VAV Systems Part 2: VAV System Duct Design

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Lisa Cherney

Education Manager, AMCA International

Webinar Moderator

- 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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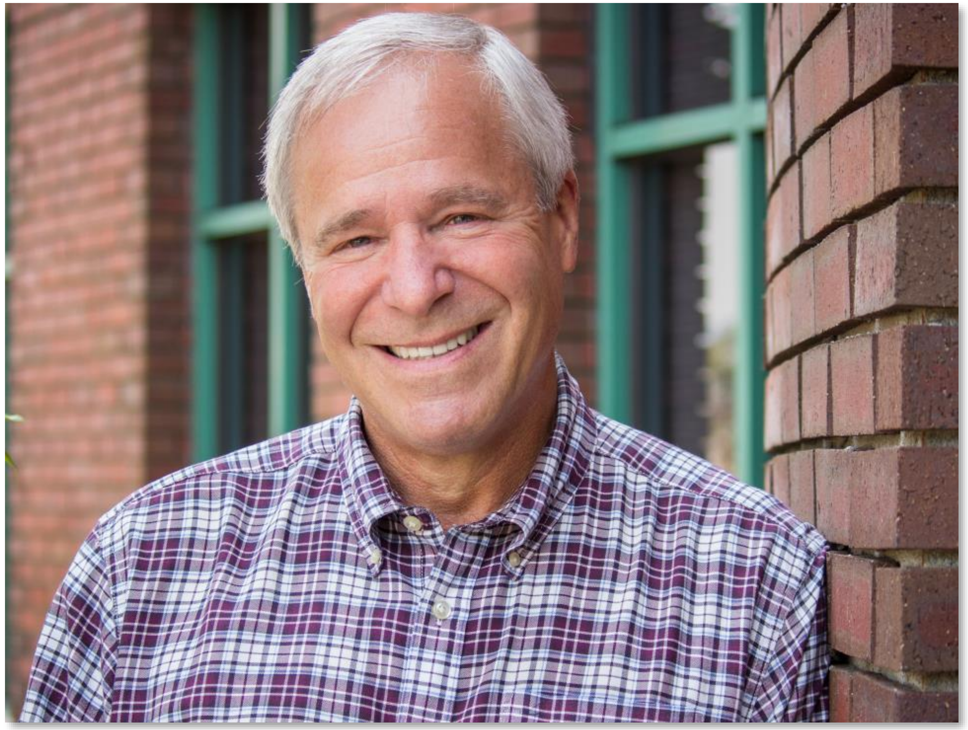
Steve Taylor, FASHRAE, P.E.

Principal Taylor Engineering LLP
& AMCA Consultant

- Specializes in HVAC system design, control system design, IAQ, computerized building analysis and HVAC system commissioning
- 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
- Fellow of ASHRAE, one of the primary authors of ASHRAE 90.1 and 62.1, and 16 year member of IAPMO Mechanical Technical Committee administering the Uniform Mechanical Code



VAV Systems Part 2: VAV System Duct Design

Purpose and Learning Objectives

The purpose of this presentation is to introduce new and optimized techniques for designing high performing VAV systems at minimal cost.

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

1. Size VAV duct mains cost effectively
2. Select VAV boxes for minimum life cycle cost
3. Explain how VAV boxes should be ducted to minimize life cycle costs
4. Compare ducted vs. plenum return systems

Agenda – VAV System Duct Design

- VAV Duct Main Sizing
- VAV Box Sizing
- VAV Box Inlet & Outlet Duct Design
- Return Air System Design

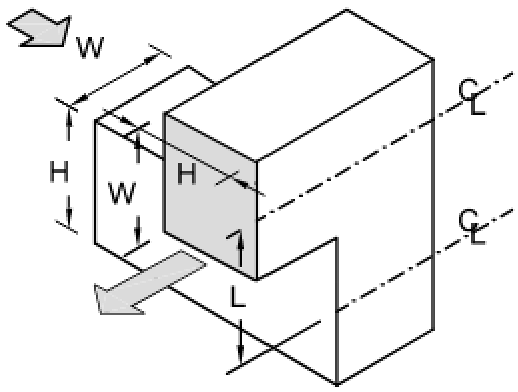
VAV Duct Main Sizing

Duct Sizing

- Ideally use Life-Cycle Costs (LCCs) balancing:
  - First Cost
    - Materials, labor
    - In the shop vs. in the field
  - Annual Costs
    - Energy
    - Pressure drop, air volume-flow rates
  - With Constraints
    - Space
    - Noise

But using LCC for duct design is not practical

- **First costs are difficult to calculate**
  - Cost is not proportional to friction rate, velocity, or even lbs. of sheet metal
  - No standard sizes or standard fittings
  - Costs vary by capabilities of shop
- **Energy costs are difficult to calculate**
  - Pressure drop not just a function of friction rate
  - Fitting losses make up the bulk of duct pressure losses
  - Duct system effects due to consecutive fittings can make up ~50% pressure drop but not readily calculated
    - ASHRAE Duct Fitting Database includes nothing on consecutive fittings
    - SMACNA HVAC Systems Duct Design manual has one: two square elbows without vanes out of plane



