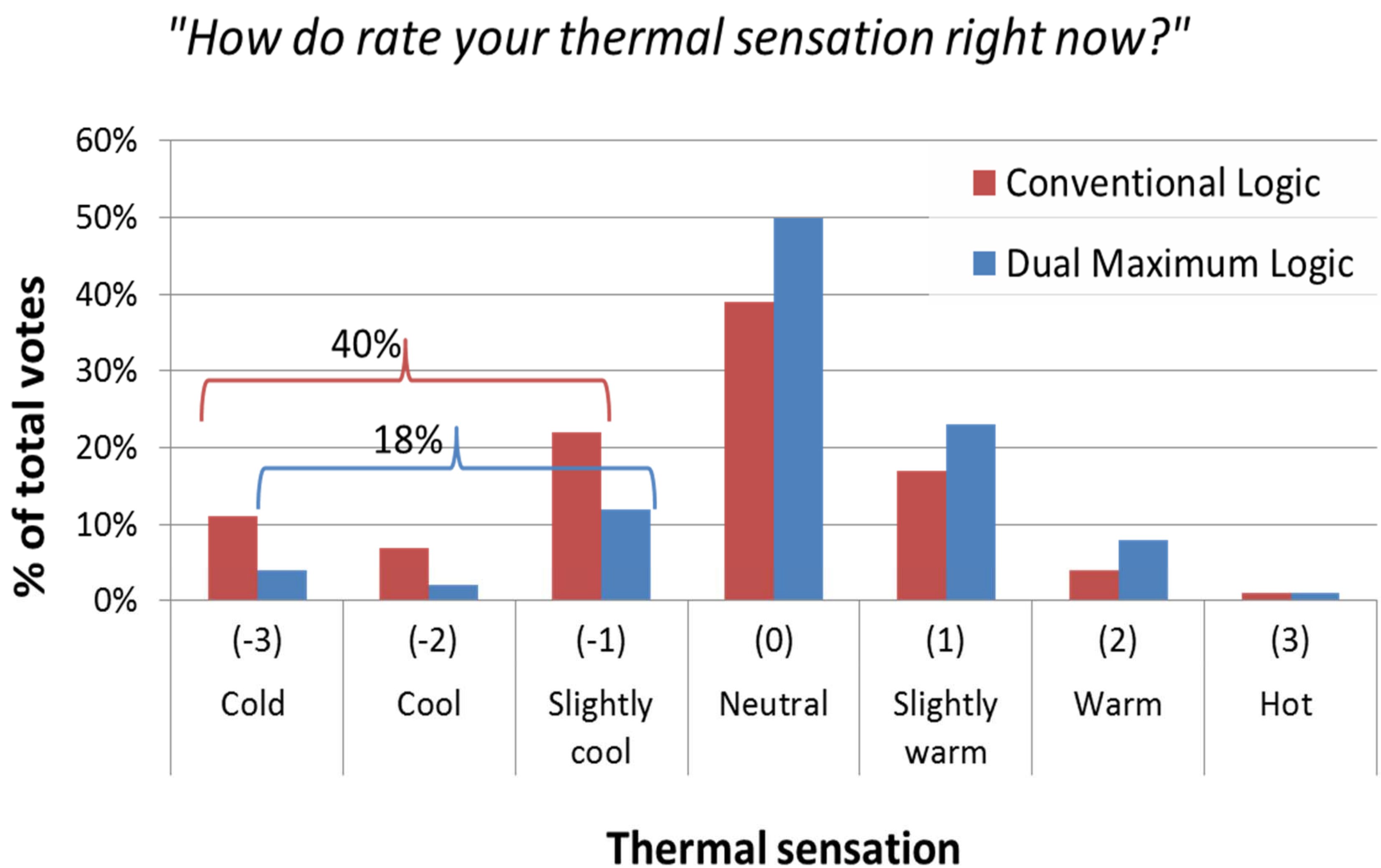
Temperature satisfaction survey results (an example: Yahoo! warm season)





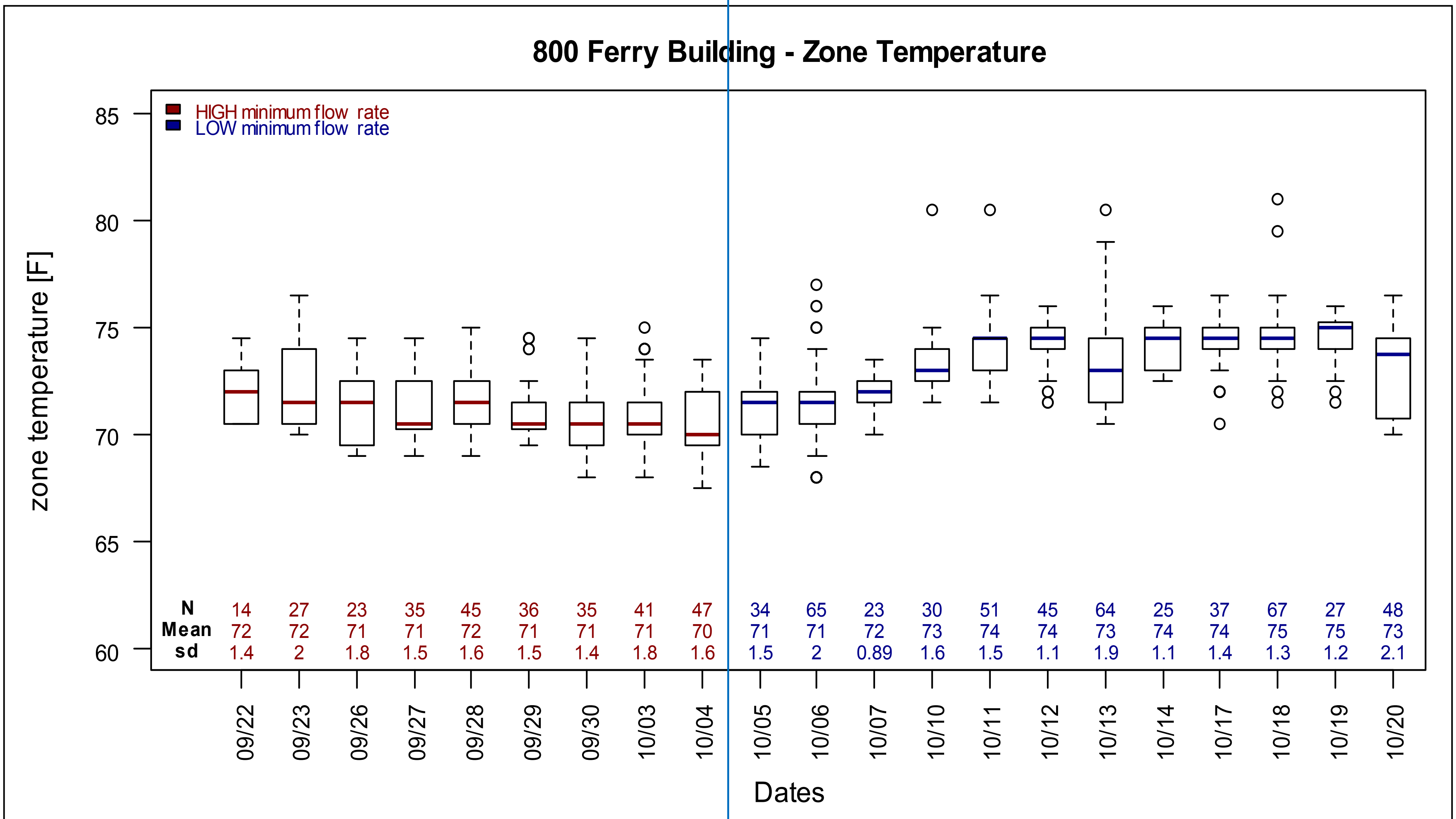
% Dissatisfied people	HIGH	LOW
800 Ferry Building	27.3%	12.5%
Yahoo! cool season	8.7%	9.4%
Yahoo! warm season	20.1%	10.3%

Thermal sensation distribution (Yahoo! warm season)



Zone air temperature under high and low minimum operations (800 Ferry building)

High minimum: average Tzone = 71.2ºF | Low minimum: average Tzone = 73.3ºF



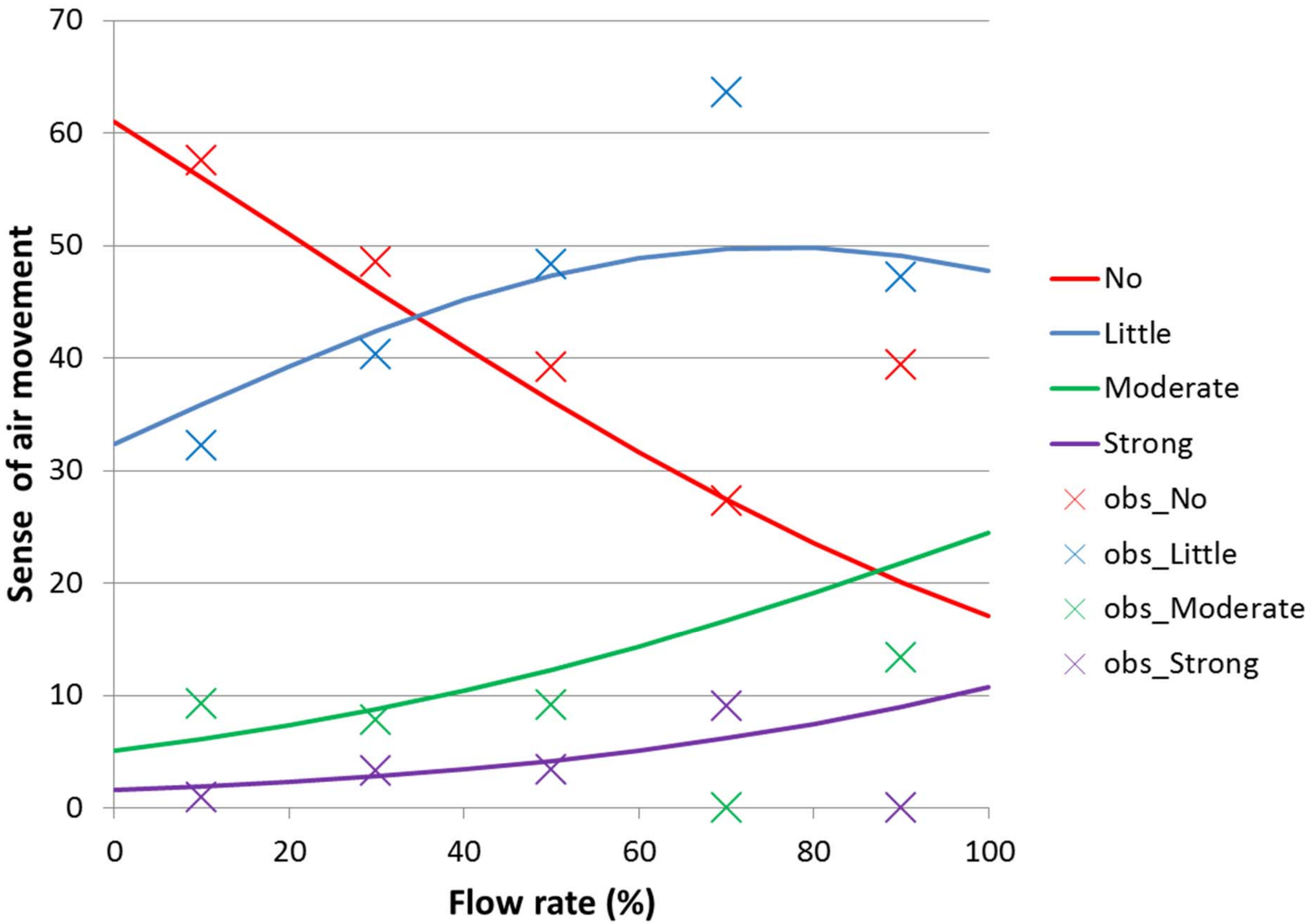
Occupant comments about summer over-cooling (800 Ferry building, high minimum operation)

Sept. 24 4 PM	**“Just cold! I have to out on a heater.”**
Sept. 24 2 PM	“I often come into my office and immediately put on a sweater because it is too cold for me. I dont have the sweater right now which is why I feel cold.”
Sept. 24 2 PM	**“I find that as the day progresses, my floor (the third of three floors) gets colder due to the air conditioner.”**
Sept. 24 2 PM	“I noticed right after lunch, I was extremely cold, but maybe because I had just eaten.”
Sept. 27 11 AM	“Its cold! Ill turn on my heater...”
Sept. 27 1:30 PM	“Its cold! Ill turn on my heater...”
Sept. 27 3 PM	“In the morning the office temp is good, but by 2:30 it starts to cool down when the sun moves away from the window.”
Sept. 28 7:30 AM	“I don’t feel the direct air flow but it is for sure cold in here always.”
Sept. 28 10 AM	“Now that this survey requires me to focus attention on my work environment several times a day, it is clear to me that my environment starts out in the morning just right. It gets progressively colder and less comfortable during the course of the day.”
Sept. 28 10:10 AM	“Very cold I’m moving around the office more and I feel more air movement then I felt just sitting down.”
Sept. 28 11:40 AM	“Very cold!”
Sept. 28 3 PM	“LITTLE MORE AIR CONDITIONED.”
Sept. 29 11:30 AM	“Its just cold all the time!”
Sept. 29 12:45 PM	“You should send this survey on Monday when its going to be freezing in this building.”
Oct. 3 10 AM	“Please help my office because it is always cold....”
Oct. 3 12:15 PM	“Cold in here.”
Oct. 3 1:30 PM	“Cold, Cold, Cold!!!!!”
Oct. 4 8:40 AM	“its cold in here. They need to turn on the heat.”
Oct. 4 10 AM	“cold in here. Turn on some heat.”
Oct. 4 11:50 AM	“cold.”
Oct. 4 11:54 AM	“cold. Need heat.”
Oct. 4, 12:10 PM	**“warmer on cold days, cooler on hot days.”**
Oct. 4 3:30 PM	“my arms are cold too, but there wasn’t a check for that.”

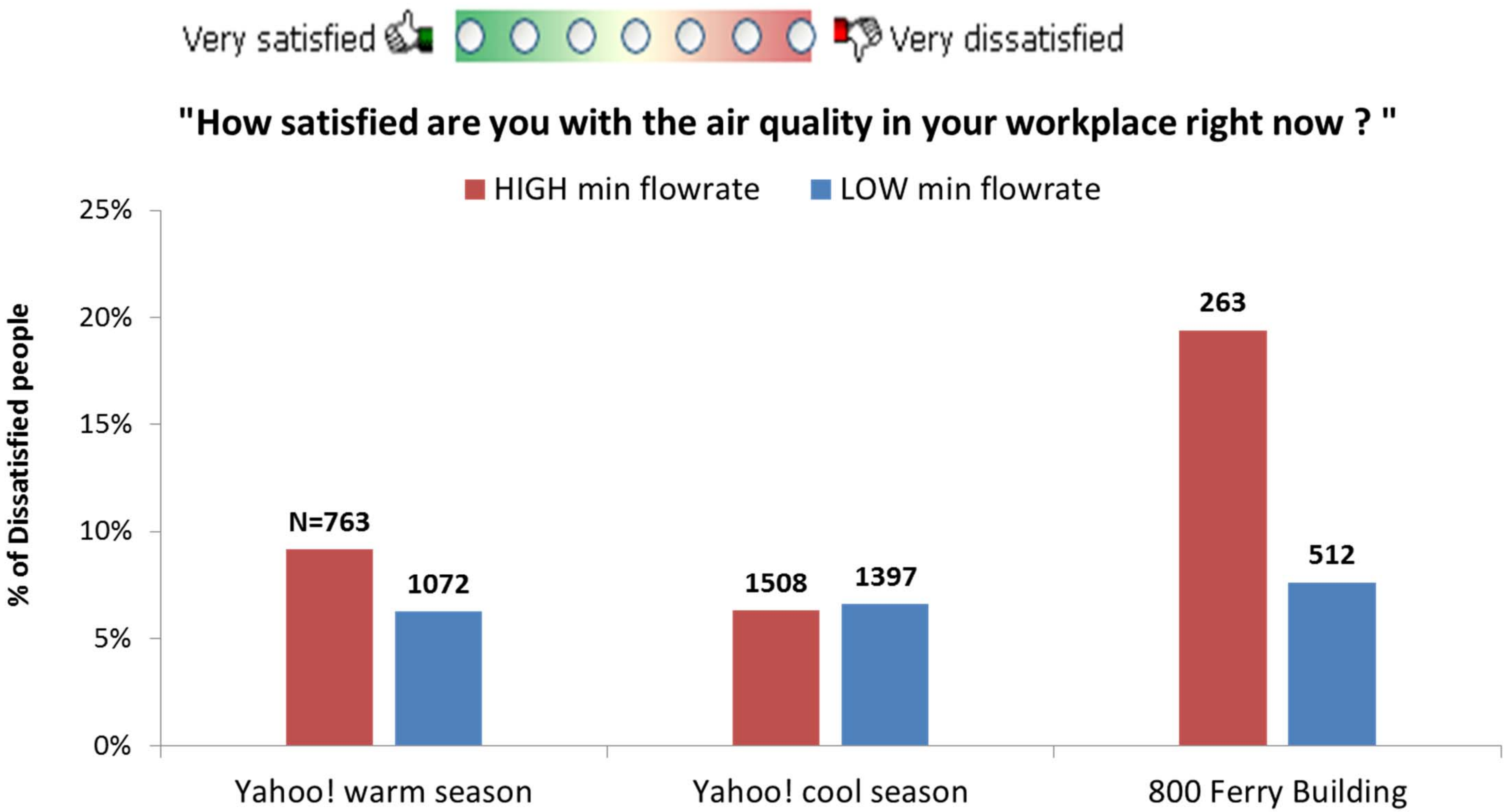
Occupant comments about summer over-cooling (800 Ferry building, low minimum operation)

Oct .7 3 :00PM	"There is less background noise in my office this afternoon. It is great!" (noise complaints were often referred to as HVAC noise)
Oct. 10 11:32 AM	"feels good today. They County must have turned on the heat."
Oct. 10 3:30 PM	"I definitely notice a difference in the noise level in my office. I hardly hear it all. Thank you if you have had anything changed!!"
Oct. 11 2:30 PM	"Office is just right today!"
Oct. 12 10:20AM	"the temperature and noise control is perfect."
Oct. 12 5:20 PM	"I love the air temp. It is warm and not cold (AC on in the winter) like it normally is.".
Oct. 13 11:00 AM	"Warm in here today. its nice outside so it is nice inside."
Oct. 13 2:26 PM	"nice day. wish they were all like this."
Oct. 14 2:44 PM	"The temp is perfect!"
Oct .19 4:40 PM	"Just right!"
Oct. 19 4:50 PM	"Great!"
Oct. 20 12:33 PM	"nice day today, which makes it warm in the building."
Oct. 20 2:30 PM	"Kinda cool outside now, but the office feels really good. Thank you!"
Oct. 20 2:30 PM	**"Thanks for your involvement. I have definitely noticed an improvement in my office environment."**

Sense of air movement (800 Ferry building)

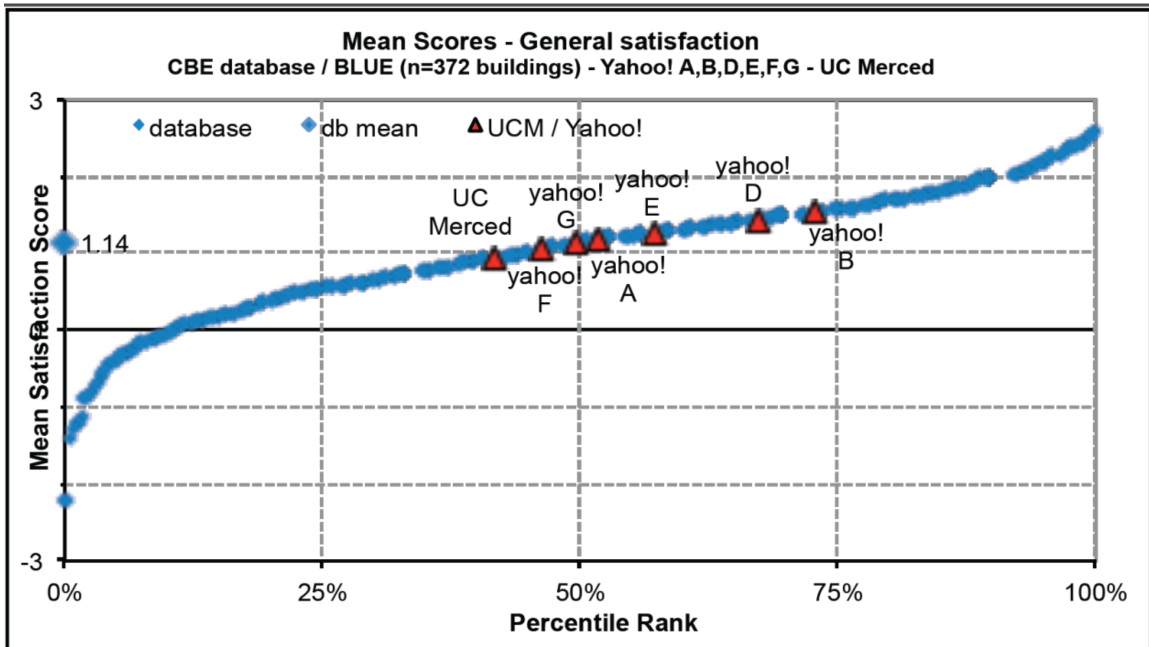


Perceived air quality (three surveys)

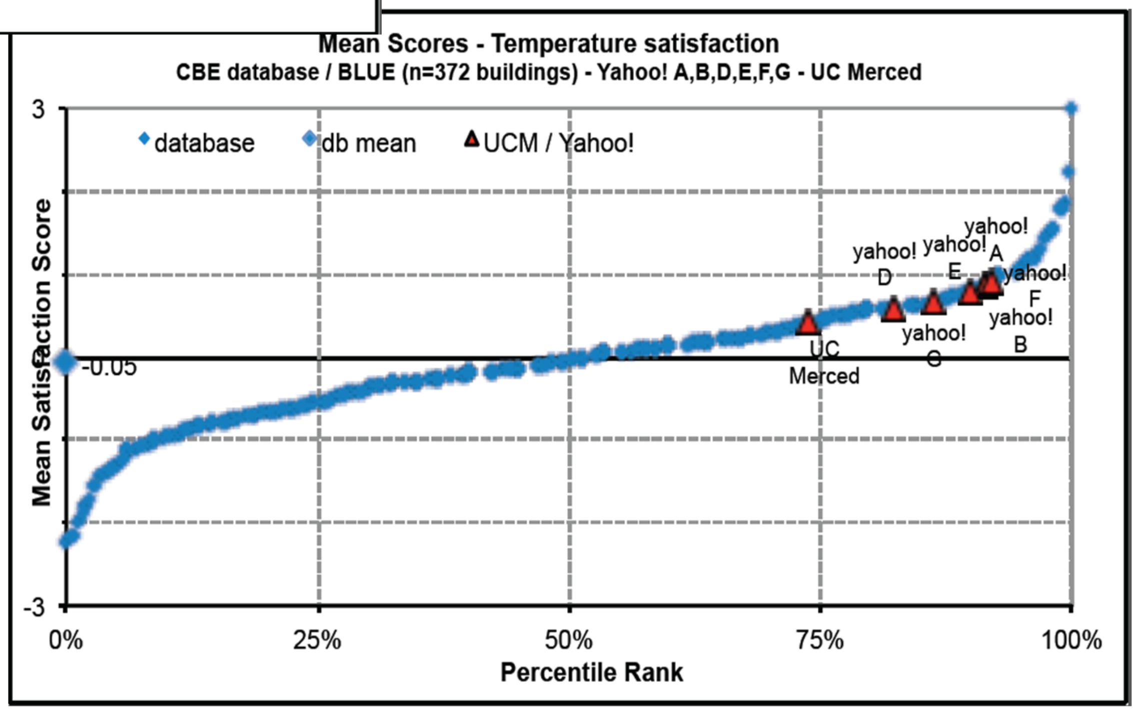


CBE background survey results

Comparison with CBE database

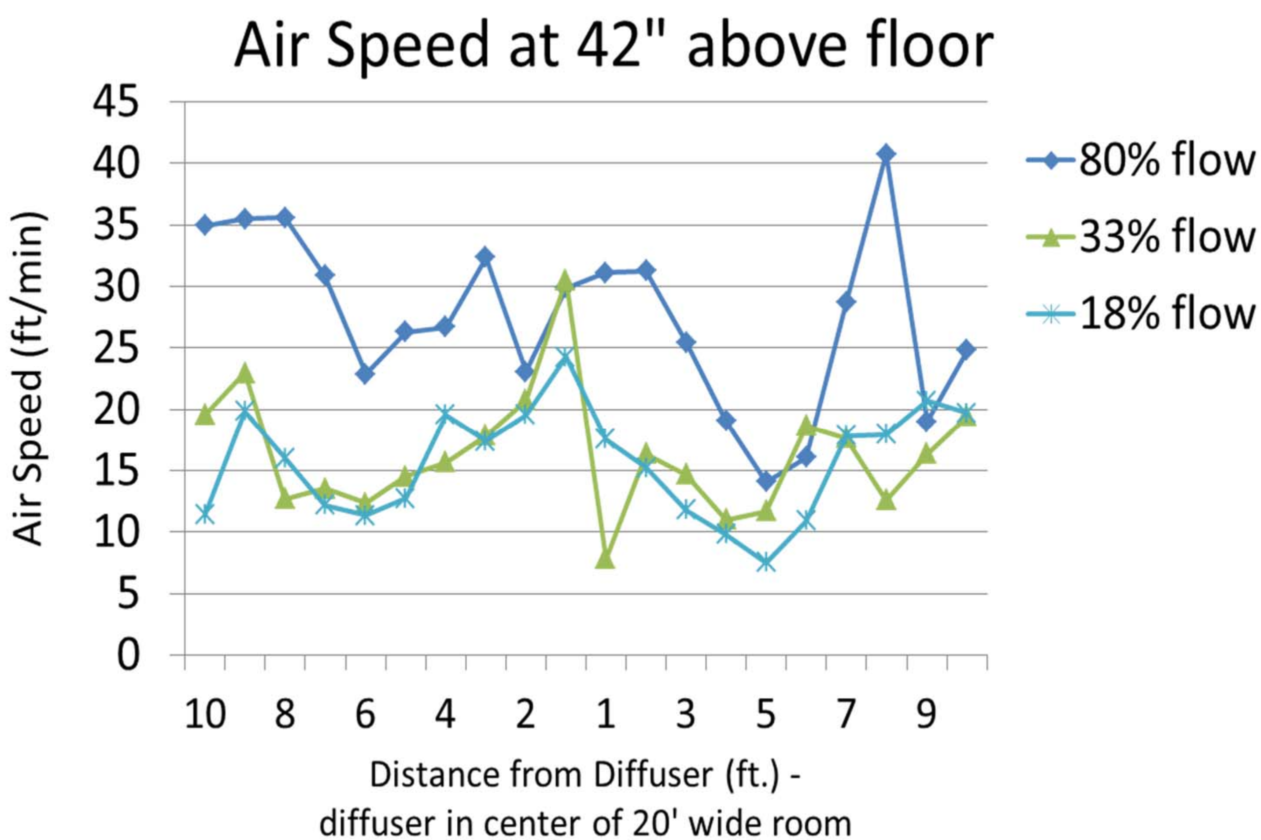


General Satisfaction



Temperature Satisfaction

Price Lab Tests



Perforated diffusers with blades in the neck Diffuser located in center of 20 ft. wide room, Cooling Mode.

Results:

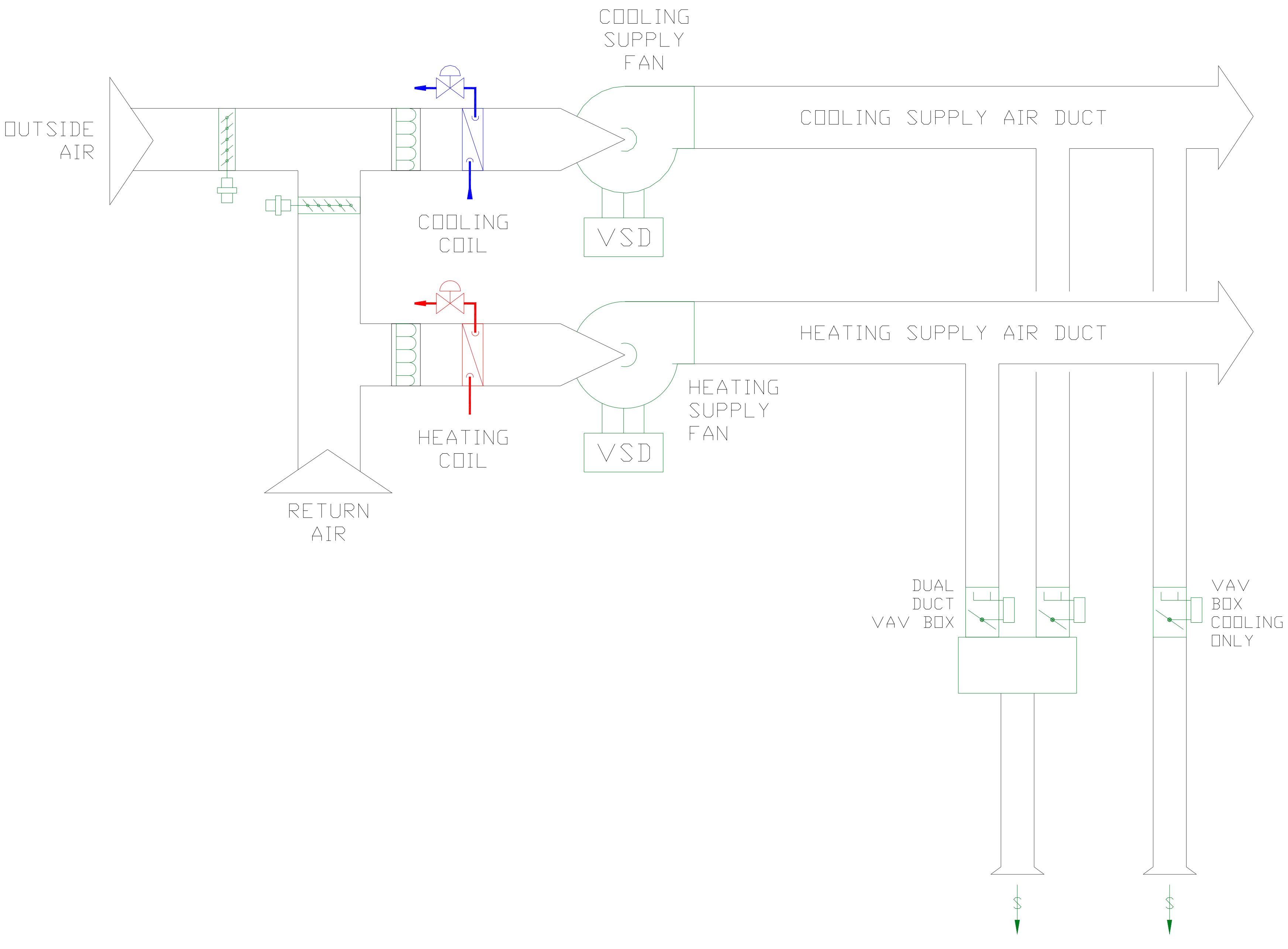
- Negligible impact on ADPI – all near 1
- Negligible impact on ACE – all near 1

RP 1515 Conclusions

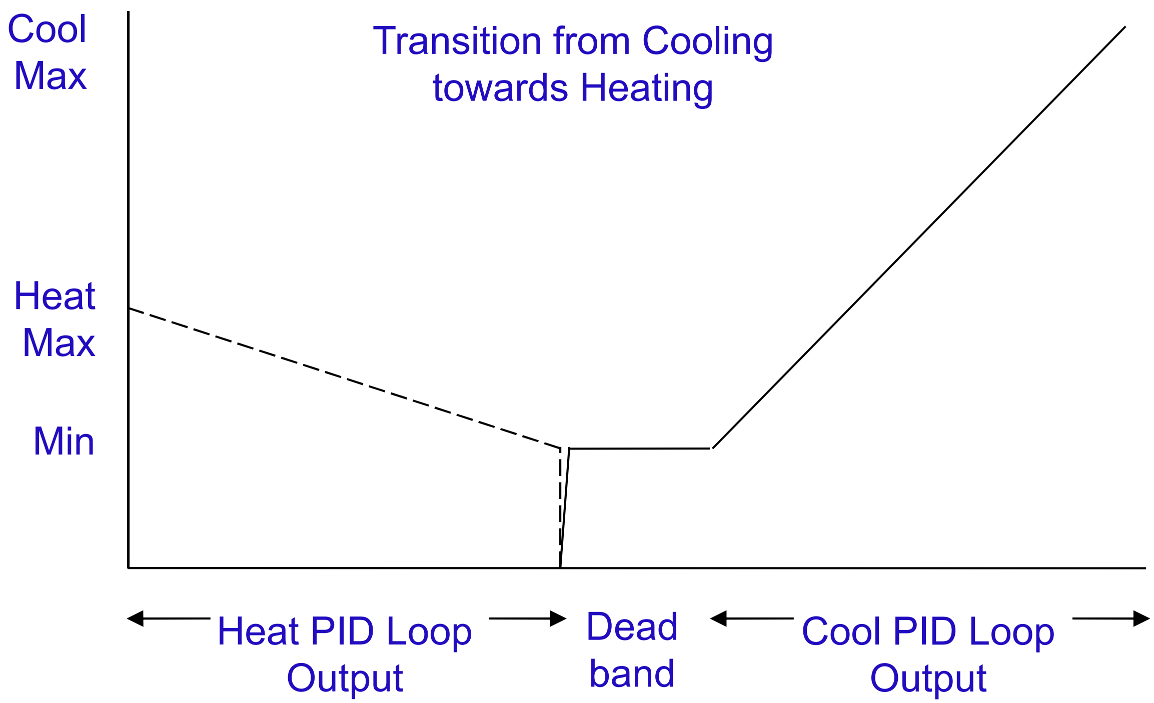
Conclusions

- Counter to they original hypothesis, comfort improves rather than gets worse with low flow operation
- Dumping & draft are not an issue at low flow
- Energy savings is significant and similar to simulation predictions

Dual Fan Dual Duct



Dual Duct Snap Acting Controls



- Works with either a single VP sensor at discharge or one at each inlet
- Eliminates need for mixing plenum since airflows do not mix
- Reduces mixing losses – space serves as slow acting mixing plenum
- Cannot work when high minimum airflow rates are needed

Off-hour Isolation (aka Zone Groups)

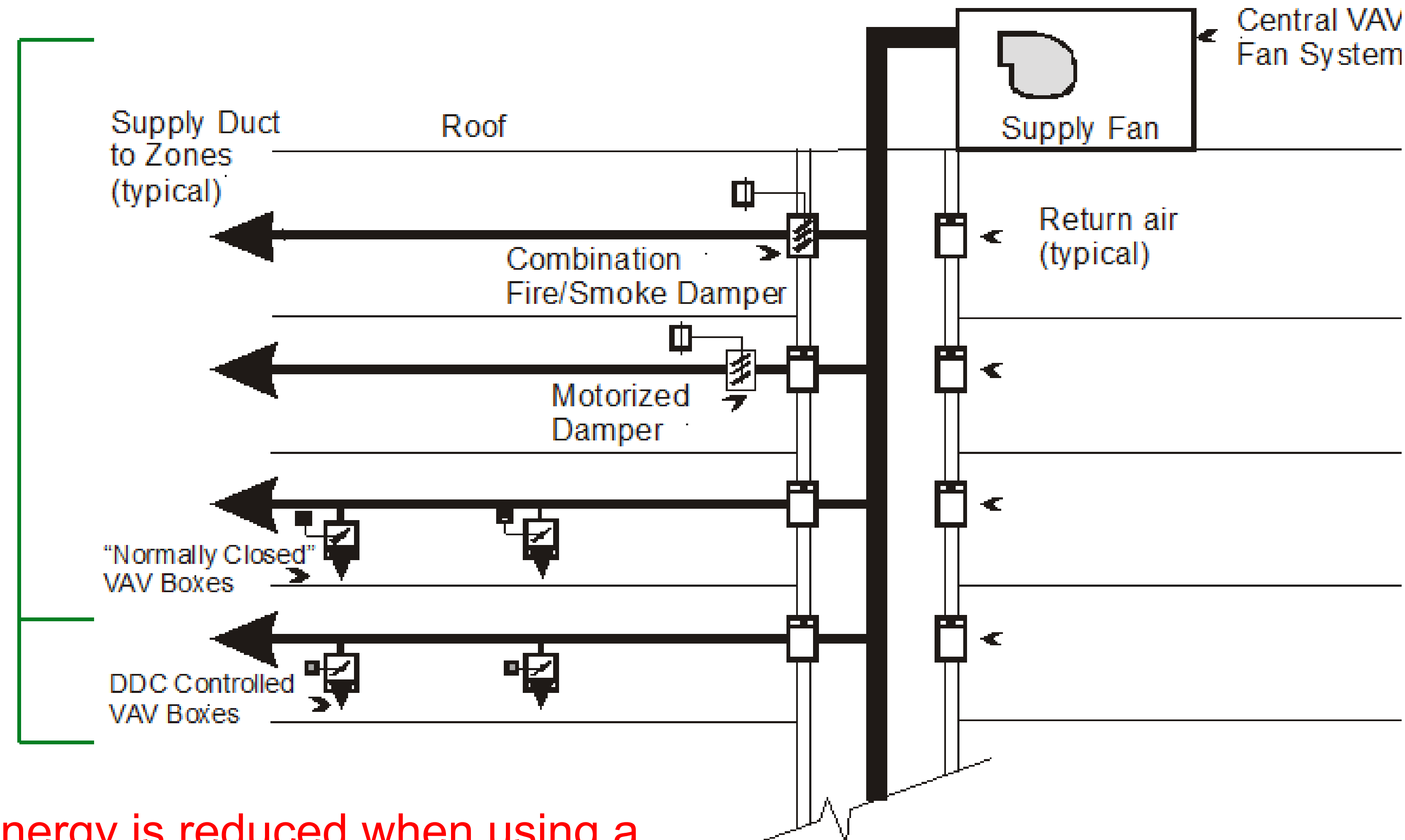
- **Large systems must be broken into isolation areas.**
  - Areas no larger than 1 story nor >25,000 ft2
  - Each area to have individual automatic off-hour controls (e.g. timeclock schedule) to allow area to operate independent of other areas
  - Central systems must be capable of stable operation with one zone operating

4-58

Isolation Area (Zone Groups) Example

Old Methods

Current Approach



Fan energy is reduced when using a central system to serve a zone-group rather than individual system!

4-59

Supply Air System

Zone Based Resets

"Trim & Respond" Reset Logic

Variable	Definition
SP_0	Initial setpoint
SP_{min}	Minimum setpoint
SP_{max}	Maximum setpoint
T_d	Delay timer
T	Time step
I	Number of ignored requests
R	Number of requests from zones/systems
SP_{trim}	Trim amount
SP_{res}	Respond amount
$SP_{res\text{-}max}$	Maximum response per time interval

"Trim & Respond" Reset Logic

Trim & Respond logic shall reset setpoint within the range SP_{min} to SP_{max}. When the associated device (e.g. fan, pump) is off, the setpoint shall be SP_0. The reset logic shall be active while the associated device is proven on, starting T_d after initial device start command. When active, every time step T, trim the setpoint by SP_{trim}. If there are more than I Requests, respond by changing the setpoint by SP_{res} times (R – I), i.e. (the number of Requests minus the number of Ignored requests). But the net response shall be no more than $SP_{res\text{-}max}$. The sign of SP_{trim} must be the opposite of SP_{res} and $SP_{res\text{-}max}$. For example, if SP_{trim} = -0.1, SP_{res} = +0.15, $SP_{res\text{-}max}$ = +0.35, R = 3, I = 2, then each time step, the setpoint change = -0.1 + (3-2)*0.15 = +0.05. If R=10, then setpoint change = -0.1 + (10-2)*0.15 = 1.1 but limited to a maximum of 0.35. If R≤2, the setpoint change is -0.1.

Basic Idea: Keep trimming the setpoint until zones "request" a response

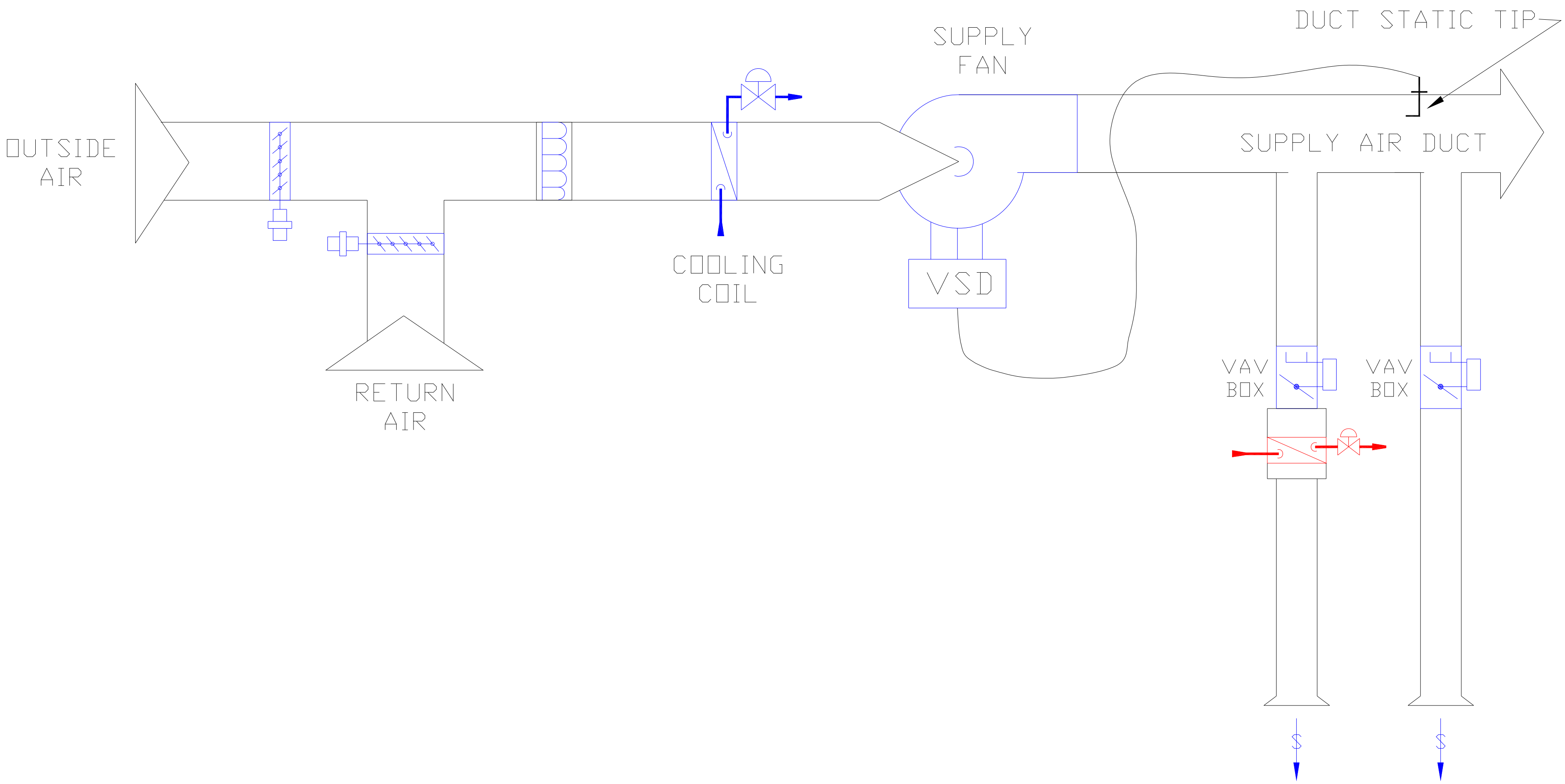
Zone "Requests"

- **Typical "Requests"**
  - If the Loop is less than 85%, send 0 requests.
  - If the Loop is greater than 95%, send 1 request.
- **Importance Multiplier (IM)**
  - Multiply zone requests by IM
    - Set manually by user
    - Default IM = 1
  - Allows "rogues" zones to be ignored (IM=0)
  - Allows critical zones to increase response non-proportionally
- **Request-Hours**
  - Integral of requests over time
  - %-request-hours displayed on graphics
  - Used to identify rogue zones