42% increase vs. individual elbows with long straight ducts

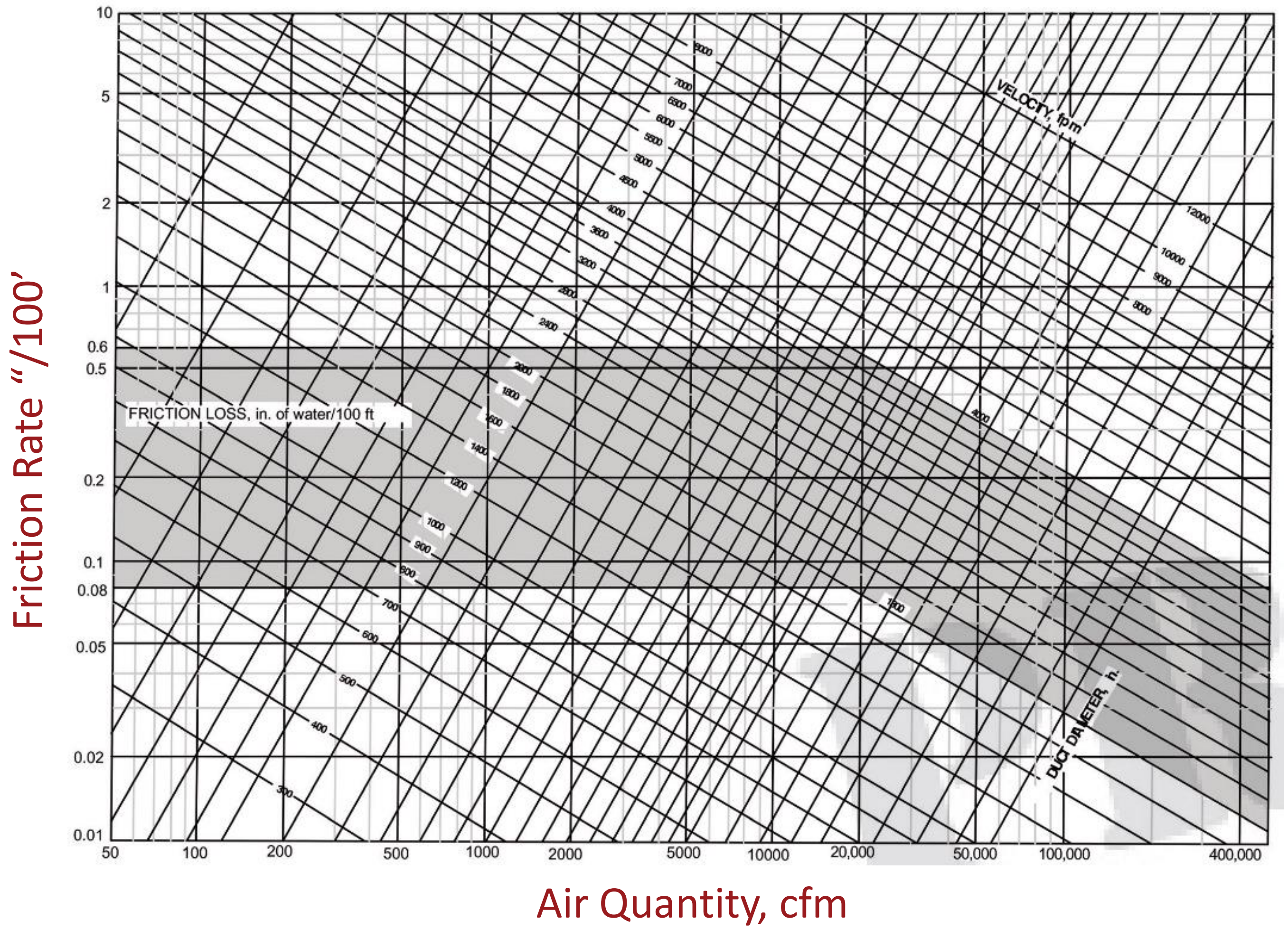
ASHRAE HoF Chapter 21 Duct Design Methods

- **Equal Friction**
  - Friction rate (loss/ft) is kept constant in each duct section.
- **Static Regain**
  - Ducts are sized such that the velocity in each section reduces, so that the dynamic and friction losses in that duct section are exactly offset by the conversion of velocity pressure into static pressure, leaving static pressure constant.
- Neither has a strong rationale for sizing ducts!

What does ASHRAE recommend for duct sizing?

- ASHRAE HoF Chapter 21
  - Friction rates “typically” range from 0.05 to 0.20 in.w.c./100 ft for low-pressure ductwork
  - Duct size tables for three friction rates: 0.08, 0.2, and 0.6 in.w.c./100 ft
    - No advice for when to use which rate!
  - One example: Friction rate (0.67 in.w.c./100 ft) is determined by the duct size that maximizes the acoustically allowable velocity (3000 fpm in the example), then this friction rate is used to size all the downstream ductwork.
    - Pretty sure no one has ever sized ducts in this way!

What does SMACNA recommend for duct sizing?



Select friction rate and velocity within shaded area (0.08" to 0.6"/100')

States that 0.1"/100' is most common friction rate for low pressure ducts

If 0.1”/100’ is “right” for low pressure CAV, what friction rate is “right” for VAV?

- For sure 0.1”/100’ cannot be the LCC best for VAV since first cost is the same but energy costs are much lower.
- If LCCs are minimized at 0.1”/100’ for CAV, then LCC minimum friction rate for VAV will be ~0.25” to 0.3”/100’
  - See ASHRAE Journal reference at the end of this presentation for calculation.
- But maybe there is a better method than equal friction for VAV duct main sizing…

EDR Advanced VAV System Design Guide:

Friction Rate Reduction Method

for ducts upstream of VAV boxes

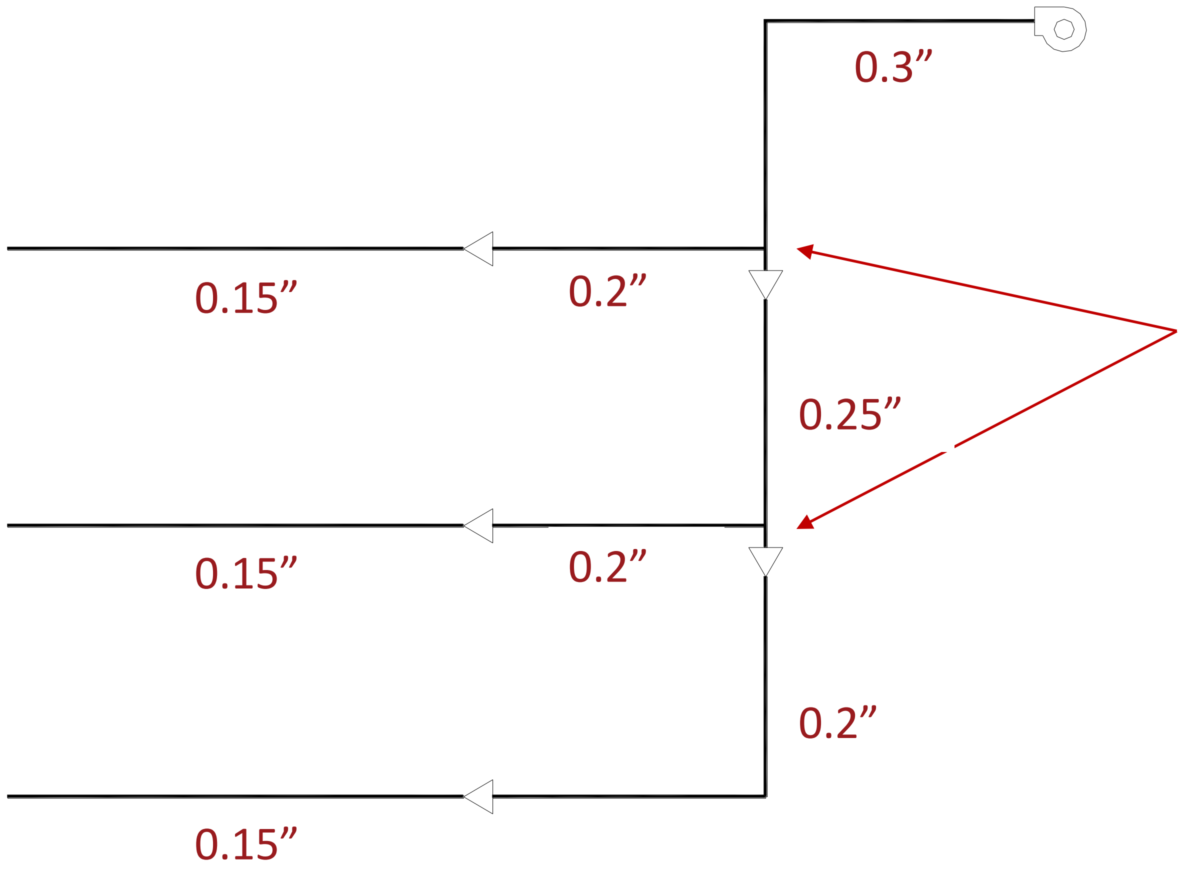
- Starting at the fan discharge, choose the duct size based on both maximum friction rate (0.3”/100;’) and velocity limits (next slide).
- At the end of the duct system, choose a minimum friction rate (typically 0.10” to 0.15”/100’)
- Decide how many transitions will occur along the hydraulically longest duct main (the run with the highest pressure drop that will determine the design pressure drop and fan power) from the fan to the most remote VAV box.
  - Typically, a transition should not be made any more frequently than every 20 feet since
    - The cost of the transition will generally offset the cost of the sheet metal savings.
    - The design is more flexible to accommodate future changes
    - The design is more energy efficient with fewer transitions.
- Take the difference between the maximum friction rate as determined in step 1 (whether determined by the friction limit or velocity limit) and the minimum friction rate from step 2 (e.g., 0.3 in. less 0.1 in. = 0.2 in.) and divide it by the number of transitions. The result is called the friction rate reduction factor.
- Size duct along the index run starting with the maximum friction rate, then reduce the friction rate at each transition by the friction rate reduction factor. By design, the last section will be sized for the minimum friction rate selected in step 2.

ASHRAE Velocity Limits

Table 1 ***Recommended Maximum Airflow Velocities to Achieve Specified Acoustic Design Criteria (Table 12 from ASHRAE Handbook, Fundamentals, Chapter 21)***

Duct Location	NC or RC Rating in Adjoining Occupancy	Maximum Airflow Velocity, f	
		Rectangular Duct	Round D
1	2	3	4
In shaft or above solid drywall ceiling	45	3500	5000
	35	2500	3500
	25 or less	1500	2500
Above suspended acoustical ceiling	45	2500	4500
	35	1750	3000
	25 or less	1000	2000
Duct within occupied space	45	2000	3900
	35	1450	2600
	25 or less	950	1700

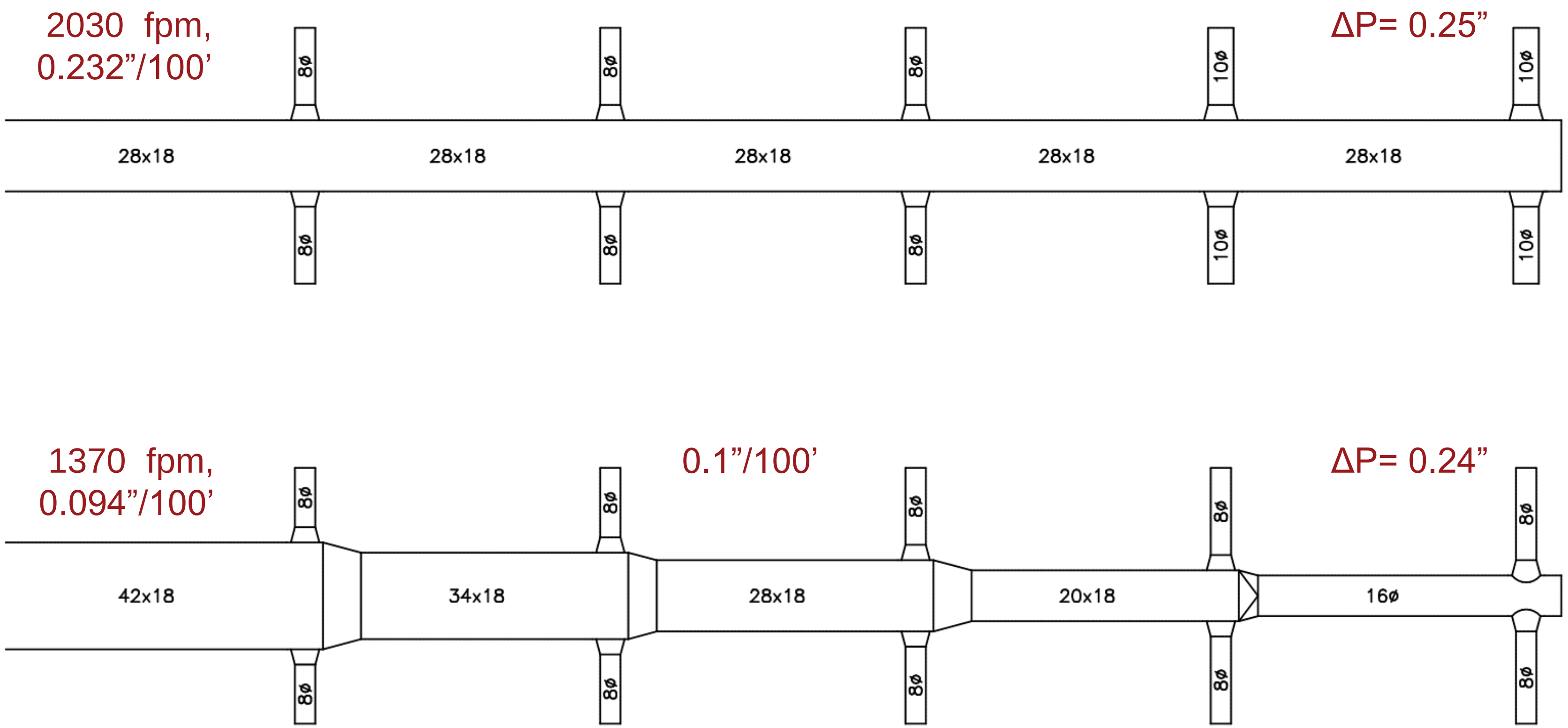
Example: Friction rate reduction method



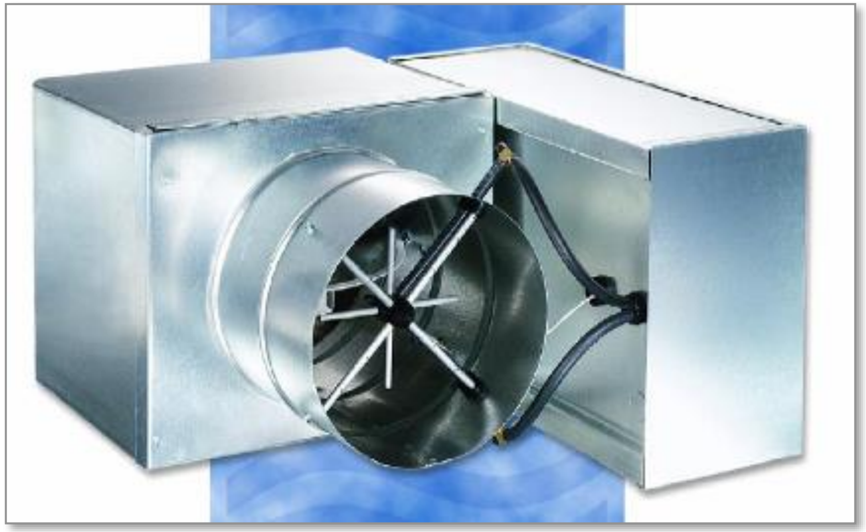
Size ducts on the other floors the same as index run for simplicity

“Start fast; end slow”

Similar pressure drop, lower costs, less space required



VAV Box Sizing



VAV Box Sizing

- Oversized box
  - Less pressure drop
  - Less noise
  - Higher box min → more reheat
  - Cost more

- Undersized box
  - More pressure drop
  - More noise
  - Lower box min → less reheat

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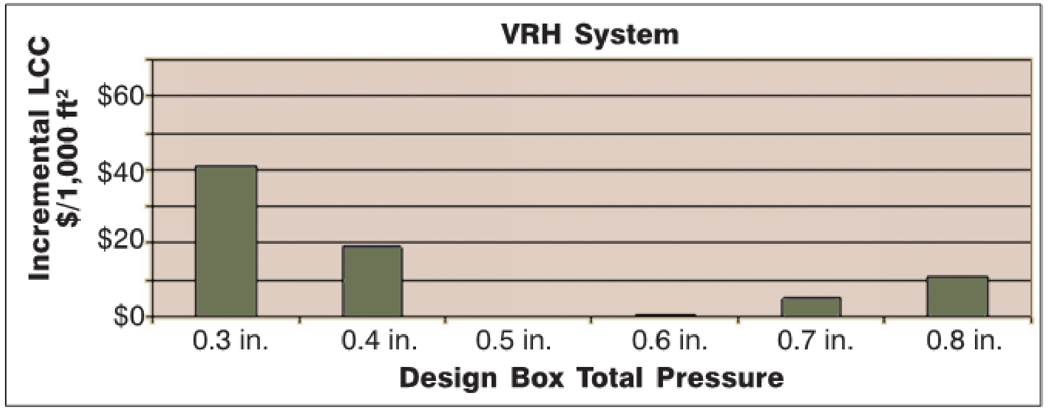
VAV RH Box Sizing: LCC Analysis