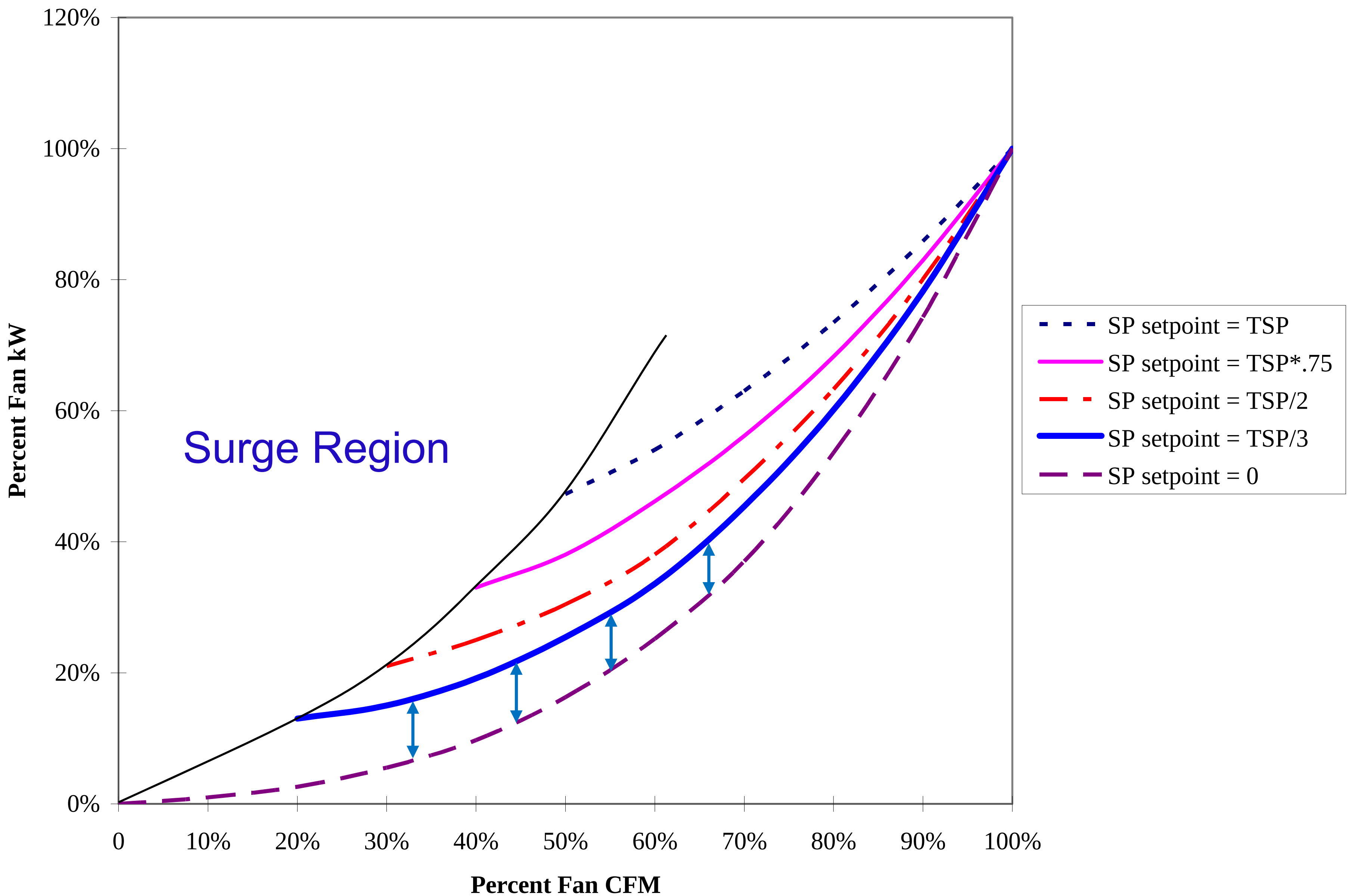
Trim & Respond vs. PID Loop

- **Advantages**
  - Easier to tune
  - Can “respond” more quickly than “trim”
  - Easier to ignore “rogue” zones
  - Reduced network traffic
  - “Requests” can also be generated by alarms and other metrics and increased/decreased by Importance Multiplier

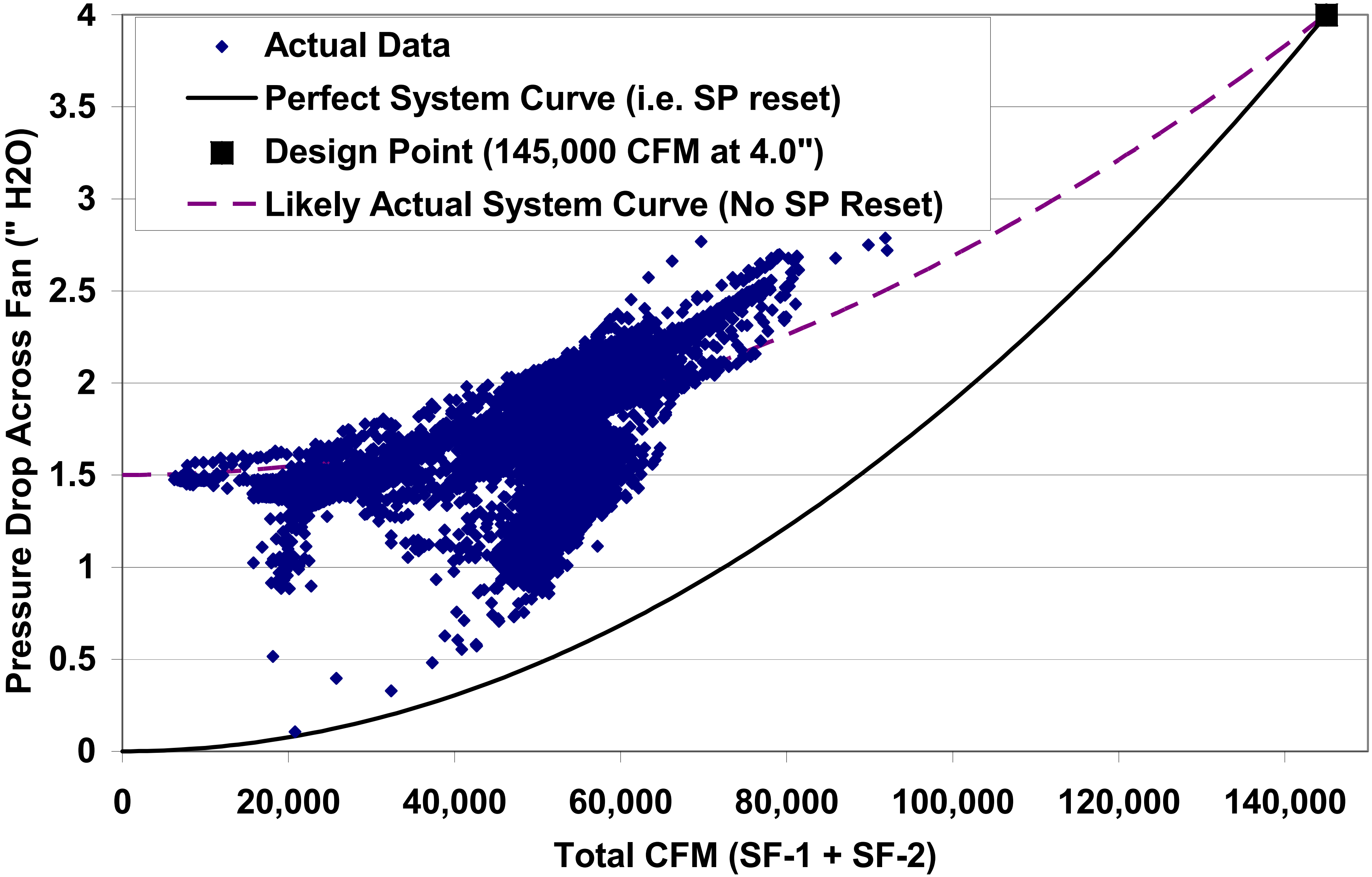
Static Pressure Setpoint Reset



Fan Energy at Varying SP Setpoints



Real Fan Systems
Many Hours At Low Loads



Zone Pressure Demand Options

- **Analog actuators**
  - Damper signal
- **Floating actuators**
  - Calculated damper position
    - PID loop output mapped to actuator; or
    - Time open/close contacts
  - Damper position feedback
  - Damper full-open end-switch
  - Airflow rate

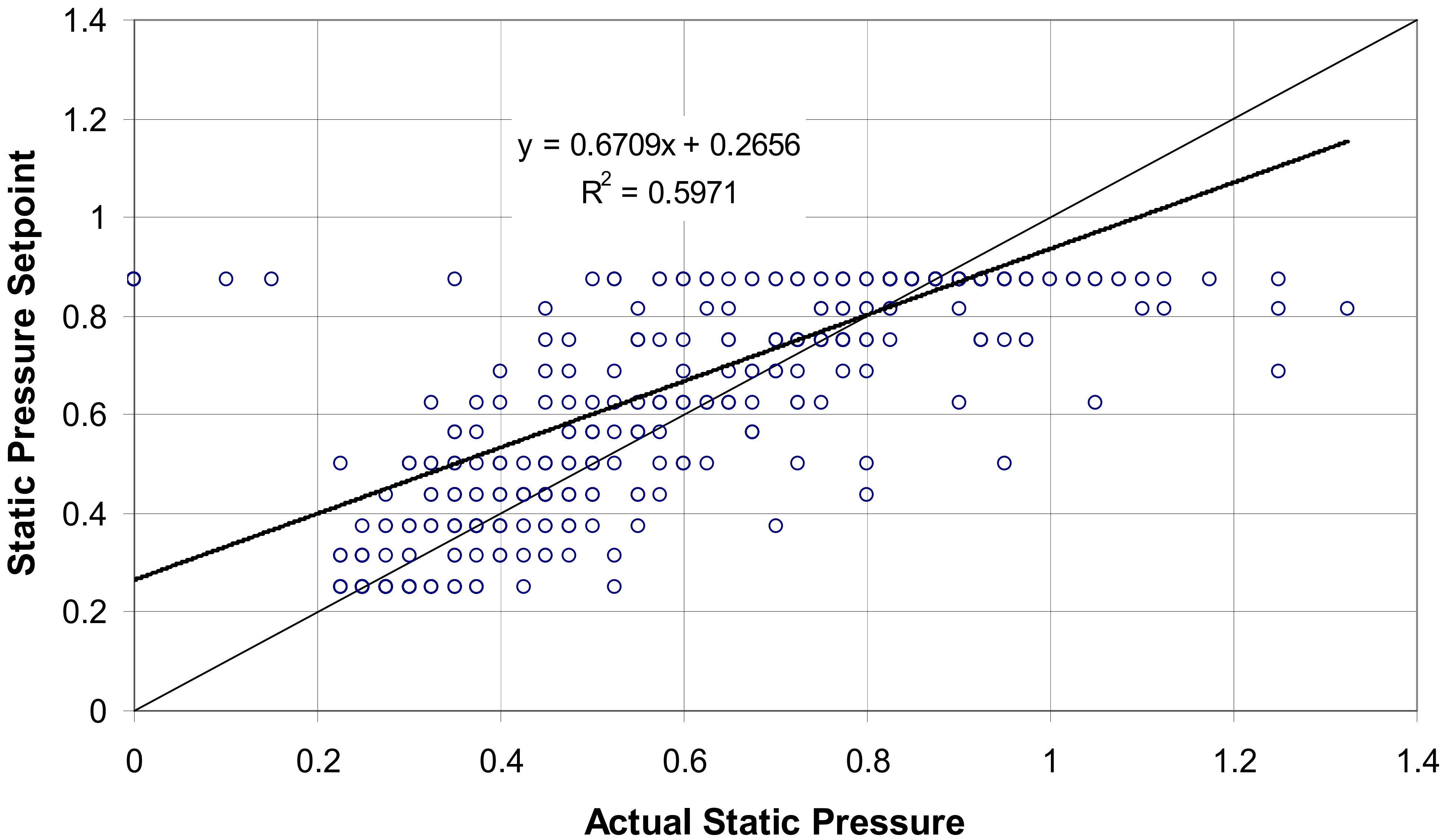
Trim & Respond Static Pressure Setpoint Reset Logic

Variable	Value
SP_0	0.5 inches
SP_{min}	0.1 inches
SP_{max}	Per §230593
T_d	10 minutes
T	2 minutes
I	2
R	Zone Static Pressure Reset Requests
SP_{trim}	-0.05 inches
SP_{res}	+0.06inches
$SP_{res-max}$	+0.13 inches