- Compared TP from 0.3” to 0.8”
- East Bay office building
- Sensitivity Analysis
  - Climate
  - Loads (internal, envelope)
  - Operating schedules
  - Load calc’ (aggressive, conservative)
  - Utility rates
  - 8 bit versus 10 bit A/D converter
  - SAT (50°F-60°F), SAT reset, SP reset



- **RESULT**: Size Standard VAV RH Boxes for 0.5” DTP

VAV Box Sizing: Calculating ΔTP

- Manufacturers all list ΔSP but not all list ΔTP

$$\Delta TP = \Delta SP + \Delta VP$$

$$= \Delta SP + \left[\left(\frac{v_{in}}{4005} \right)^2 - \left(\frac{v_{out}}{4005} \right)^2 \right]$$

- Need to know Outlet Area

VAV Box Sizing: Sample Calc.

Nominal size	Inlet dia. (in.)	Outlet width (in.)	Outlet height (in.)	ΔSP (in. w.g.)*	ΔVP (in. w.g.)	ΔTP (in. w.g.)	Max CFM	Radiated NC*
4	4	12	8	0.08	0.42	0.50	230	21
5	5	12	8	0.15	0.35	0.50	333	20
6	6	12	8	0.24	0.25	0.49	425	21
7	7	12	10	0.25	0.25	0.50	580	20
8	8	12	10	0.33	0.17	0.50	675	22
9	9	14	13	0.27	0.23	0.50	930	17
10	10	14	13	0.32	0.18	0.50	1100	19
12	12	16	15	0.32	0.17	0.49	1560	19
14	14	20	18	0.31	0.19	0.50	2130	18
16	16	24	18	0.32	0.18	0.50	2730	22

*From selection software using ARI 885-95 and assuming inlet SP = 1.5 and outlet SP = 0.25

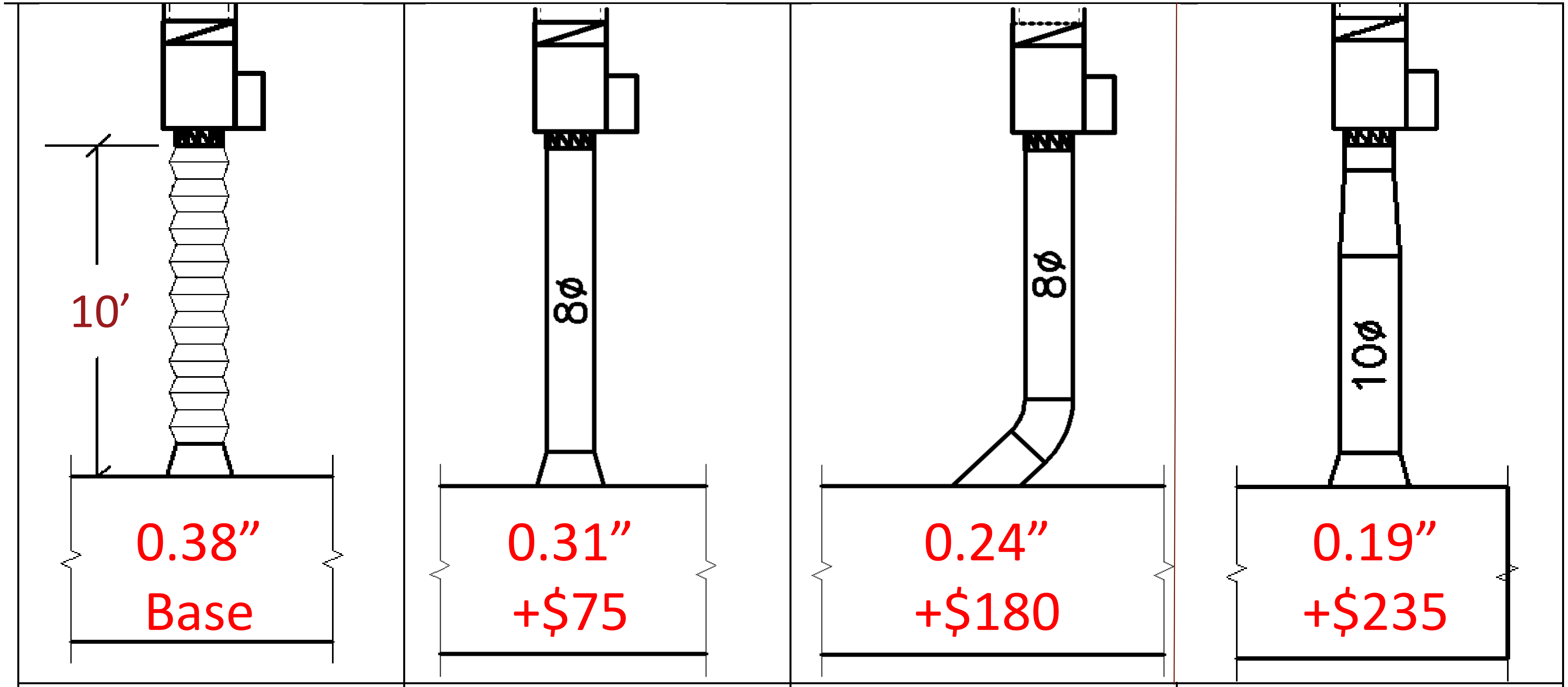
Include this Option: “Oversized” reheat coil

- Box and coil are the standard size of the next larger box size
  - E.g., the box and coil are for a standard 10-inch VAV box but the damper and velocity pressure sensor are 8 inch
- Benefits
  - Lower air pressure drop
  - ~10F larger HW ΔT
    - Reduces pump and pipe sizes
    - Improve condensing boiler efficiency
    - Improved ΔT on low temperature heat pump systems
  - Allows less expensive discharge plenum (more on this later)
  - Good payback
- Standard factory option for many manufacturers
  - Be very clear in VAV box schedules and specs to avoid contractor backlash
- The more of us who specify this option, the more available and the lower the cost.
- **Note**: 0.5” ΔTP selection optimum is for standard coil size, so select VAV inlet size assuming standard coil

VAV Box Inlet & Outlet Duct Design

VAV Box Inlet Ducts off Rectangular Main

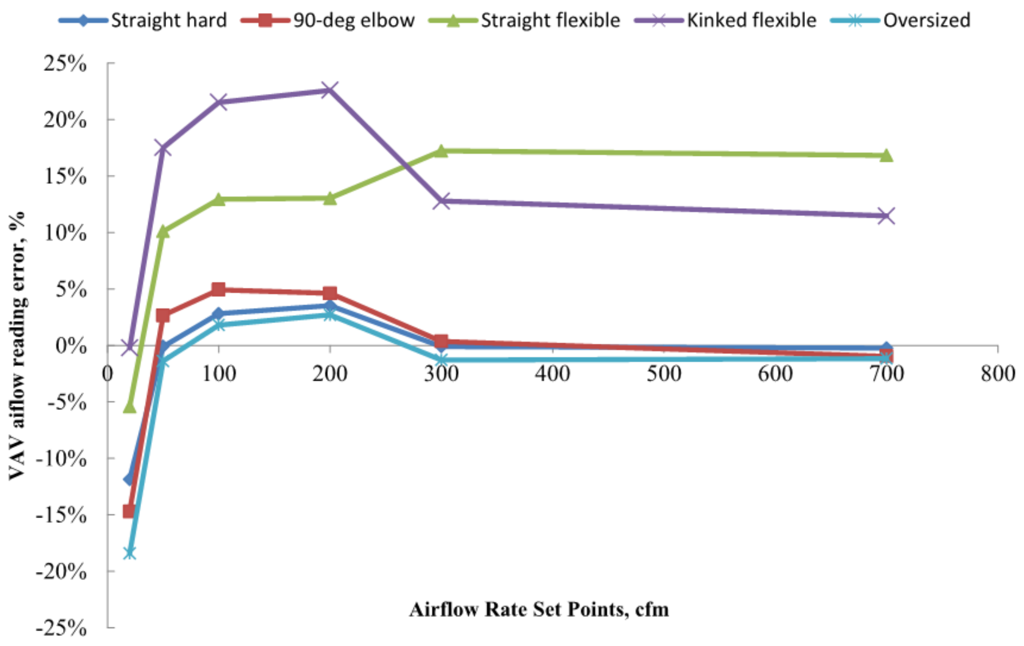
(Based on 8-inch inlet Box, 630 cfm, 1500 fpm duct main velocity)



A. Conical, Flex | B. Conical, Hard | C. 45°, Hard | D. Oversized Conical, Hard

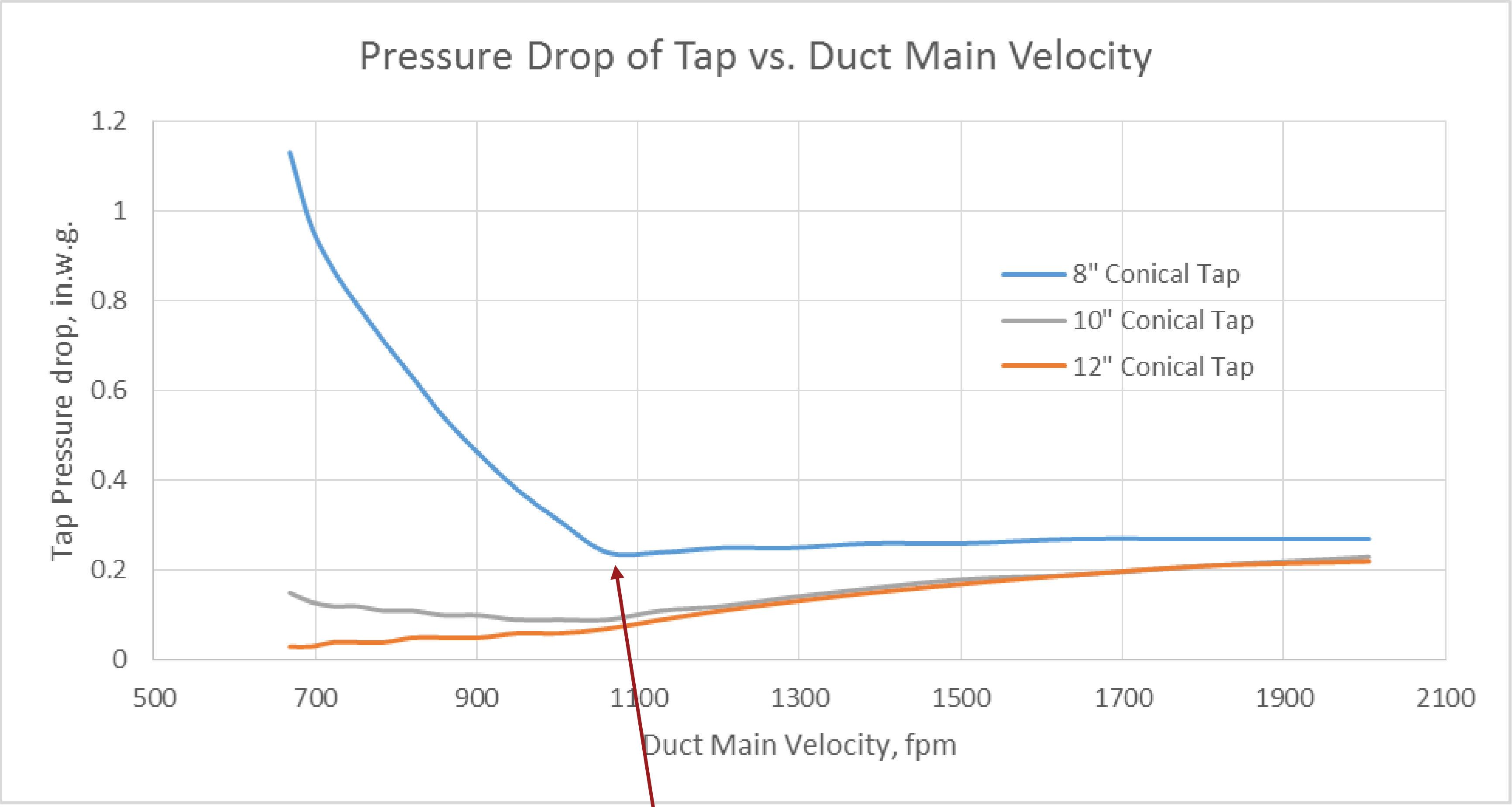
Avoid flexible duct at inlets to VAV Boxes