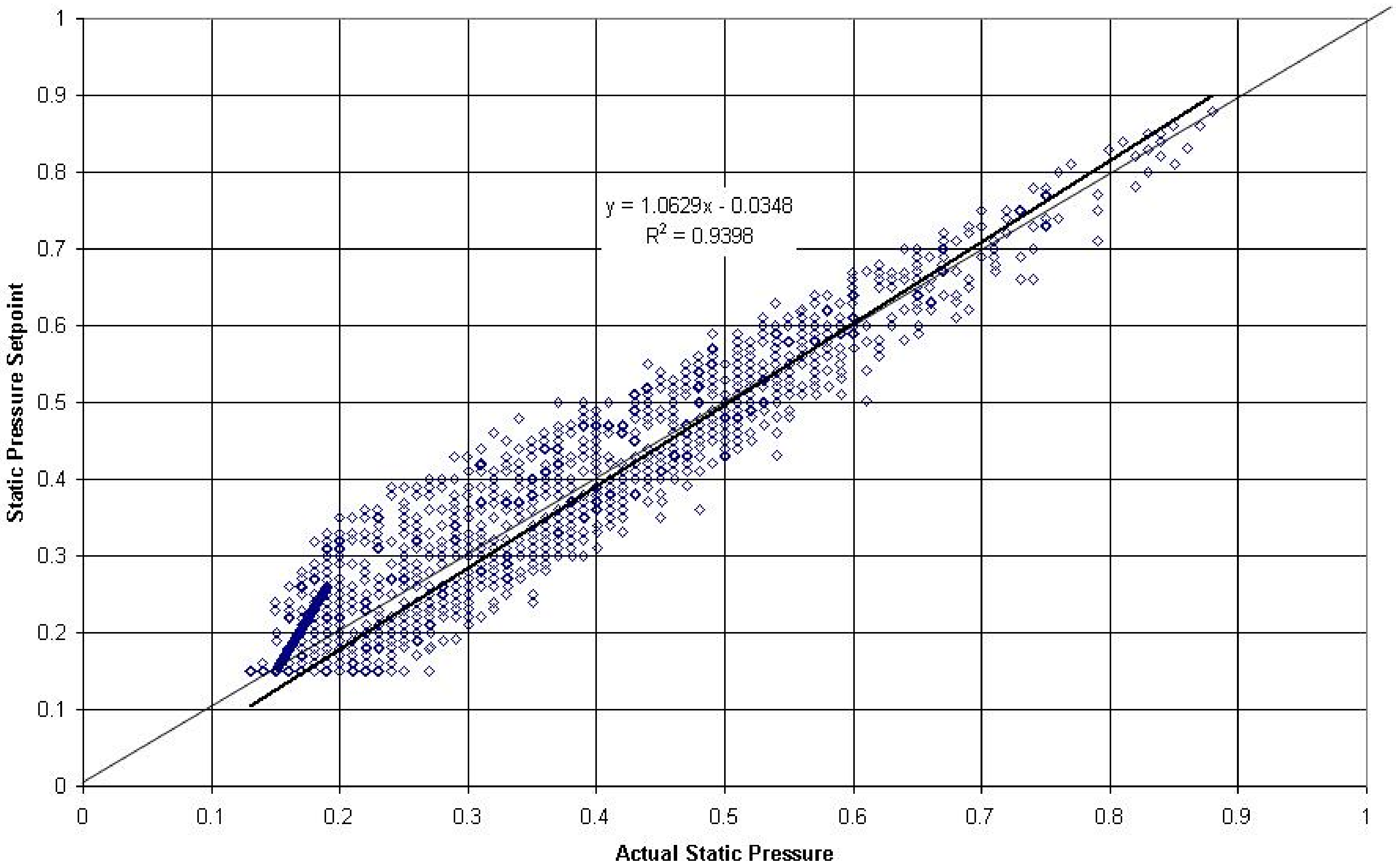
Set by TAB Contractor

Adjustable to limit dominance of rogue zones

Tuning – Unstable Control

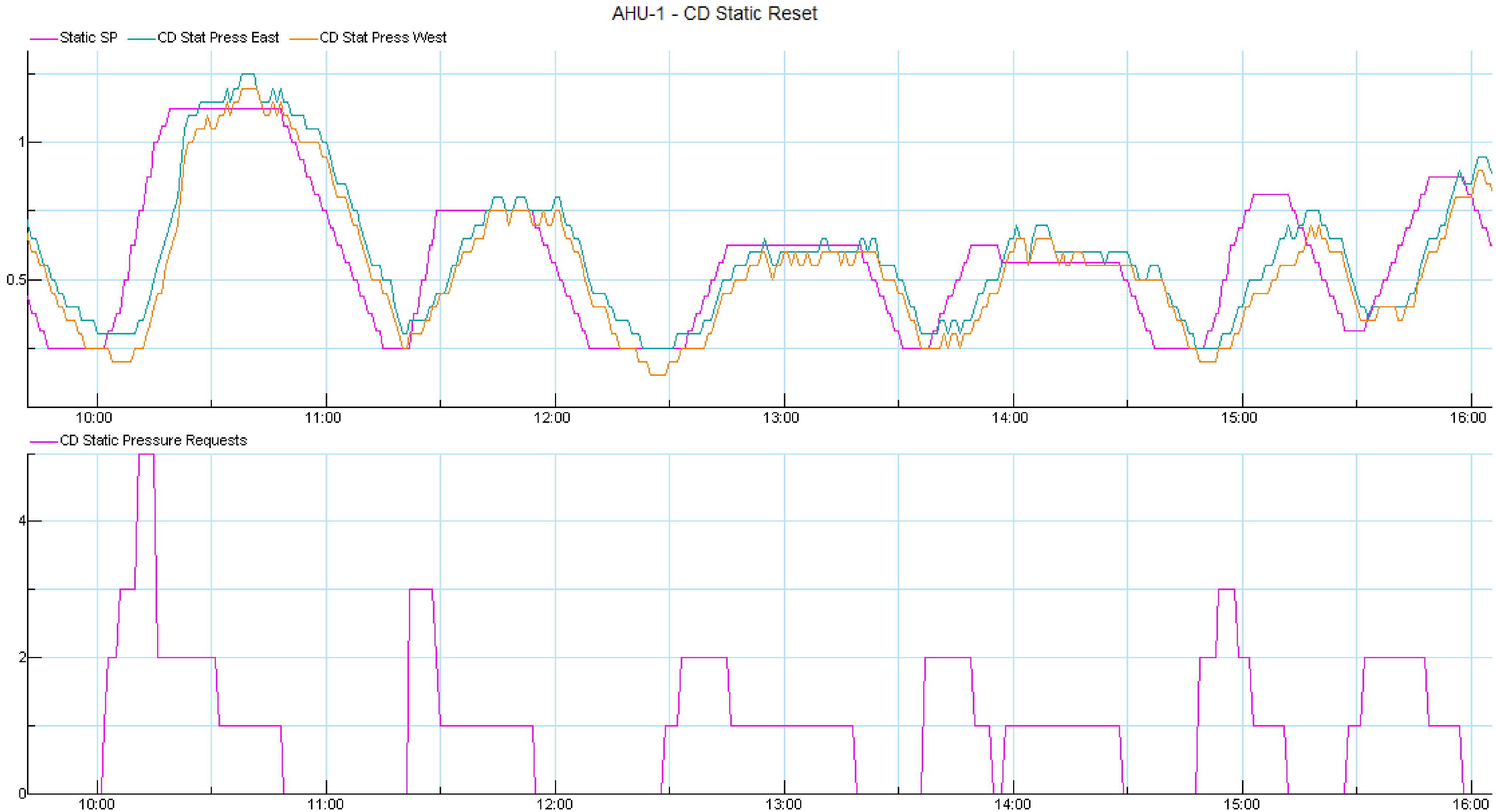


Tuning – Stable Control



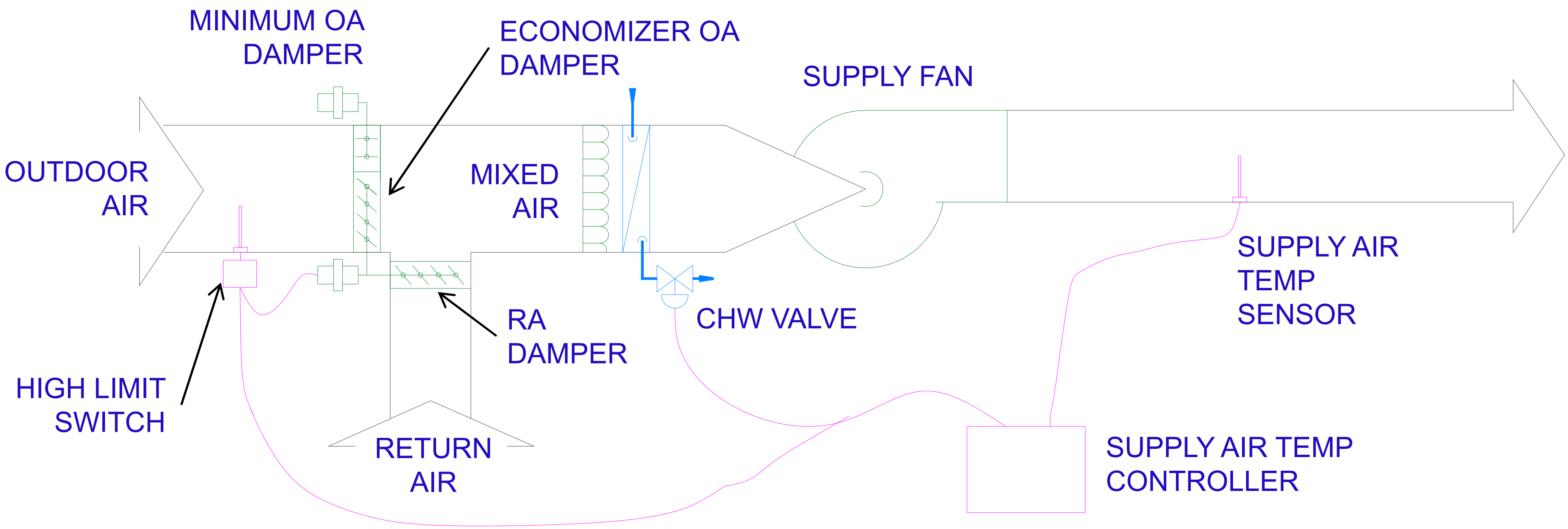
Demand Based Reset Control

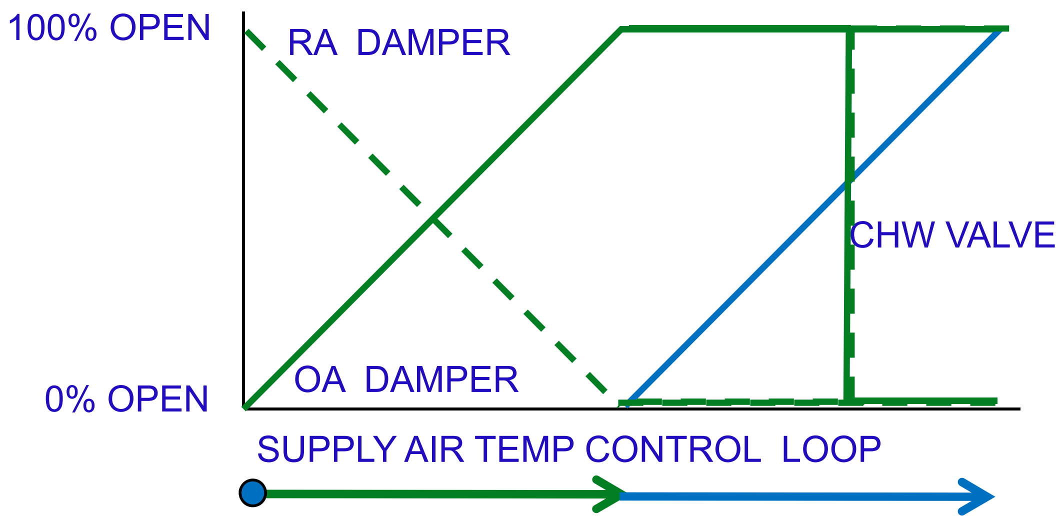
Trim and Respond Example



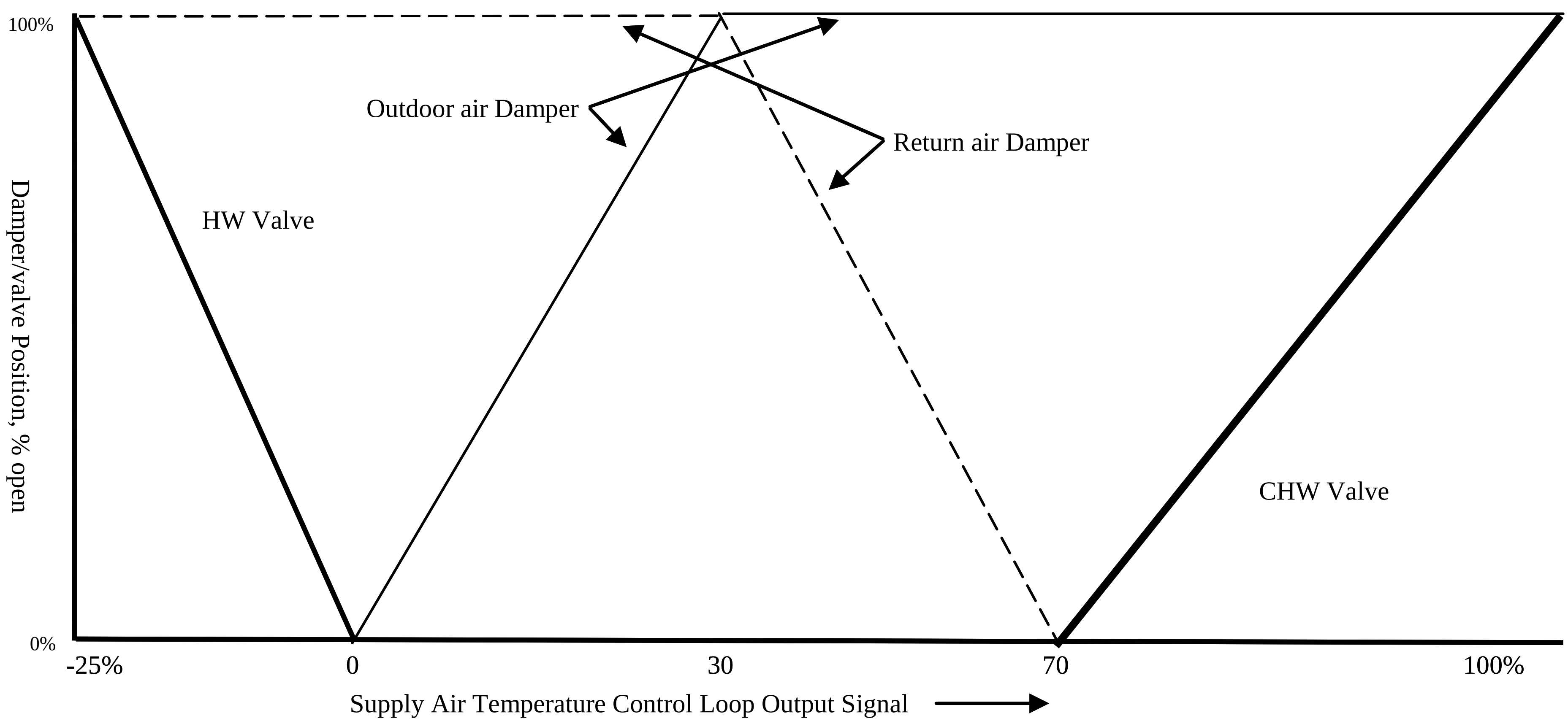
Outdoor air Economizers

Integrated Air Economizer Control





Sequencing OA & RA dampers



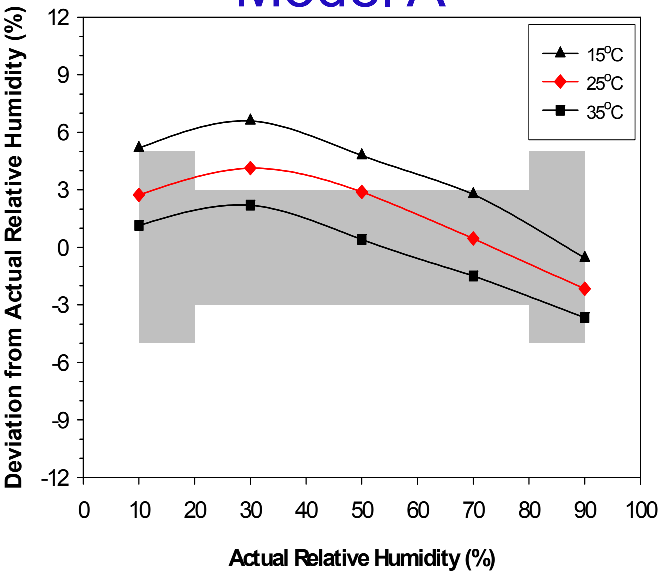
High Limit Devices

High Limit Devices

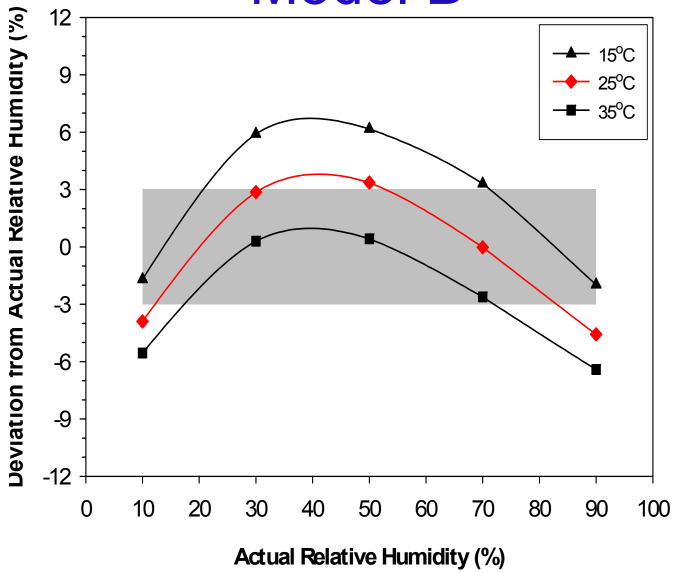
- Fixed Drybulb Temperature
  - Compares outdoor air drybulb to a fixed setpoint
- Differential (Differential) Drybulb Temperature
  - Compares outdoor air drybulb to return air drybulb
- Fixed Enthalpy
  - Compares outdoor air enthalpy to a fixed setpoint
- Differential (Differential) Enthalpy
  - Compares outdoor air enthalpy to return air enthalpy
- Combinations of the above
  - E.g. Fixed drybulb plus fixed enthalpy