- High pressure drop, particularly if kinked
- Roughness can cause errors in velocity pressure sensor readings (RP-1353)



- Flexible duct is largely transparent to breakout noise

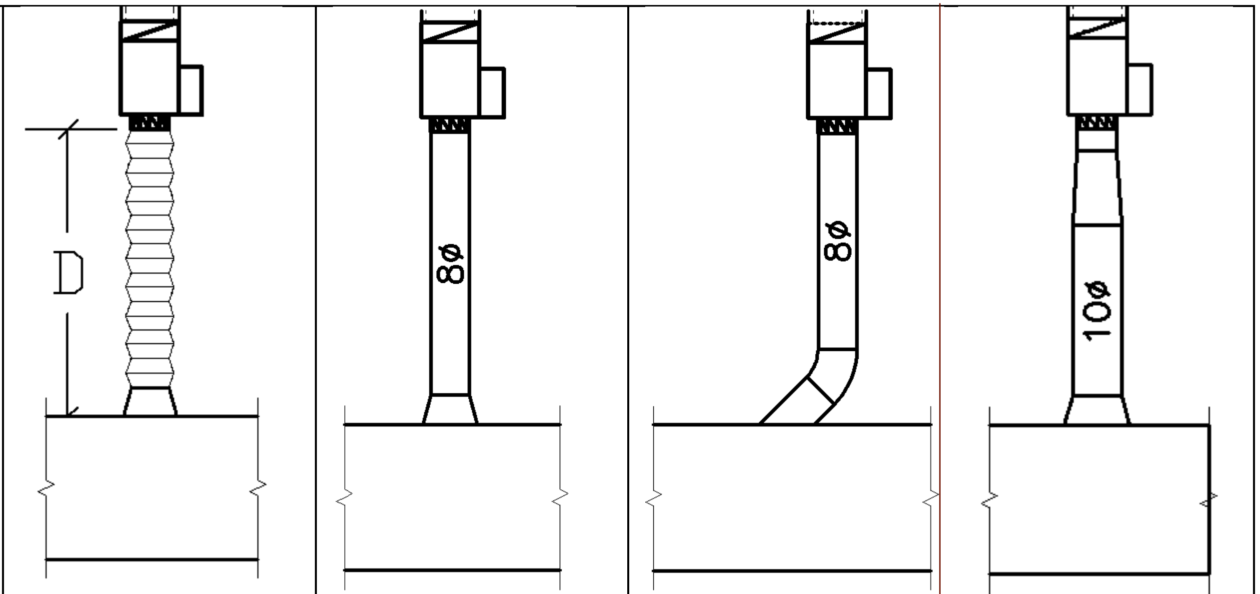
Taps into low velocity mains



Inflection starts when duct main velocity ~60% of tap duct velocity

VAV Box Inlet Ducts off Rectangular Main

Summary



Option		A. Conical, Flex			B. Conical, Hard			C. 45°, Hard			D. Oversized Conical, Hard		
Dimension D (ft)		5	10	15	5	10	15	5	10	15	5	10	15
Relative First Cost		Base	Base	Base	$55	$75	$90	$160	$180	$200	$210	$235	$260
Total Pressure Drop (in.w.g.)	Tap	0.25	0.25	0.25	0.25	0.25	0.25	0.18	0.18	0.18	0.16	0.16	0.16
	Duct	0.06	0.13	0.20	0.03	0.06	0.10	0.03	0.06	0.10	0.01	0.02	0.03
	Taper	–	–	–	–	–	–	–	–	–	0.01	0.01	0.01
	Total	**0.31**	**0.38**	**0.45**	**0.28**	**0.31**	**0.35**	**0.21**	**0.24**	**0.28**	**0.18**	**0.19**	**0.20**
Application Note		1	1	1	2	2	2	3, 4	3, 4	3	4, 5	4, 5	5, 6

Application Notes:

1. Not recommended
2. Recommended for most VAV boxes but not at low velocity main ducts or for "obviously critical" VAV boxes
3. Recommended when VAV box is at a 45º angle to main (not shown in option figure)
4. Recommended "obviously critical" VAV boxes
5. Recommended at low velocity main ducts
6. Recommended for VAV boxes that are greater than about 15 feet from main

Why not Option D everywhere?