Measured Accuracy of New Sensors

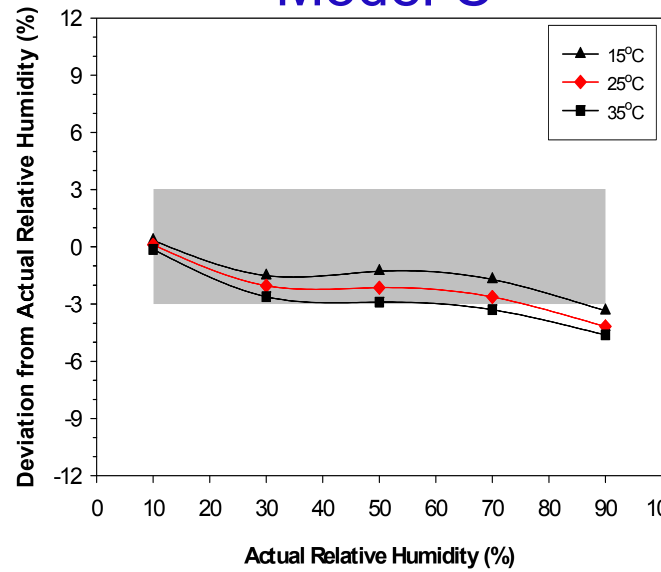
Model A



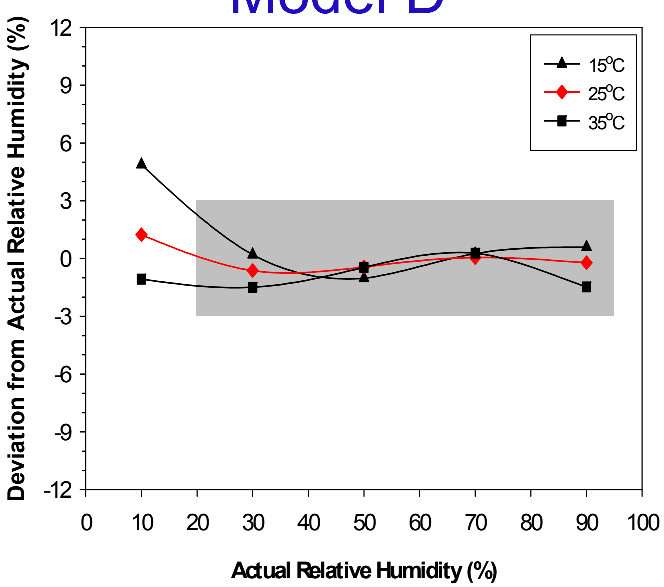
Model B



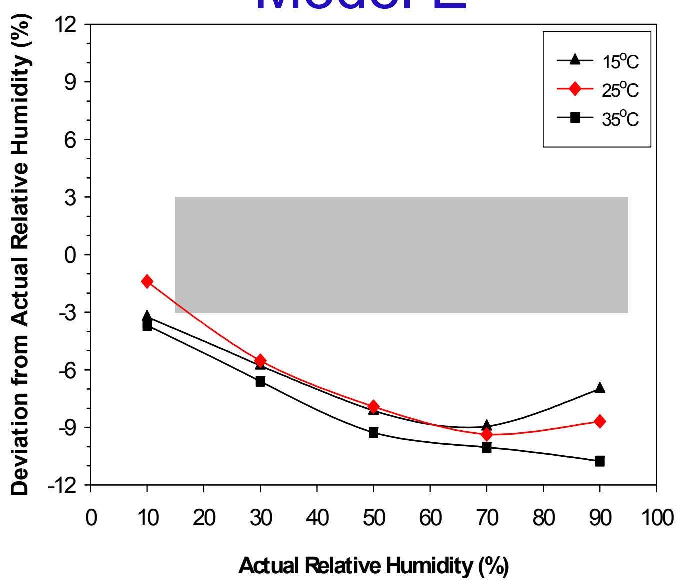
Model C



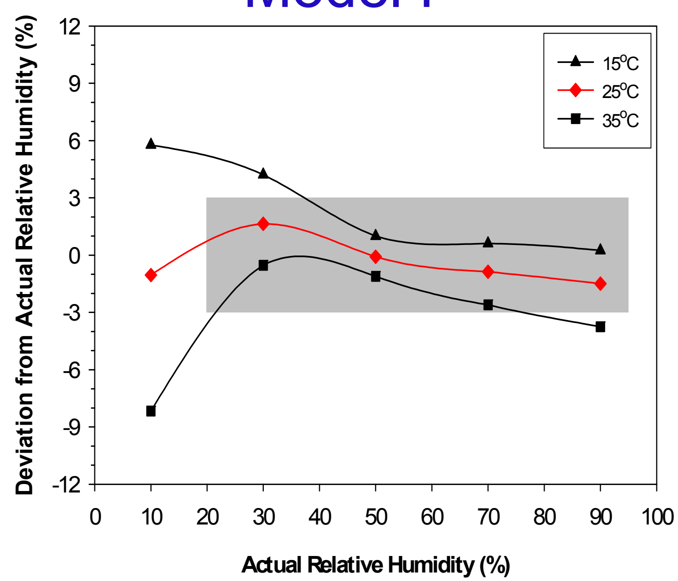
Model D



Model E

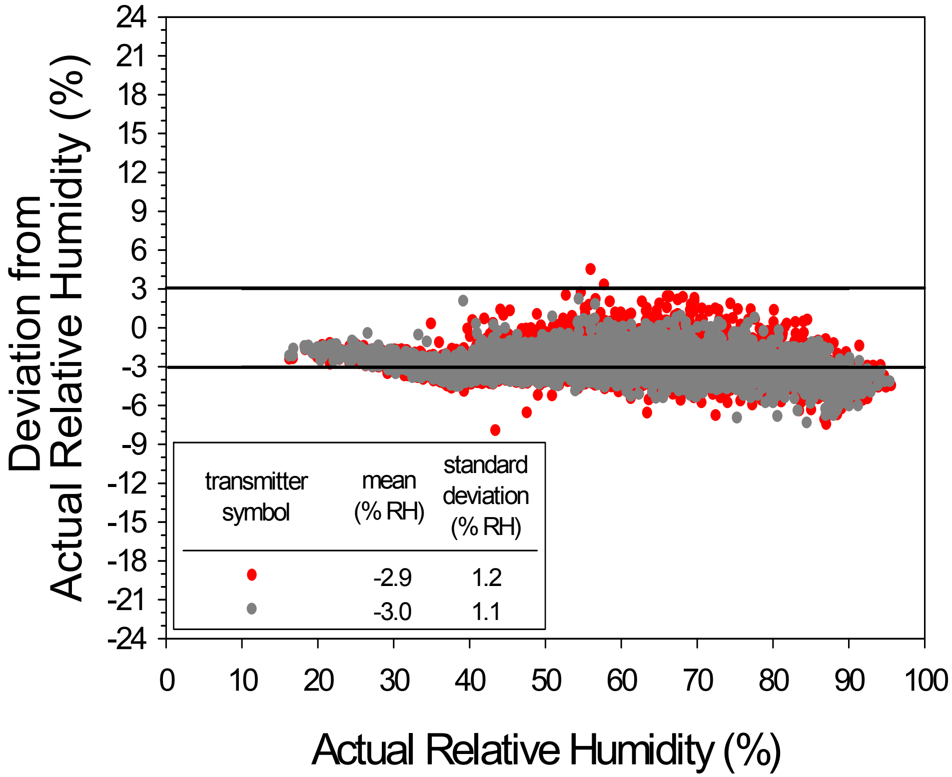


Model F

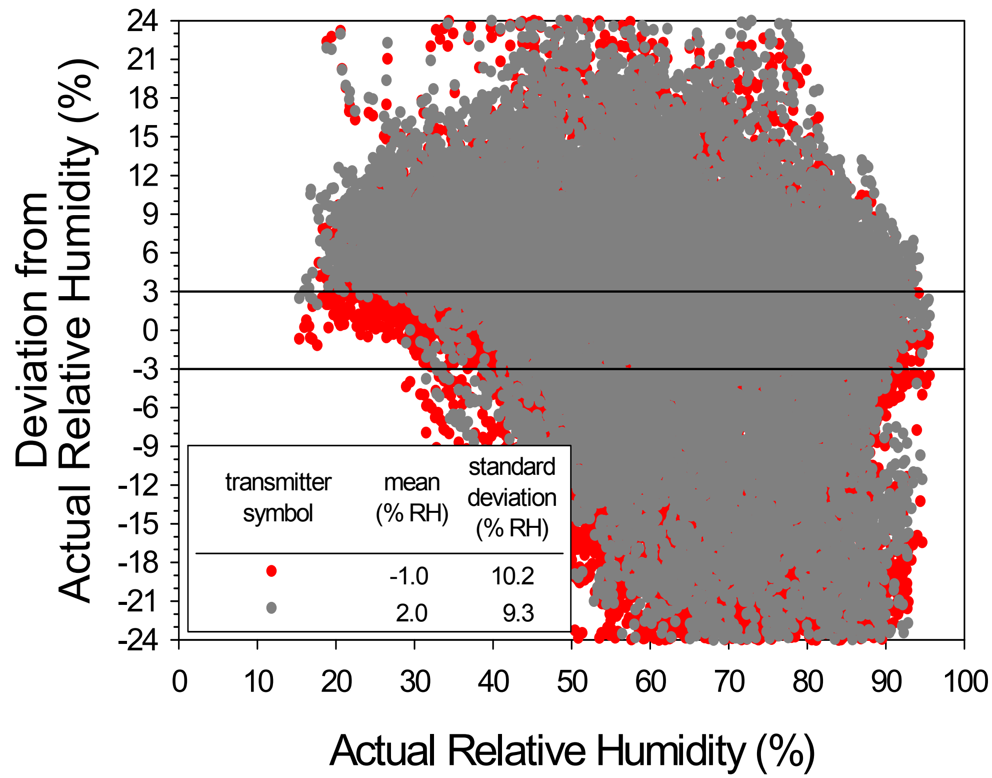


Aging / Drift Testing Results

Model C



Model E

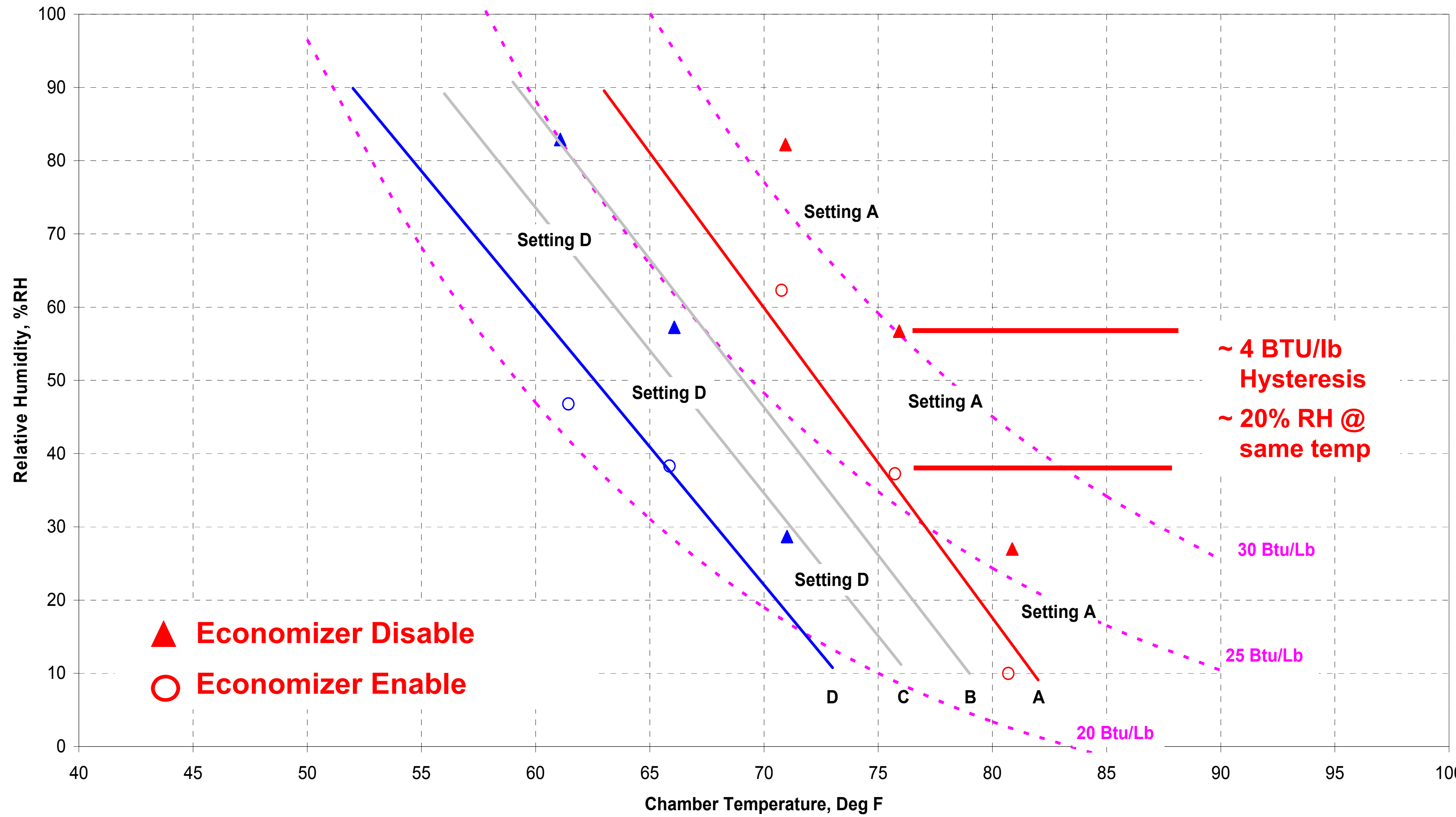


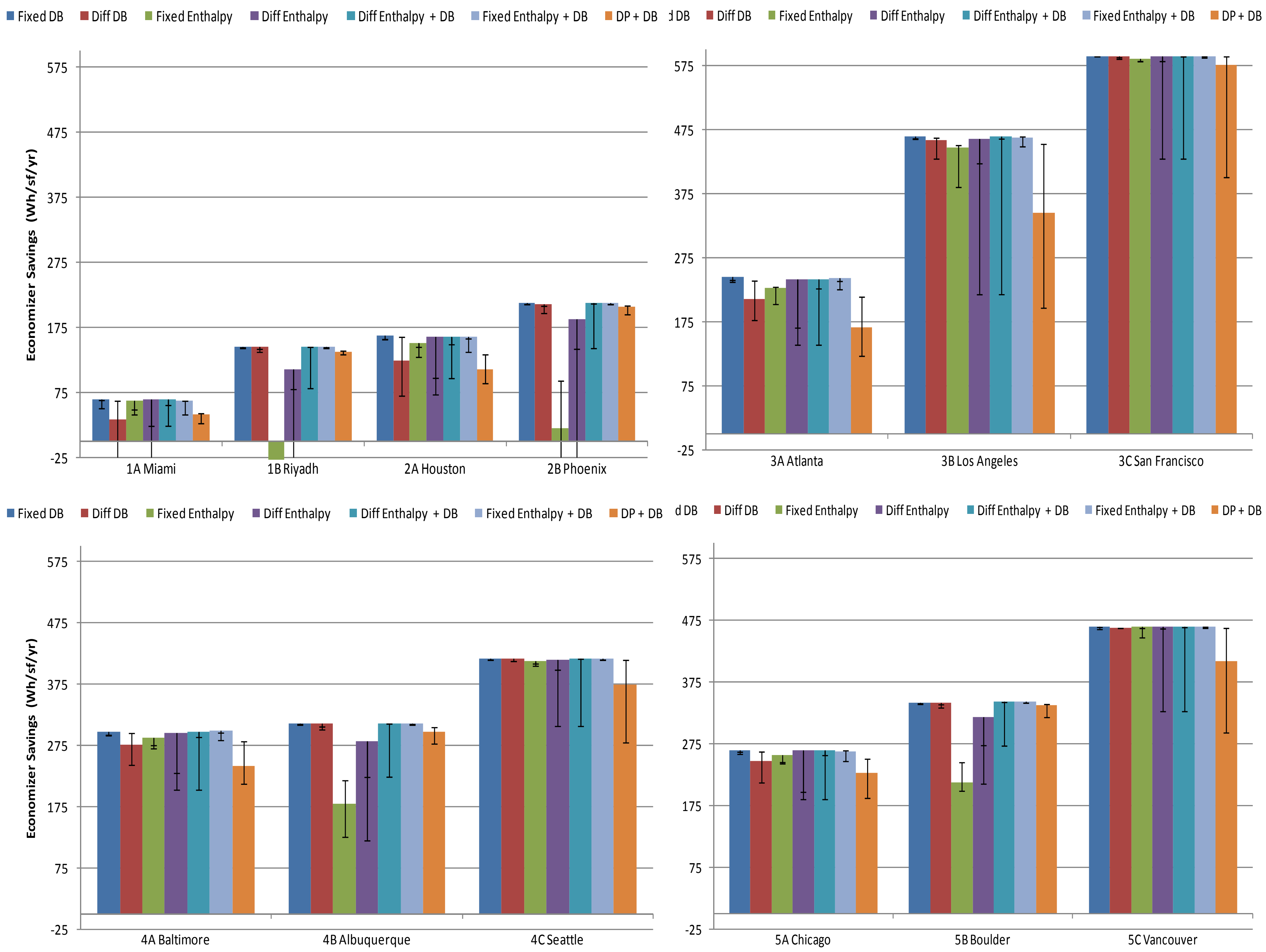
- One year of data collected at 15 minute intervals
- Reference: Precision Grade ±1% RH in-situ reference sensor

Performance – Solid State Enthalpy Switch

■ Actual Test Data

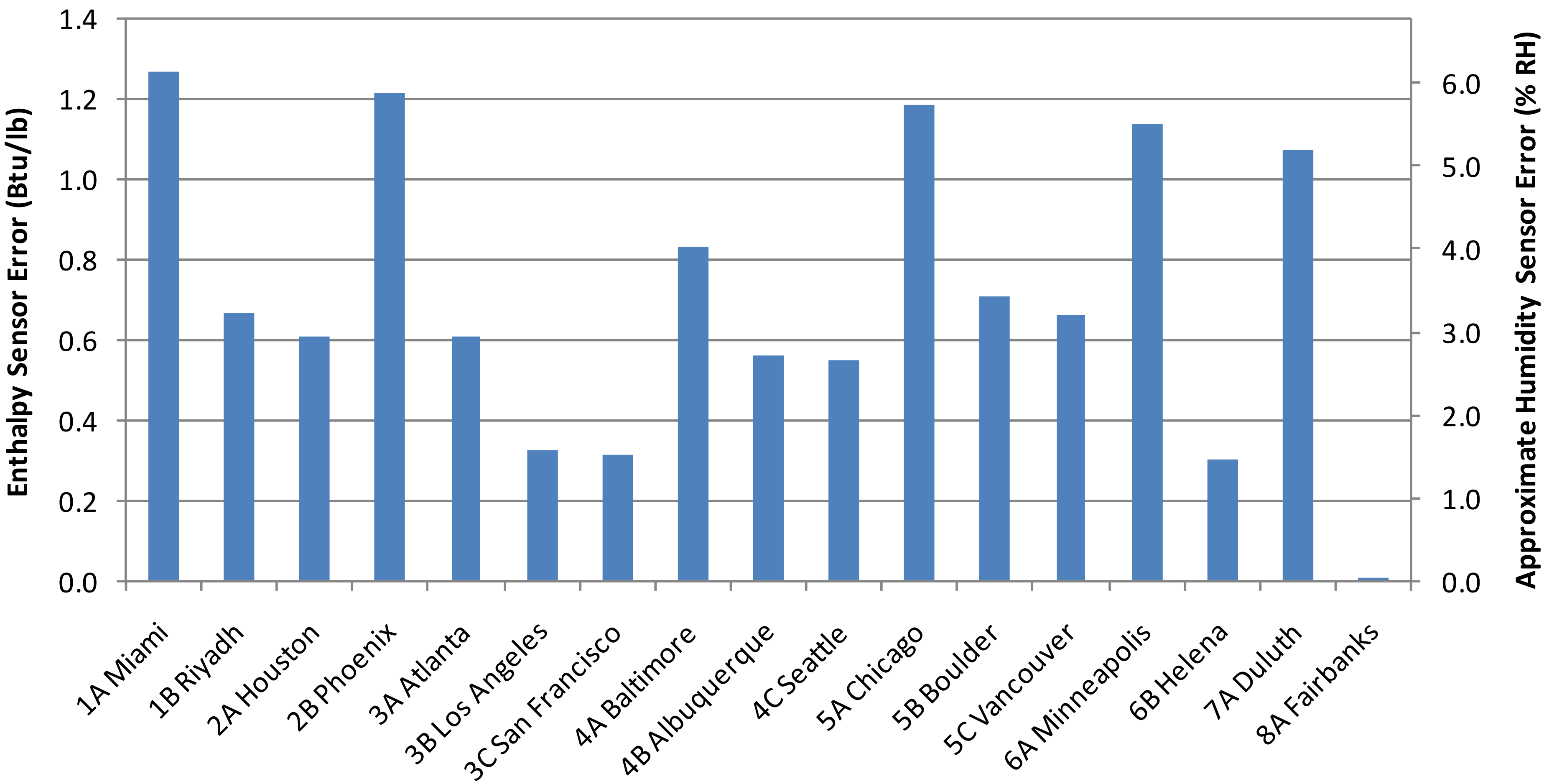
- Enthalpy switch action curve





Fixed DB
Diff DB
Fixed Enthalpy
Diff Enthalpy
Diff Enthalpy + DB
Fixed Enthalpy + DB
DP + DB
Economizer Savings (Wh/sf/yr)
575
475
375
275
175
75
-25
1A Miami
1B Riyadh
2A Houston
2B Phoenix
3A Atlanta
3B Los Angeles
3C San Francisco
4A Baltimore
4B Albuquerque
4C Seattle
5A Chicago
5B Boulder
5C Vancouver

Required Maximum Differential Enthalpy Error to Match Fixed Drybulb with ±2°F Error



Conclusions

- [Dew point + fixed drybulb] logic should not be used anywhere.
- Differential drybulb control should not be used in humid climates
- Fixed enthalpy control should not be used in dry climates
- Best with no sensor error: Differential enthalpy and Differential/fixed drybulb
- Worst with sensor error: Differential enthalpy
- Best with sensor error: fixed drybulb control with setpoint optimized by climate
- [Fixed enthalpy + fixed drybulb] performs well but not measurably better than fixed drybulb alone even without error
- Electronic enthalpy switches are worse than drybulb switch even without error and wide differential

High Limits – Standard 90.1-2013

Control Type	Allowed Only in Climate Zone at Listed Setpoint	Required High-Limit Setpoints (Economizer Off When):	
		Equation	Description
Fixed dry-bulb temperature	1b, 2b, 3b, 3c, 4b, 4c, 5b, 5c, 6b, 7, 8	$T_{OA} > 75°F$	Outdoor air temperature exceeds 75°F
	5a, 6a	$T_{OA} > 70°F$	Outdoor air temperature exceeds 70°F
	1a, 2a, 3a, 4a,	$T_{OA} > 65°F$	Outdoor air temperature exceeds 65°F
Differential dry-bulb temperature	1b, 2b, 3b, 3c, 4b, 4c, 5a, 5b, 5c, 6a, 6b, 7, 8	$T_{OA} > T_{RA}$	Outdoor air temperature exceeds return air temperature
Fixed enthalpy with fixed dry-bulb temperature	All	$h_{OA} >$ 28 Btu/lb[a] or $T_{OA} > 75°F$	Outdoor air enthalpy exceeds 28 Btu/lb[a] of dry air[a] or outdoor air temperature exceeds 75°F
Differential enthalpy with fixed dry-bulb temperature	All	$h_{OA} > h_{RA}$ or $T_{OA} > 75°F$	Outdoor air enthalpy exceeds return air enthalpy or outdoor air temperature exceeds 75°F

Key changes:

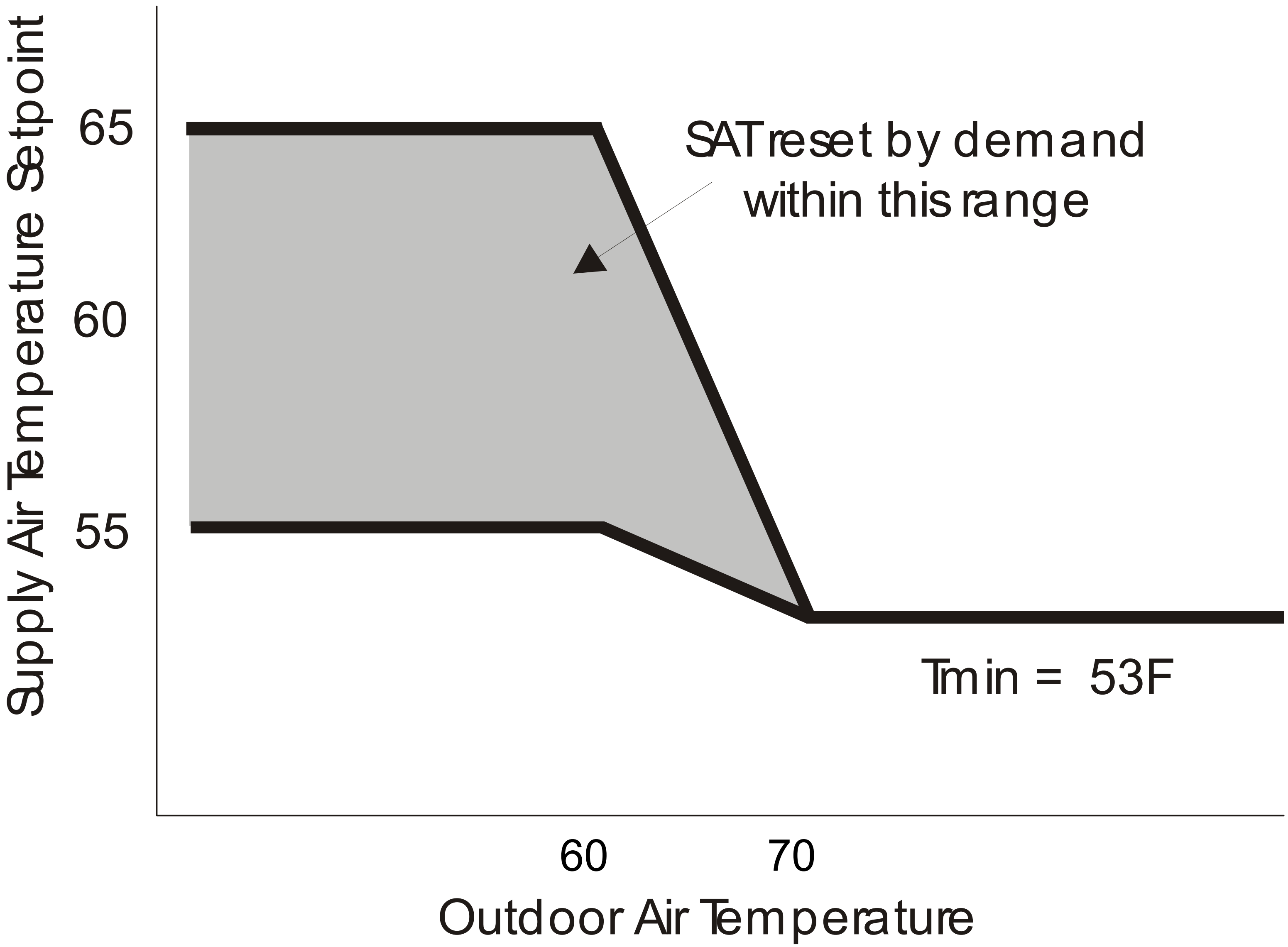
- Fixed drybulb allowed in all climate zones
- Enthalpy limits can only be used along with fixed drybulb
- Electronic enthalpy eliminated

Recommendation

- **Use fixed drybulb in all climate zones at the setpoint required by 90.1 (or customized for climate via simulations)**
  - lowest first cost
  - inherently high energy efficiency
  - minimal sensor error
  - minimal impact even when there is sensor error
  - low maintenance costs

Supply Air Temperature Reset

RP-1455 - Reheat System SAT Reset Logic



VAV Reheat System SAT Reset Logic

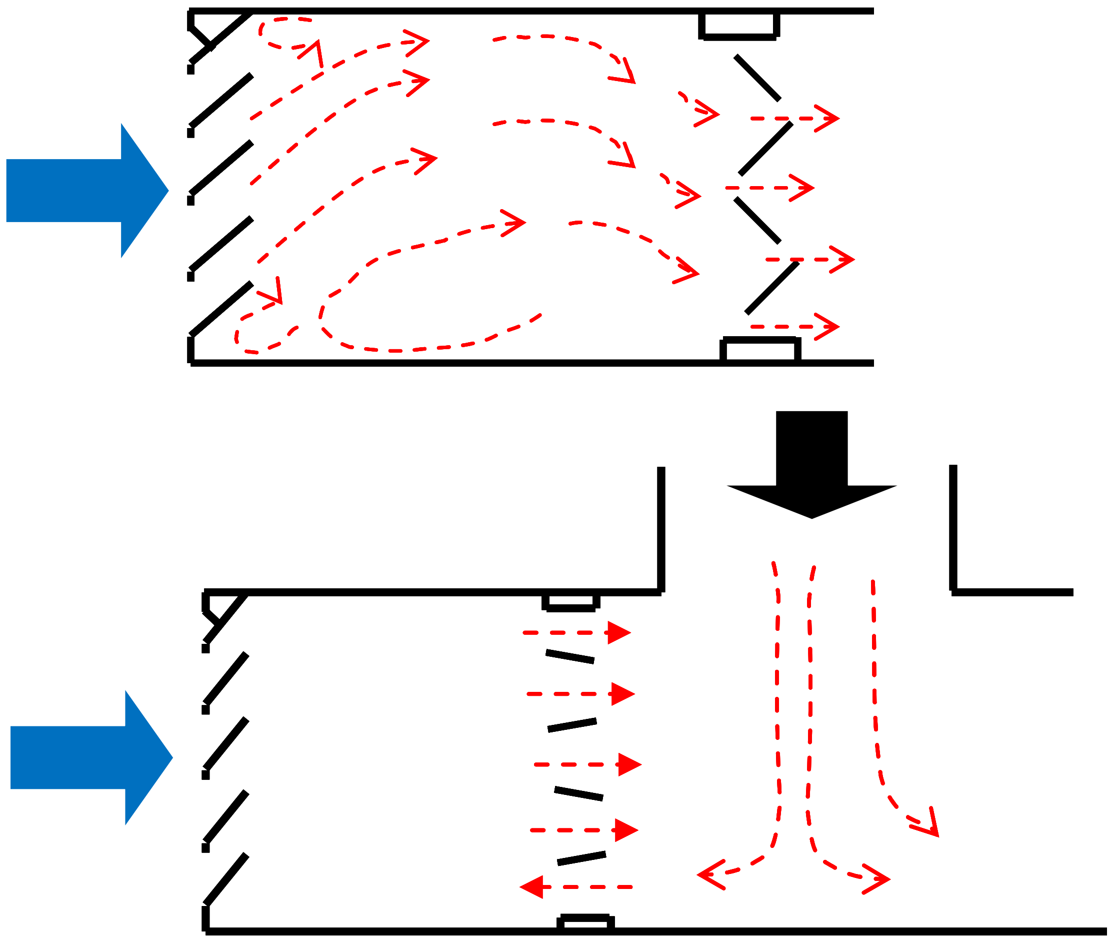
During occupied mode: Setpoint shall be reset from T-min (the design cooling coil leaving air temperature per coil schedule) when the outdoor air temperature is *70*°F and above, proportionally up to T-max when the outdoor air temperature is *60*°F and below. T-max shall be reset using Trim & Respond logic with the following parameters:

Variable	Value
SP_0	SP_{max}
SP_{min}	Design cooling coil leaving temperature from AHU schedule
SP_{max}	65ºF
T_d	10 minutes
T	2 minutes
I	2
R	Zone Cooling SAT Requests
SP_{trim}	+0.2ºF
SP_{res}	-0.3ºF
$SP_{res-max}$	-1.0ºF

Minimum Outdoor Air Control

Need to measure OA flow. But OA intake measurements are challenging!

- **Low air speeds, near detection limits of many sensors**
  - Especially at minimum rates of OA supply
- **Spatially variable (non-uniform) direction of air flow**
- **Limited space**
- **Air flow rates & temperatures vary over time**
- **Sensors may be exposed to moisture and dust**
- **Effects of winds**



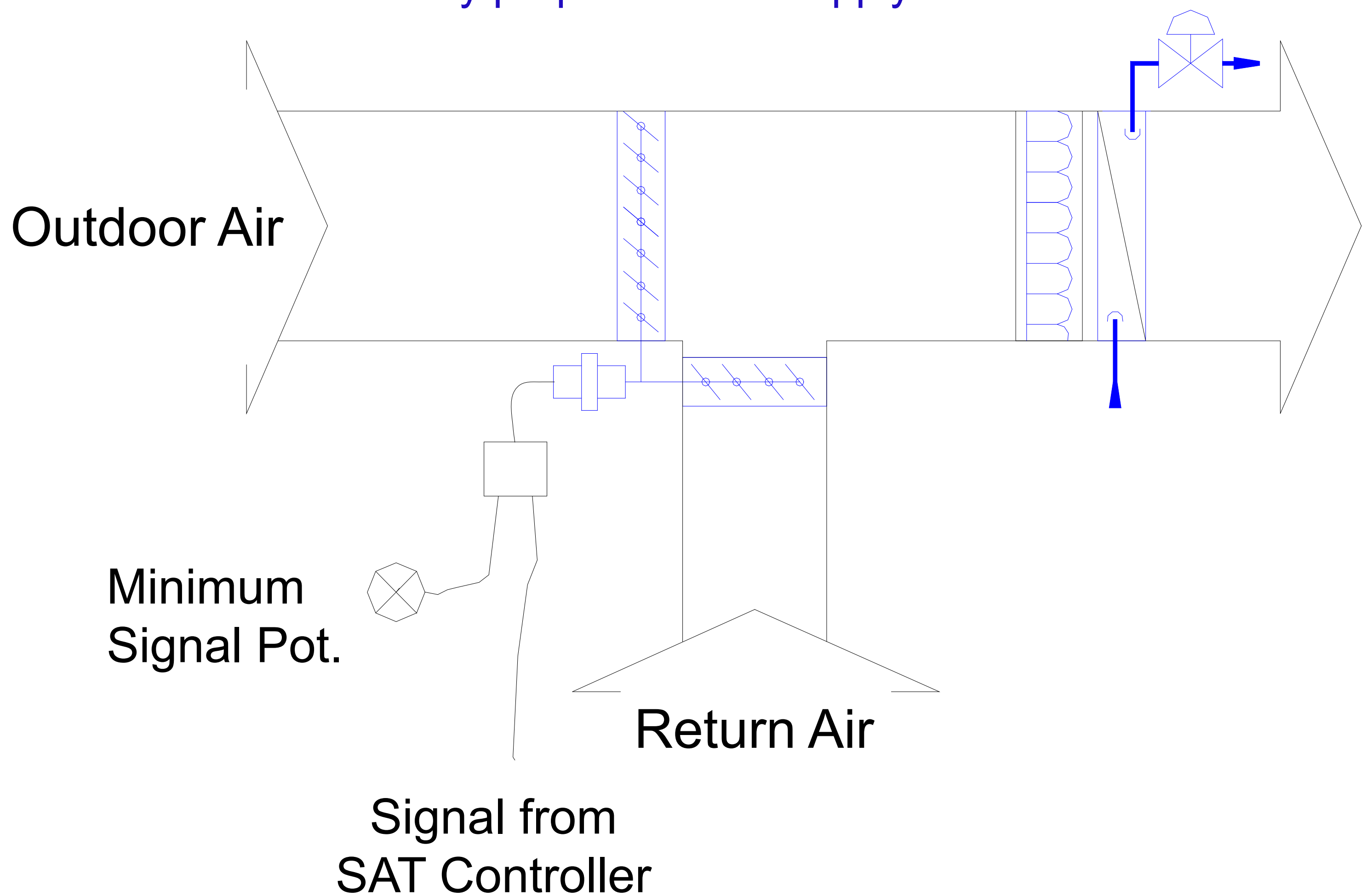
Lab and Field Tests

- **Fisk et al (LBNL 2004, 2005)**
  - Measured performance of 5 measurement technologies in lab and a few in the field
  - Unfortunately only tested a few products – many more available but untested
- **Fisk et al (Building Energy Research Grant. 2010)**
  - Measured only one product
- **ASHRAE RP-980 (2007)**
  - Theoretical review and lab tests of several common airflow measurement concepts
- **May be the only unbiased tests (not performed by manufacturers)**

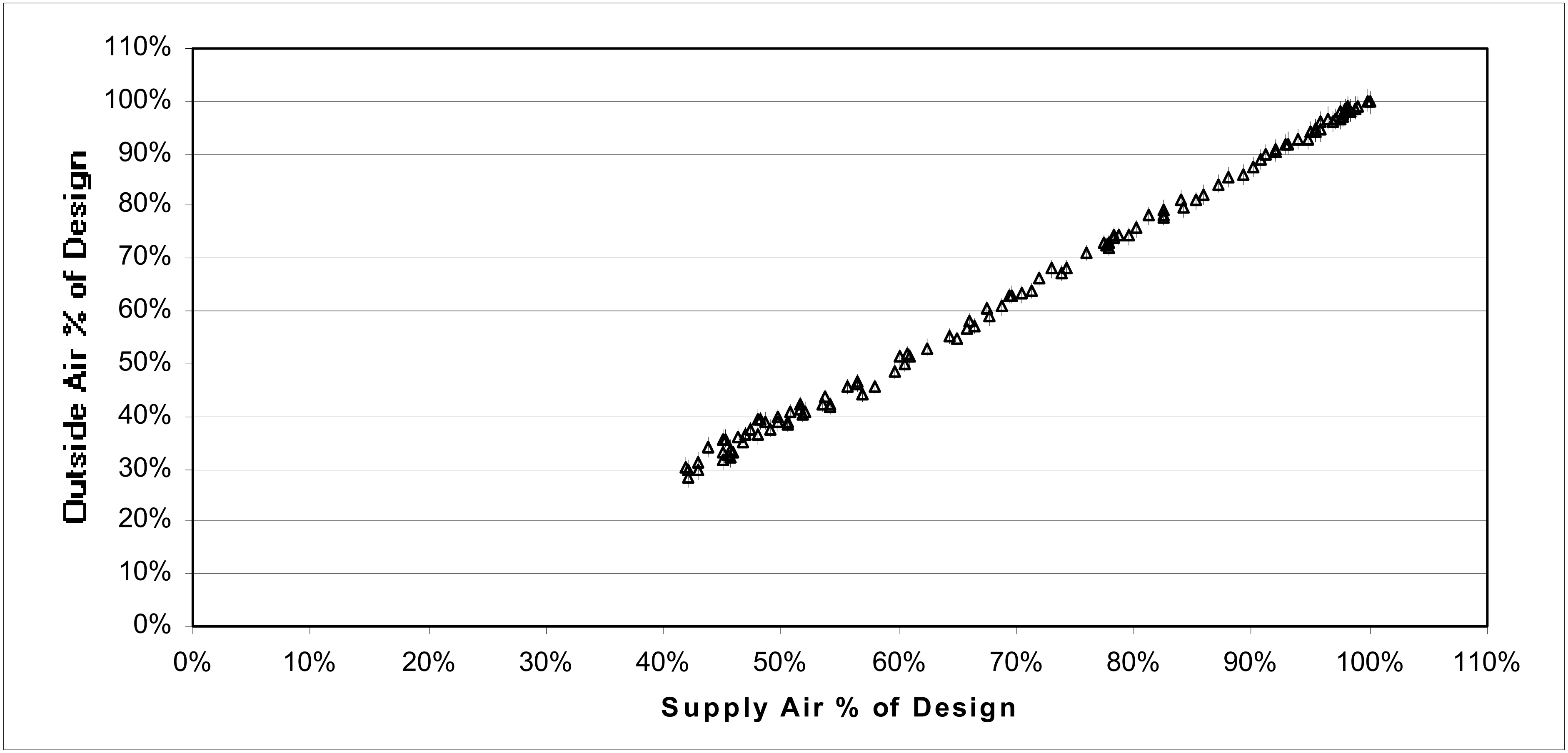
Fixed Minimum OA Damper Position

Most Common Approach

Does NOT WORK for VAV since mixed air plenum pressure varies!! Outdoor air flow will vary proportional to supply air flow.



RP-980 Lab Results
Fixed Minimum OA Damper

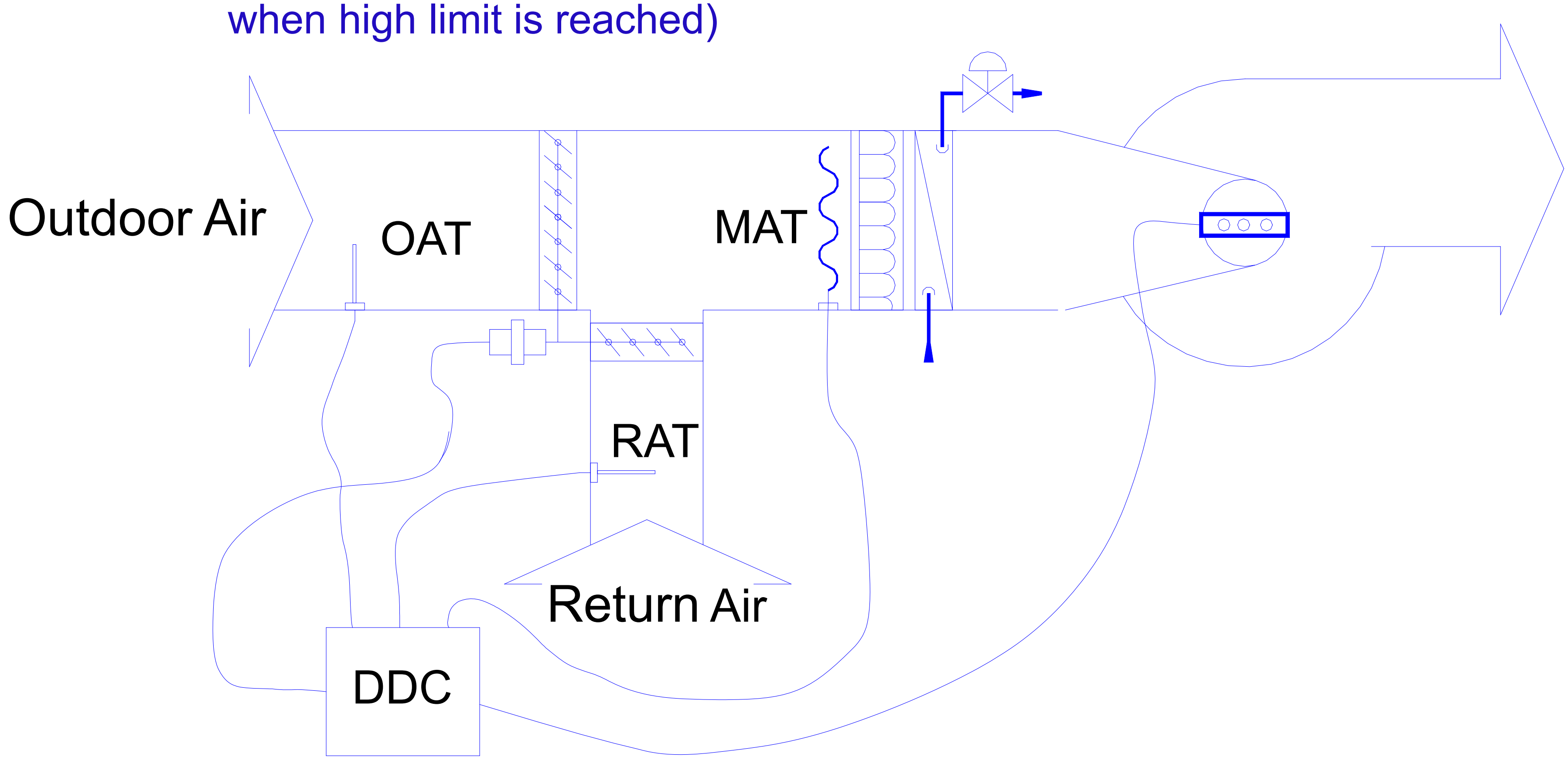


Dual Minimum Position

- Minimum damper position is set proportionally based on fan speed between setpoints determined when the fan is at full speed and minimum speed
- Low cost
- Poor accuracy due to
  - Nonlinear response between min and max
  - Affected by wind, stack effective, filter loading

Energy (or CO_2) Balance

Does NOT WORK when OAT ~ RAT (which it is when high limit is reached)

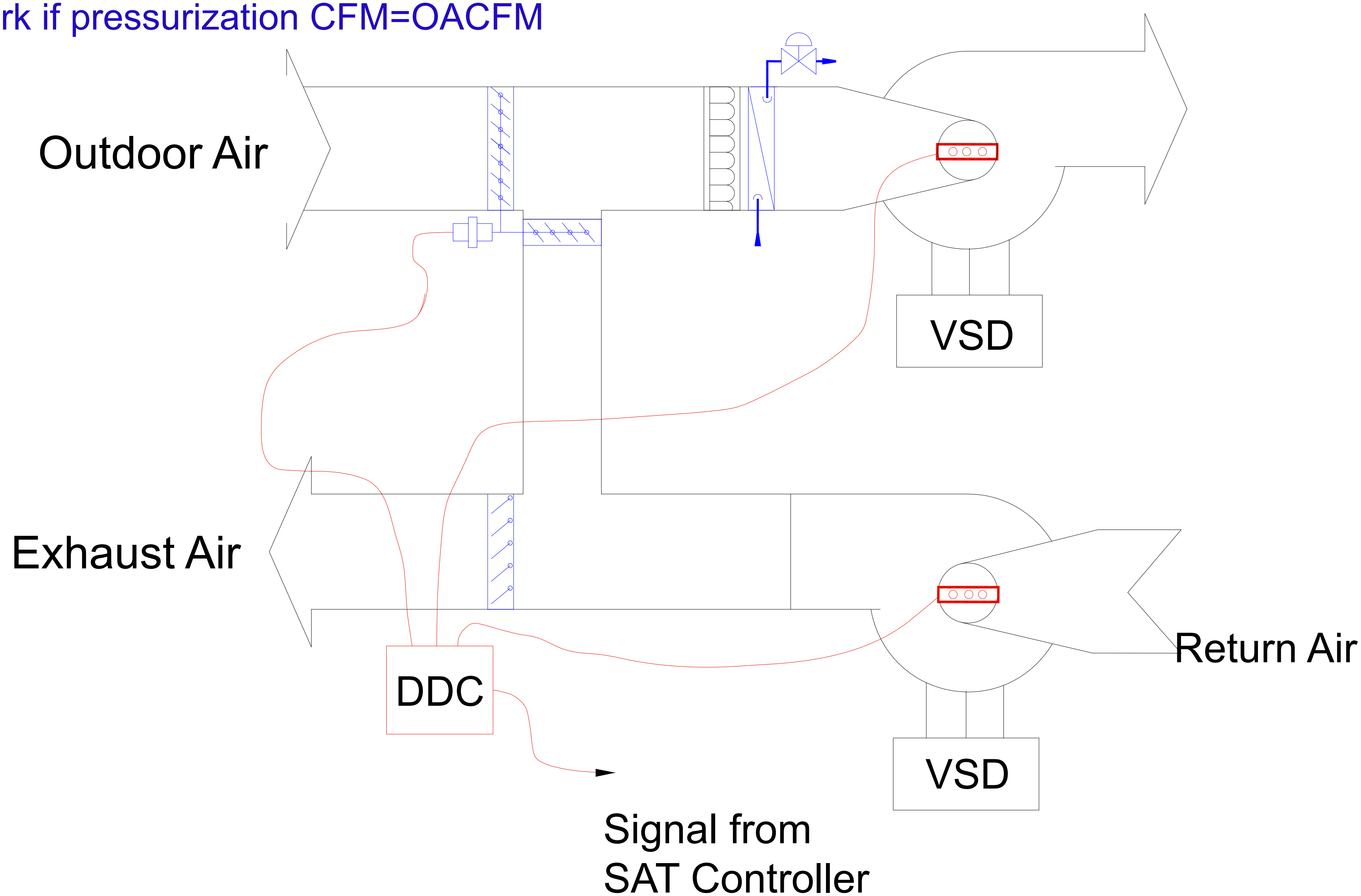


%OA = (MAT - RAT) / (OAT - RAT)

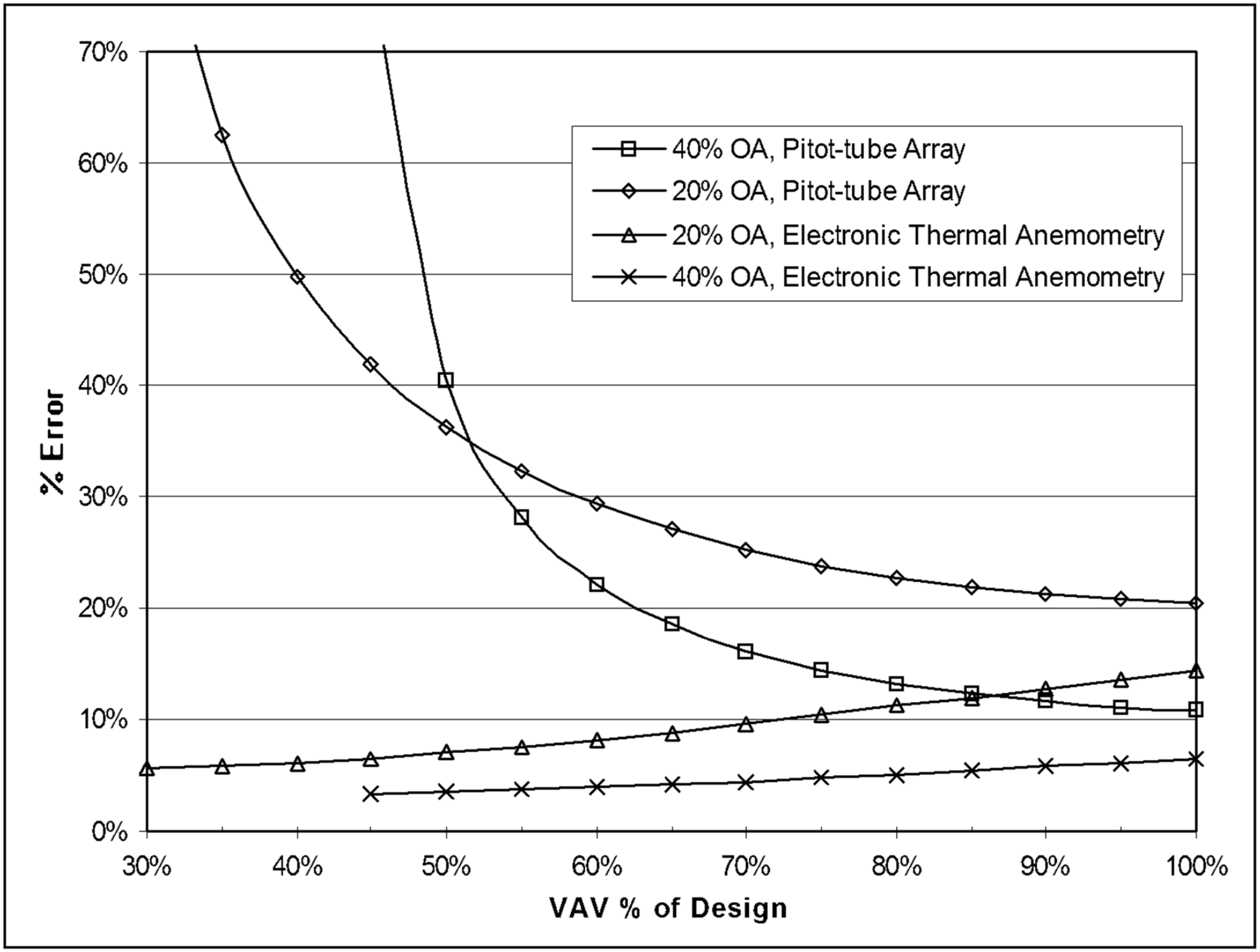
CFM-OA = %OA * CFM-SA

Return Fan Tracking

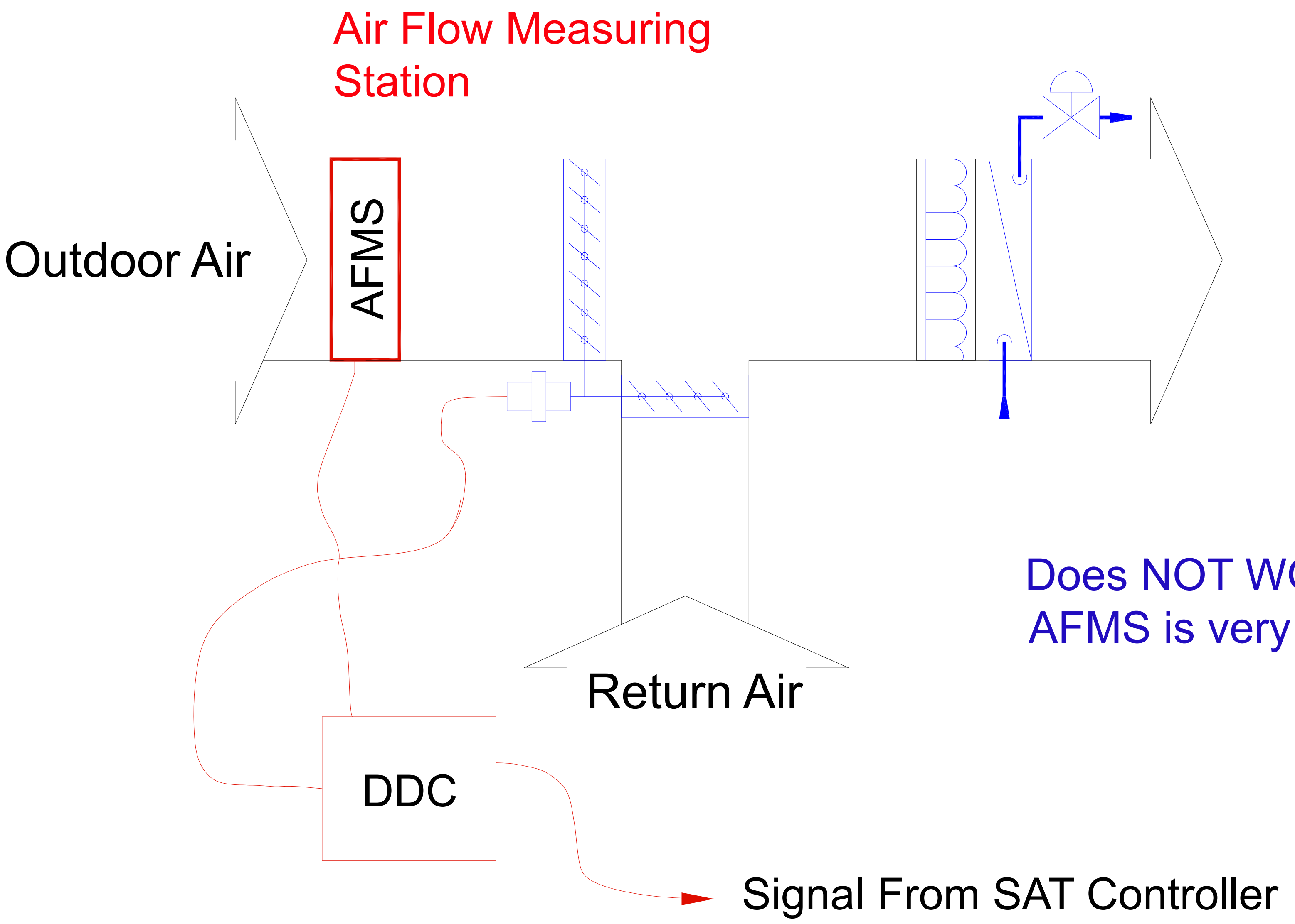
May NOT WORK due to cumulative error in flow sensors and possible flow reversal, and ONLY could work if pressurization CFM=OACFM



RP-980 Return Fan Tracking Predicted Error

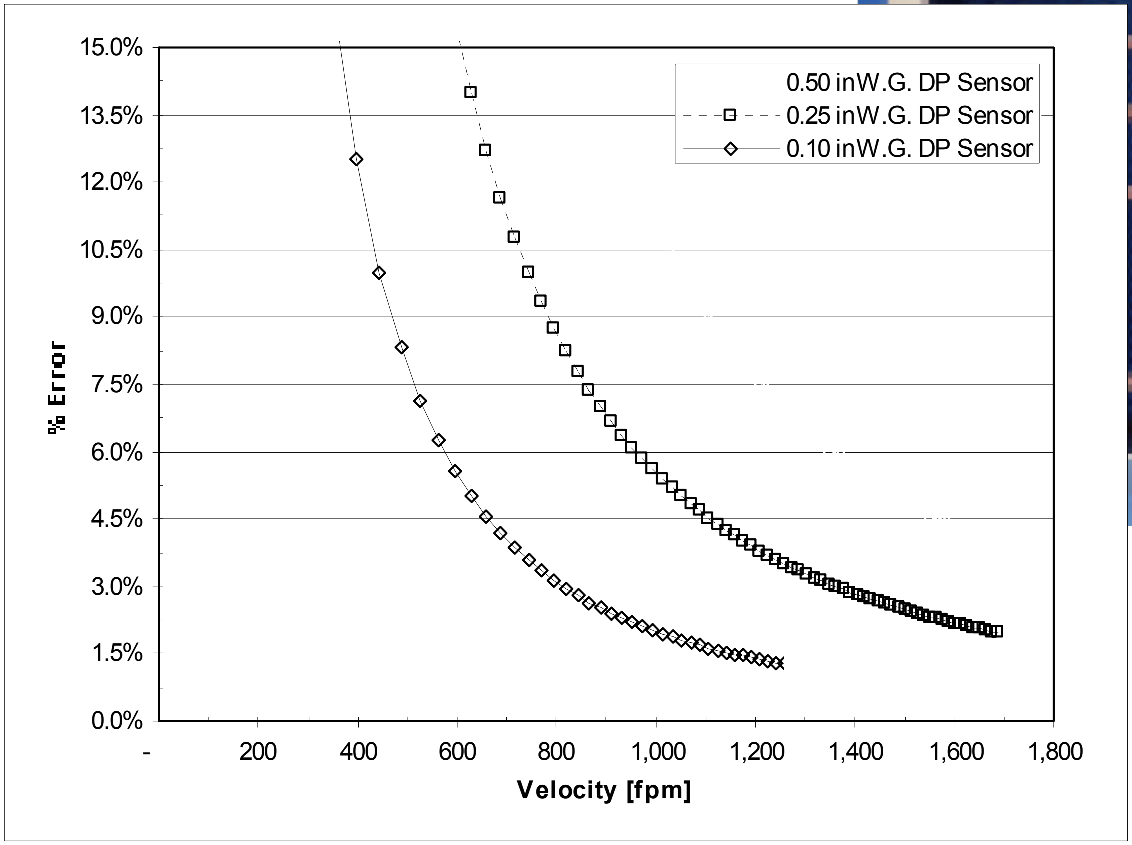


Air Flow Measurement of 100% OA

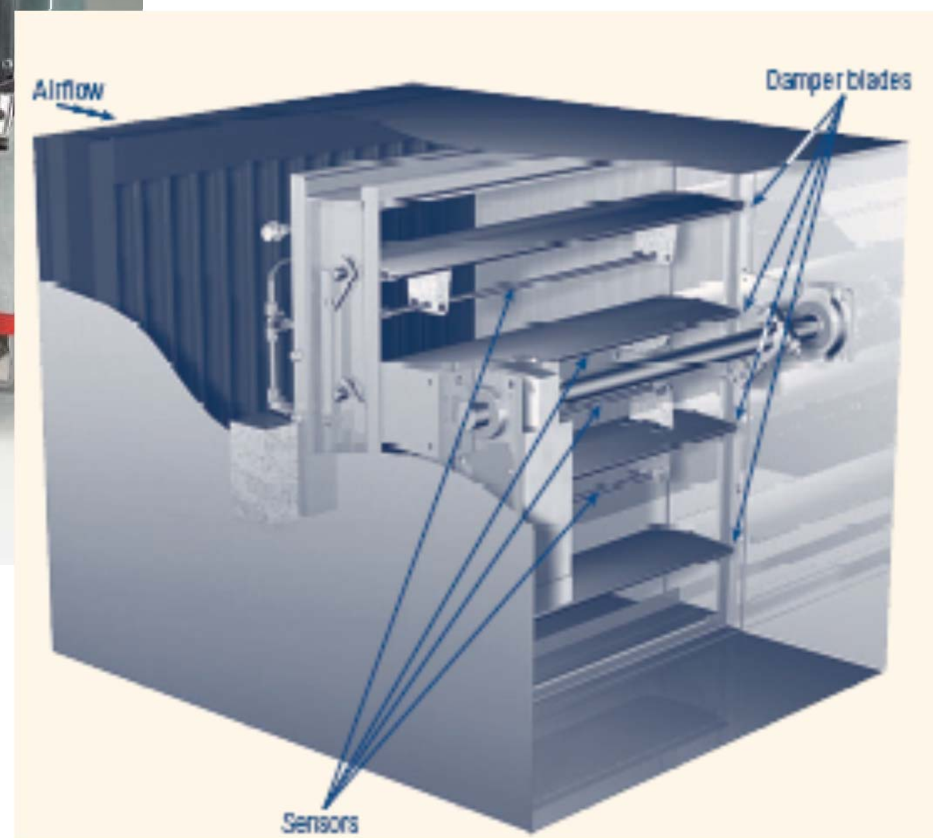


Does NOT WORK unless AFMS is very accurate at low flow

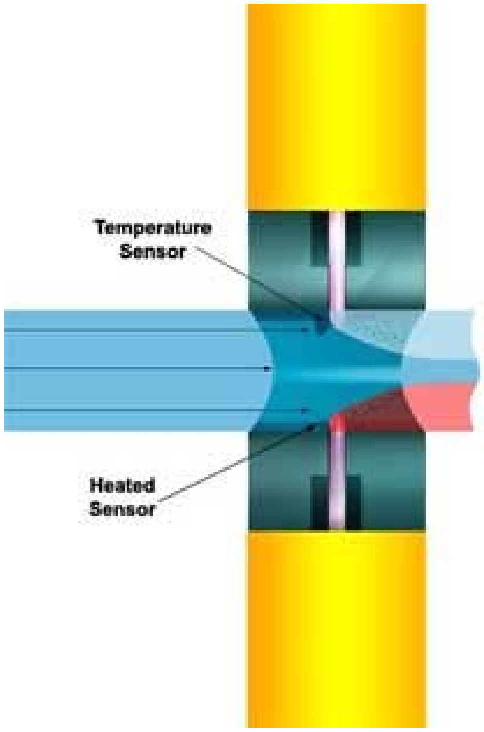
Typical Pitot Array



Other Systems:
Minimum 300-400 fpm



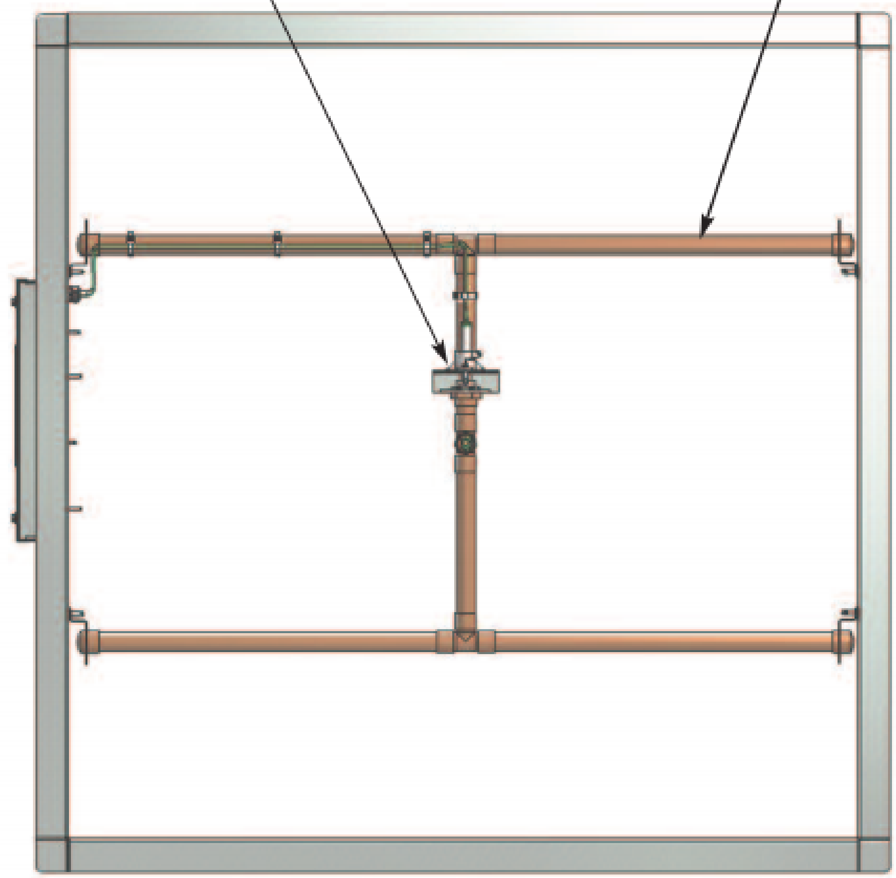
Thermal Dispersion Anemometer



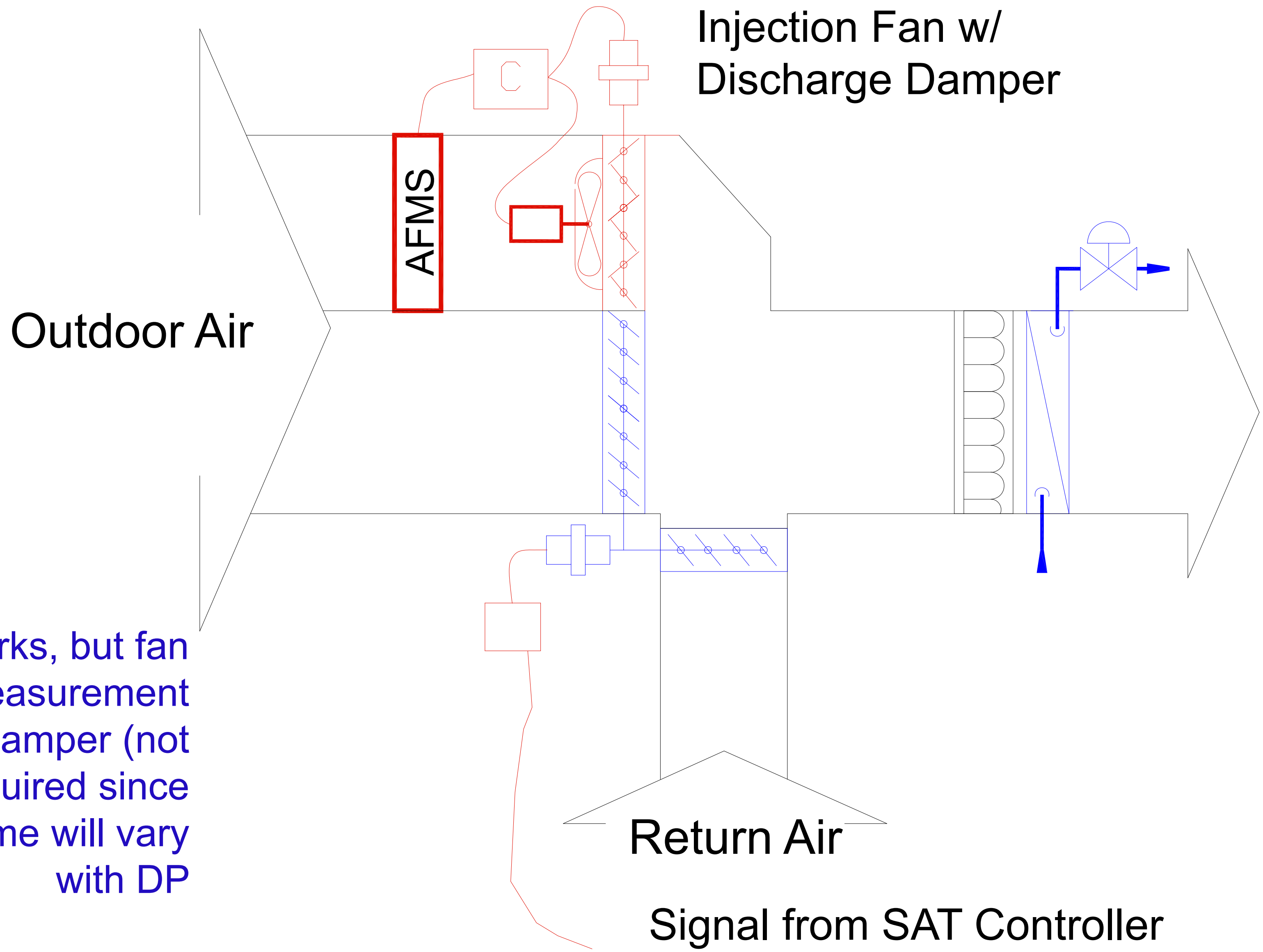
Manufacturer ‘s claim: ±2% of reading ≥50 fpm

Other Thermal Mass Flow Sensor

- $\pm$ 3% accuracy ≥100 fpm
- AMCA Certified

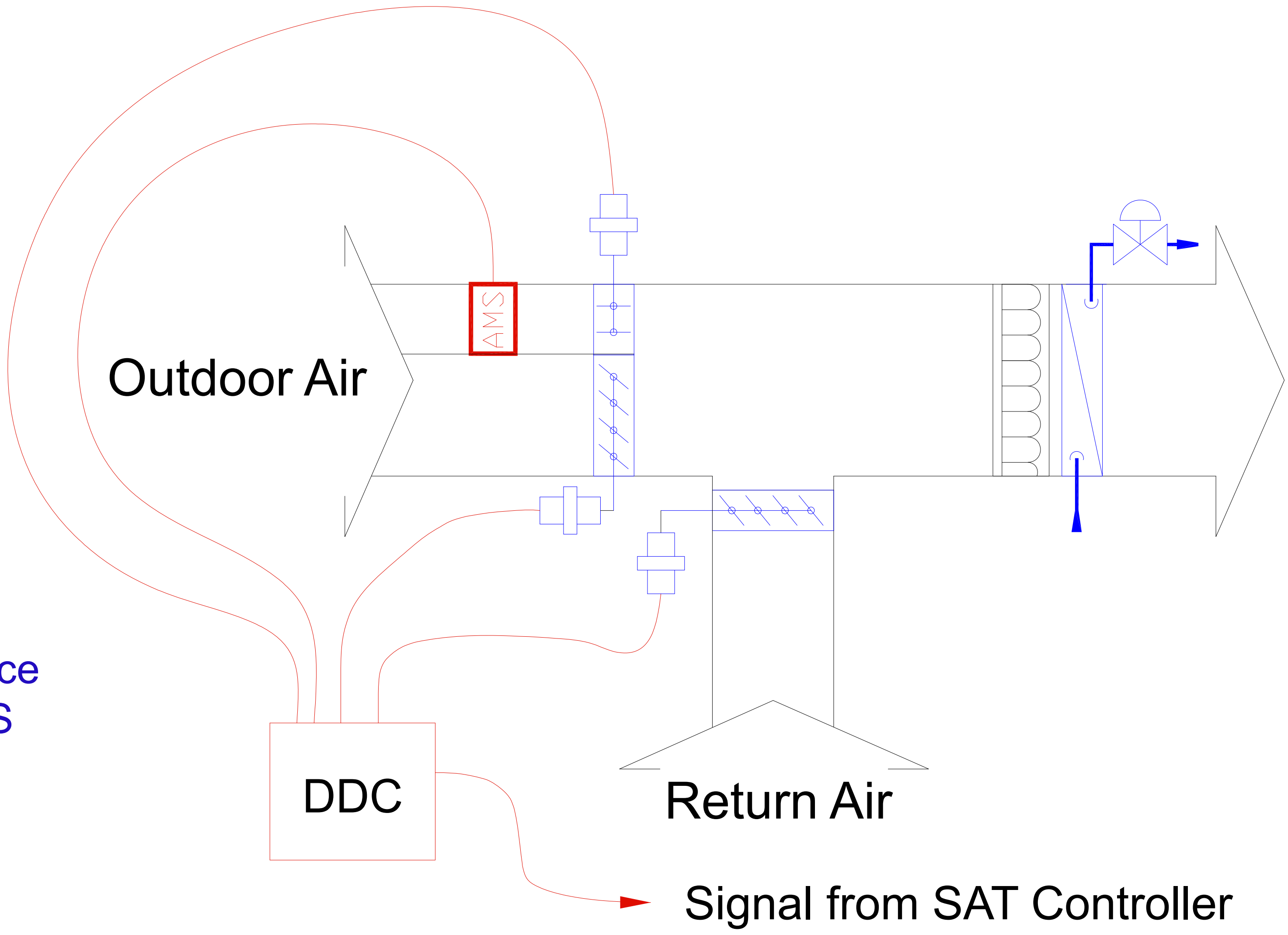


Injection Fan w/ AFMS



Works, but fan airflow measurement and damper (not VFD) required since fan volume will vary with DP

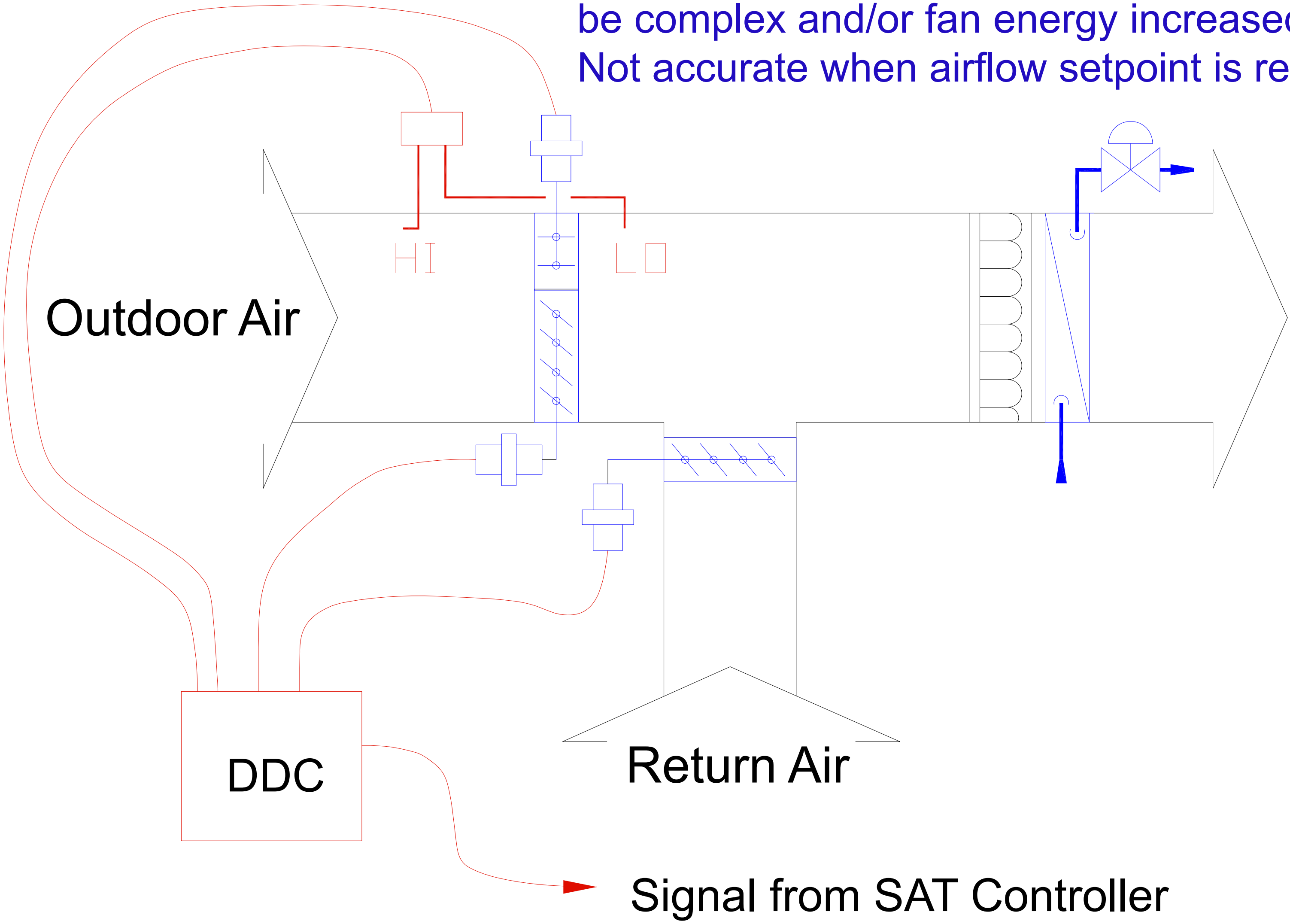
Dedicated Minimum Outdoor Air Section with AFMS



Works! But space needed for AMS

Fixed Minimum OA Damper w/ Plenum Pressure Control

Works, and lowest cost, but control sequence can be complex and/or fan energy increased slightly. Not accurate when airflow setpoint is reset



Summary of OSA Control Methods

METHOD	ACCURACY
Fixed Minimum	**Very poor**
Dual Minimum	**Fair**
Energy/CO_2 Balance	**Very Poor**
Return Fan Tracking	**Poor to Good (if app)**
100% AFMS	**Poor to Good**
Injection Fan	**Good to Excellent**
Dedicated Min AFMS	**Good to Excellent**
ΔP Across OA Damper	**Good**

Demand Control Ventilation

ASHRAE 1547-RP CO_2-BASED DEMAND CONTROLLED VENTILATION FOR MULTIPLE ZONE HVAC SYSTEMS

Demand Controlled Ventilation Requirements

- **Standard 62.1 allows DCV**
  - Occupant ventilation component can be reduced based on actual occupancy
    - CO_2 sensors listed as example
  - No current reduction allowed in building component

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z$$

6.2.7.1.2 The breathing zone outdoor airflow (V_{bz}) shall be reset in response to current occupancy and shall be no less than the building component ($R_a \cdot A_z$) of the DCV zone.

Note: Examples of reset methods or devices include population counters, carbon dioxide (CO_2) sensors, timers, occupancy schedules or occupancy sensors.

- **Standard 90.1 requires DCV for most VAV applications with DDC**

6.4.3.8 Ventilation Controls for High-Occupancy Areas. Demand control ventilation (DCV) is required for spaces larger than 500 ft^2 and with a design occupancy for ventilation of greater than ≥25 people per 1000 ft^2 of floor area and served by systems with one or more of the following:

a. Air-side economizer
b. Automatic modulating control of outdoor air damper
c. Design outdoor airflow greater than 3000 cfm.

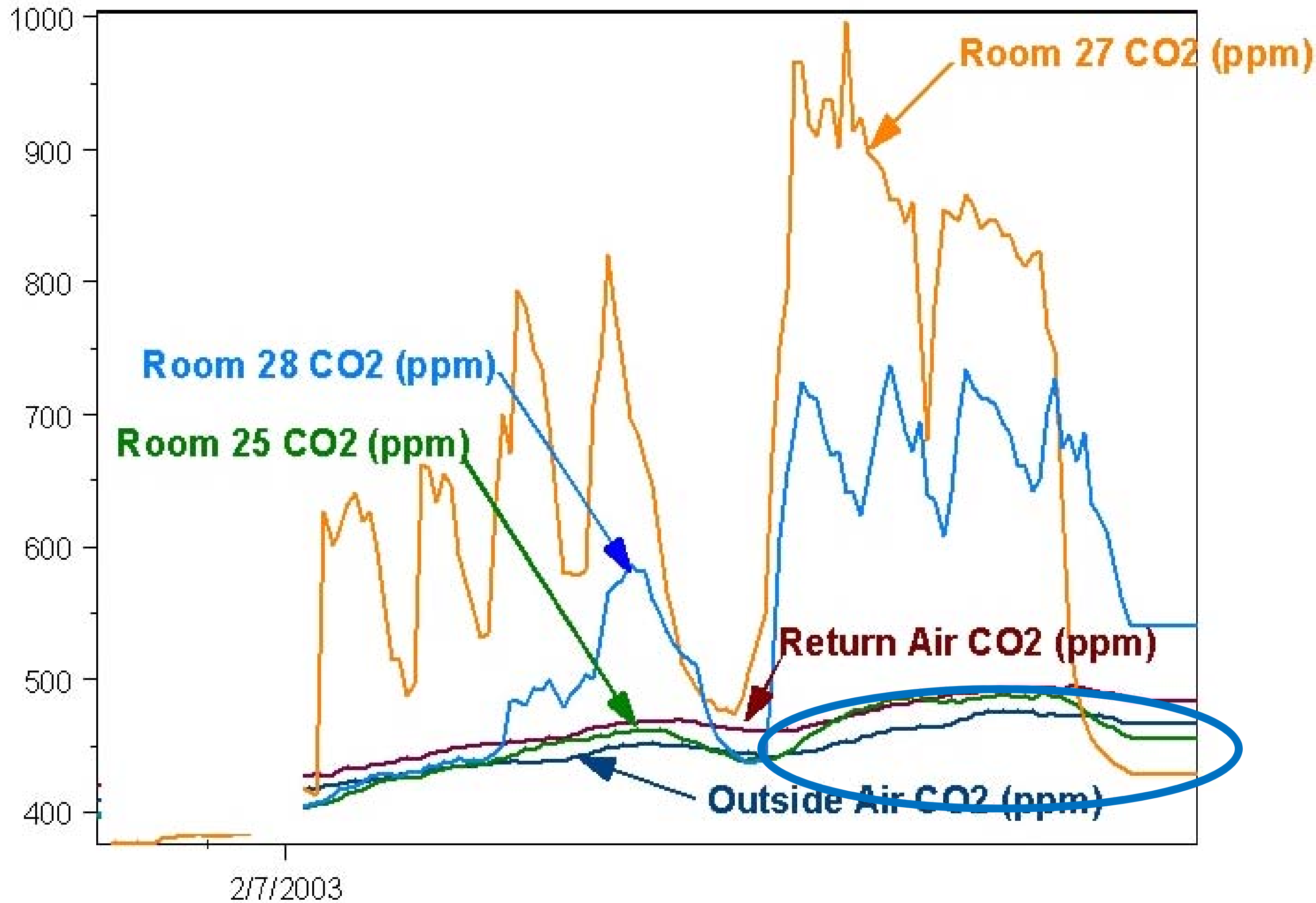
Exceptions:

1. Systems with the exhaust air energy recovery complying with Section 6.5.6.1
2. Multiple-zone systems without DDC of individual zones communicating with a central control panel

CO_2 Demand Controlled Ventilation

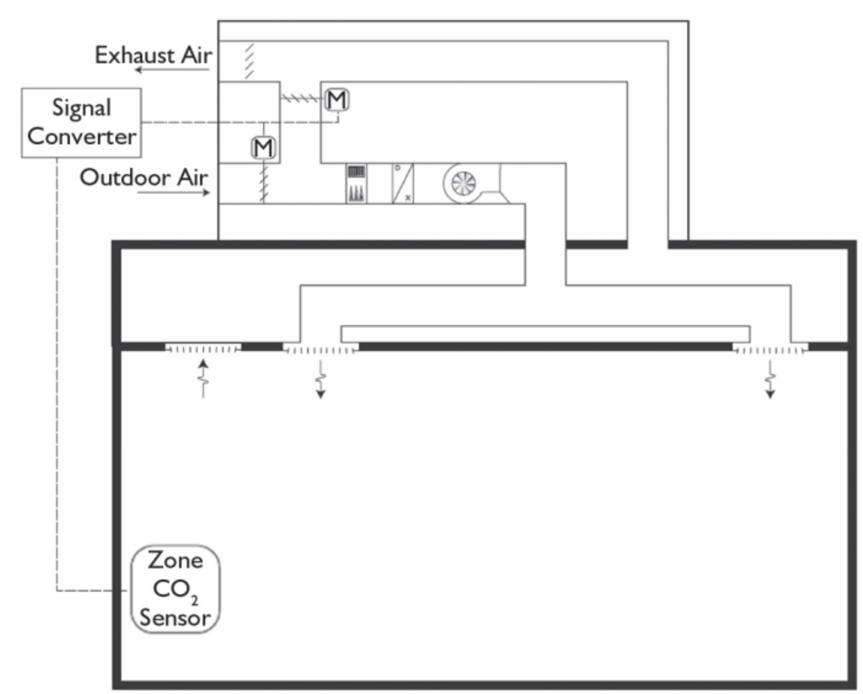
- **Key assumptions:**
  - The per-person ventilation rates required by Standard 62.1 are based on a bioeffluent concentration "with which a substantial majority (80% or more) of the <occupants> exposed do not express dissatisfaction"
  - Bioeffluent generation rate is proportional to number of occupants and their activity level and that the relationship is predictable and fixed
  - CO_2 generation rate is proportional to bioeffluent generation rate
- **RP 1547 basically affirmed these assumptions based on existing research**

Why Return CO_2 Sensors Don't Work

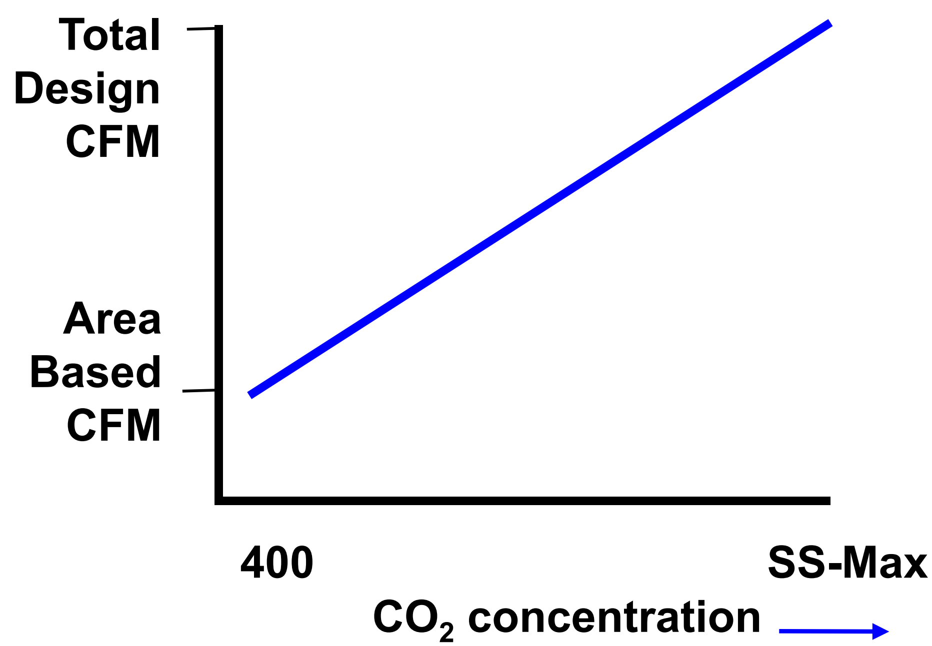


CO_2 sensors must sense CO_2 in the occupied space

Single Zone CO_2 DCV Control Schematic

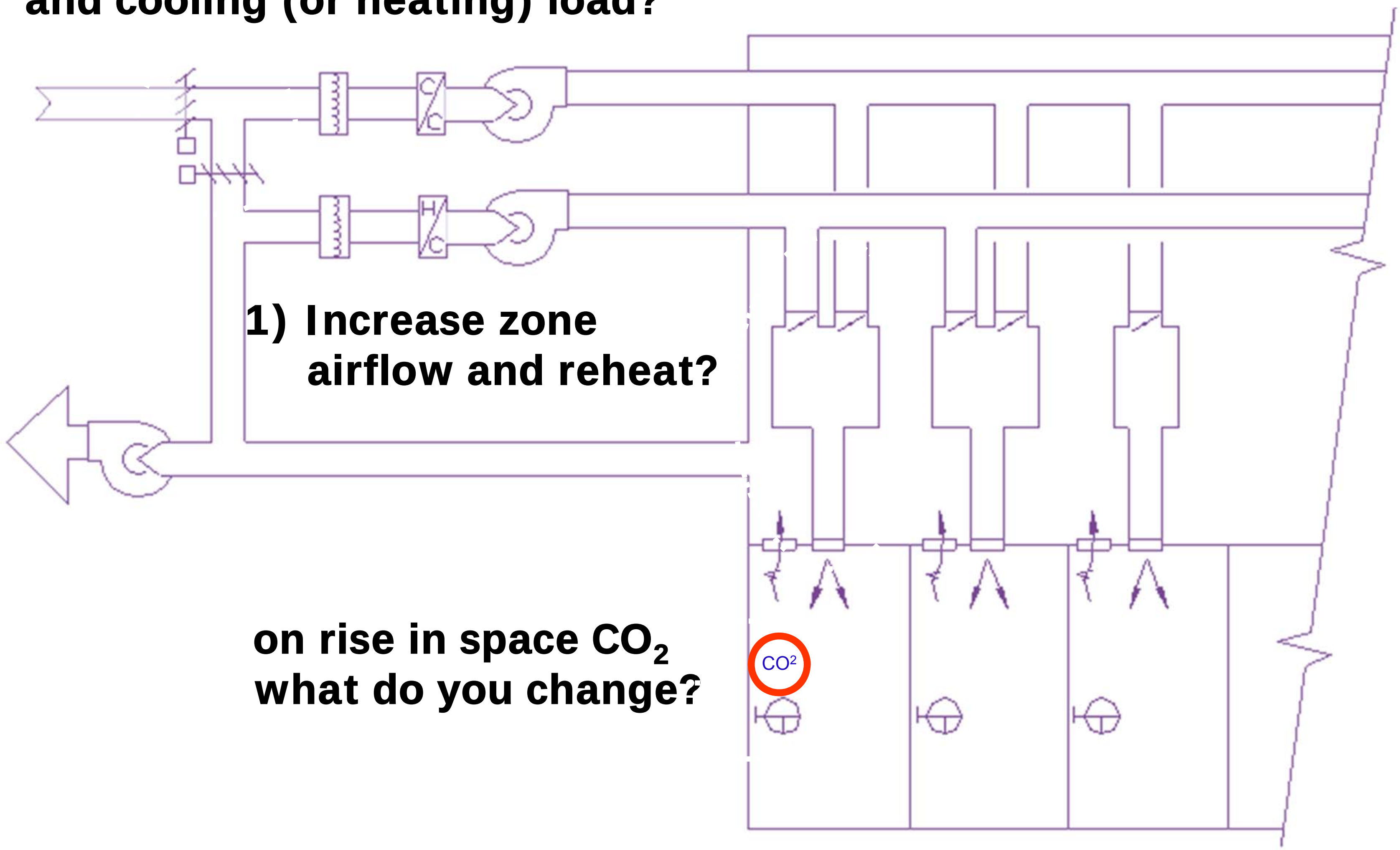


Occupancy Category	Steady State CO_2 Concentration
Classrooms (age 9 plus)	1025 ppm
Restaurant Dining Rooms	1570 ppm
Conference/Meeting	1755 ppm
Lobbies/Prefunction	1725 ppm
Office Space	990 ppm
Sales	1210 ppm



CO_2 DCV with Multiple Zone Systems

2) Increase minimum system OA
and cooling (or heating) load?



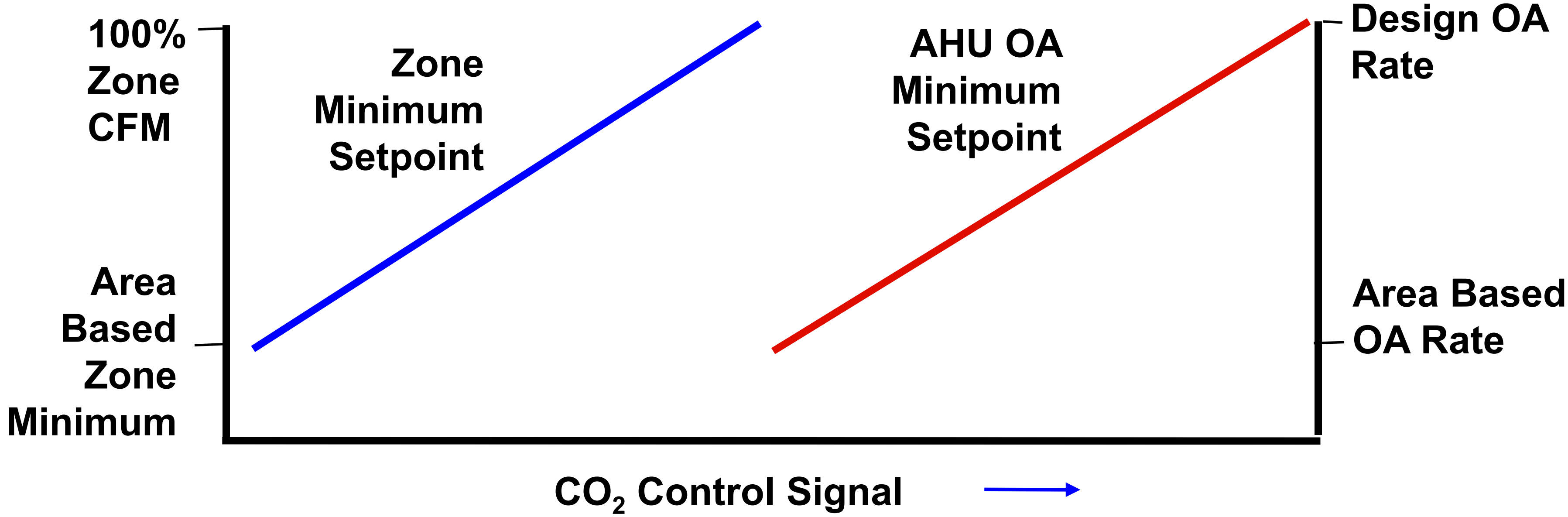
1) Increase zone
airflow and reheat?

on rise in space CO_2
what do you change?

Multiple Zone System CO_2 DCV

❑ Simplified Approach

- First: Increase the zone damper up to 100% of zone maximum based on zone CO_2 signal
- Then: Increase the minimum OA setpoint from unoccupied minimum rate to design minimum rate based on maximum zone CO_2 signal



RP-1547 Approach (Option 1)

- **AHU Design**
  - Design AHU outdoor air intake is sum of zone design airflow rates
    - Optionally adjusted for occupant diversity
  - Required sensors:
    - Supply air CO_2
    - Return air CO_2
    - Outdoor Airflow Measuring Station at both minimum and economizer intakes
- **Zone Design**
  - Cool and Heat maximum setpoints determined normally
  - Minimum airflow setpoints:
    - CO_2 zones: building component
    - Occupancy sensor zones: building component
    - Other zones: both building and occupant component
- **AHU Controls**
  - Dynamically recalculate required outdoor air intake based on Standard 62.1 multiple spaces equation
    - Setpoint varies from sum of design zone minimums to Design rate
  - Control minimum outdoor air rate with dampers
  - Economizer dampers controlled normally
- **Zone Controls**
  - If outdoor air rate (including economizer) is below setpoint, find “critical zone” and increase zone minimum until this satisfies AHU setpoint

RP-1547 Approach

- **Advantages**
  - No need to use "multiple spaces equation" for design AHU outdoor air rate – just add up zone rates
  - VAV box minimums simply equal to the zone ventilation rate
  - Very high HVAC energy savings
    - 25%-46% depending on climate
- **Disadvantages**
  - Only applies to single path VAV systems
  - Impact of CO_2 sensor inaccuracy not known
  - Future RPs needed
    - Multiple path systems
    - Error analysis and field study on CO_2 sensors

AFDD: Automatic Fault Detection & Diagnostics

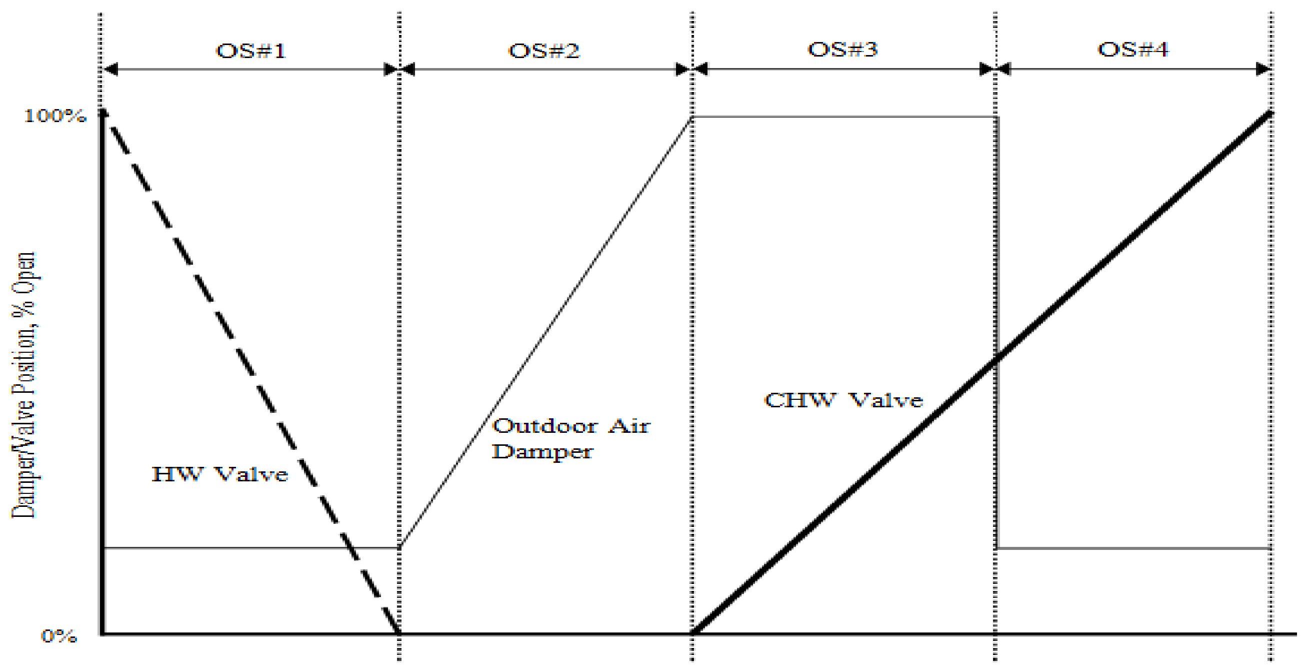
- Based on research by House, Bushby and Schein at NIST in 2000-2006
- Only for air handlers (APAR). VAV box FDD (VPACC) requires too much tuning
- Finds fault and diagnosis by evaluating equations (mostly energy balance)

AFDD Fault Conditions

FC #1	**Equation**	$DSP < DSPSP - \varepsilon_{DSP}$ <u>and</u> $VFDSPD \geq 99\% - \varepsilon_{VFDSPD}$	**Applies to OS #1 – #5**
	Description	Duct static pressure is too low with fan at full speed	
	Possible Diagnosis	Problem with VFD Mechanical problem with fan Fan undersized SAT Setpoint too high (too much zone demand)	
FC #2	**Equation**	$MAT_{AVG} + \varepsilon_{MAT} < \min[(RAT_{AVG} - \varepsilon_{RAT}), (OAT_{AVG} - \varepsilon_{OAT})]$	**Applies to OS #1 – #5**
	Description	MAT too low; should be between OAT and RAT	
	Possible Diagnosis	RAT sensor error MAT sensor error OAT sensor error	

AFDD Equations Depend on AHU Operating State

Operating State	Heating Valve Position	Cooling Valve Position	Outdoor Air Damper Position
#1: Heating	> 0	= 0	= MIN
#2: Free Cooling, Modulating OA	= 0	= 0	MIN < X < 100%
#3: Mechanical + Economizer Cooling	= 0	> 0	= 100%
#4: Mechanical Cooling, Min OA	= 0	> 0	= MIN
#5: Unknown or Dehumidification	No other OS applies		



Hierarchical Alarm Suppression

- Nuisance alarms are a huge problem for operators
- If upstream equipment (e.g. AHU) and downstream equipment (e.g. VAV boxes) are both in alarm, this suppresses downstream alarms
- Must define upstream/downstream relationships for air, cooling, and heat
- Upstream equipment passes "OK" token to downstream equipment when it's working right. Until getting "OK", downstream alarms are suppressed

Summary

- **In this class, you have learned to optimizing VAV System Controls for**
  - VAV terminal units per RP-1455 and RP-1515
  - AHUs per RP-1455
  - Ventilation Systems per RP-980 and RP-1547
- **And more!**

Resources

- **TE Articles**
  - “Sizing VAV Boxes”, ASHRAE Journal, March 2004
  - “CO2-Based DCV Using Standard 62.1-2004”. ASHRAE Journal May 2006:
  - “Increasing Efficiency with VAV System Static Pressure Reset”, ASHRAE Journal July 2007
  - “Economizer High Limit Devices and Why Enthalpy Economizers Don't Work”, ASHRAE Journal November 2010
  - “Dual Maximum VAV Box Logic”, ASHRAE Journal, December 2012
  - Available at no charge from http://www.taylor-engineering.com/publications/articles.shtml
- **Dickerhoff D., Stein J.; “Stability and Accuracy of VAV Terminal Units at Low Flow”, PG&E 0514, http://www.etcc-ca.com/reports/stability-and-accuracy-vav-terminal-units-low-flow**
- **Lui R., Wen J.; Stability and Accuracy of VAV Box Control at Low Flows”, ASHRAE 1353-RP**
- **Iowa State Energy Center National Building Controls Information Program http://www.energy.iastate.edu/Efficiency/Commercial/nbcip.htm#ptreports**

Questions