- Example: 60,000 cfm VAV system, 70 zones
- Adding 0.15 in.w.g. to the fan design pressure for Option B versus D increased energy costs only a few hundred dollars per year.
- Excellent payback if one zone was always the critical zone and Option D were only applied to it.
- But if all 70 zones in the system were designed using Option D, the payback would be 75 years.
- To get a 15-year payback, no more than 20% of the potentially critical zones could be ducted using Option D.

Choosing which zones are potentially critical requires judgement

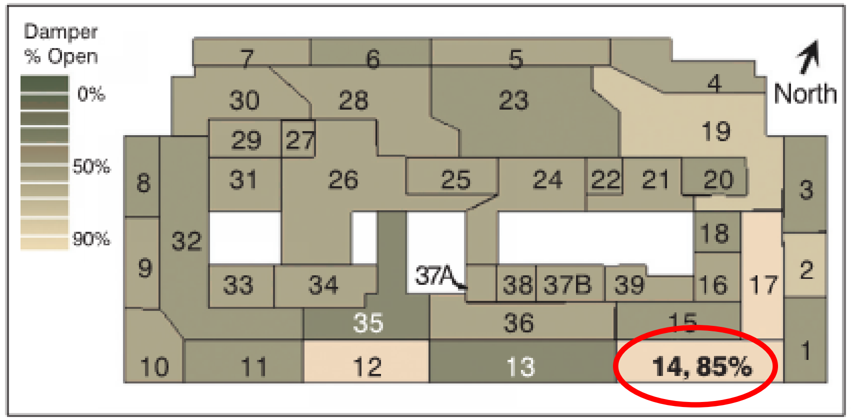


Figure 6: Site 3 VAV box demand (7 a.m., Aug. 5, 2002).

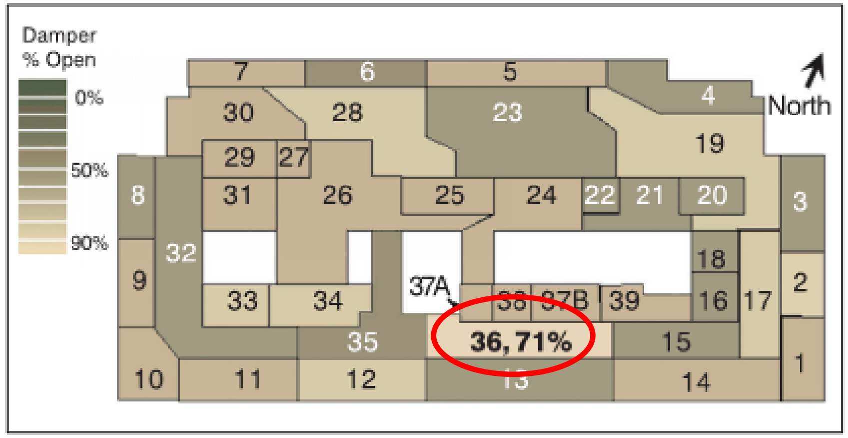


Figure 7: Site 3 VAV box demand (9 a.m., Aug. 5, 2002).

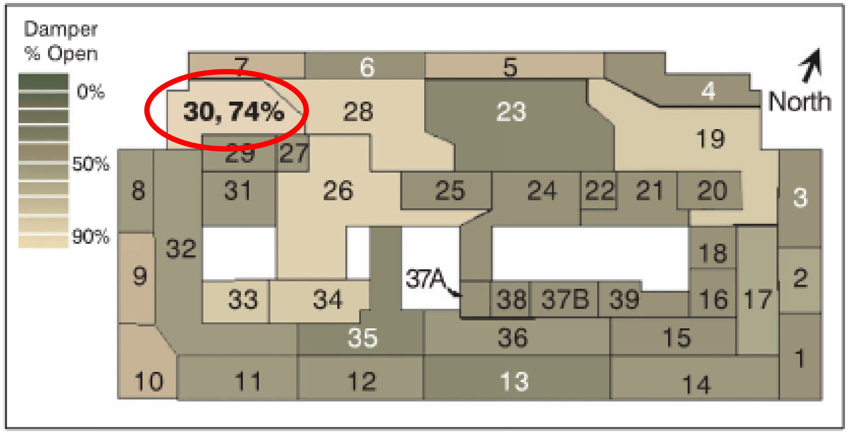
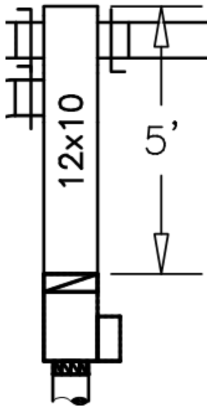
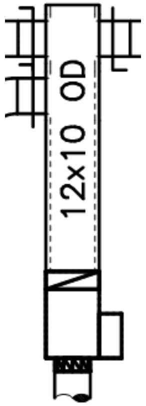
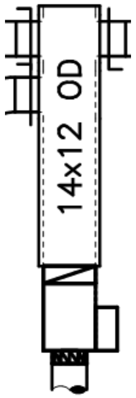
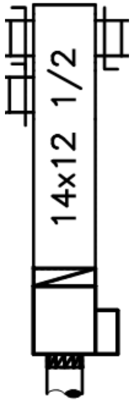
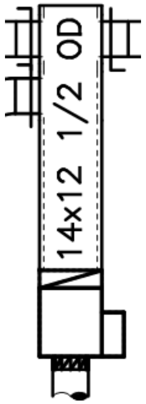


Figure 8: Site 3 VAV box demand (5 p.m., Aug. 5, 2002).

VAV Box Discharge Ducts

Based on 8-inch inlet Box, three 210 cfm diffuser taps

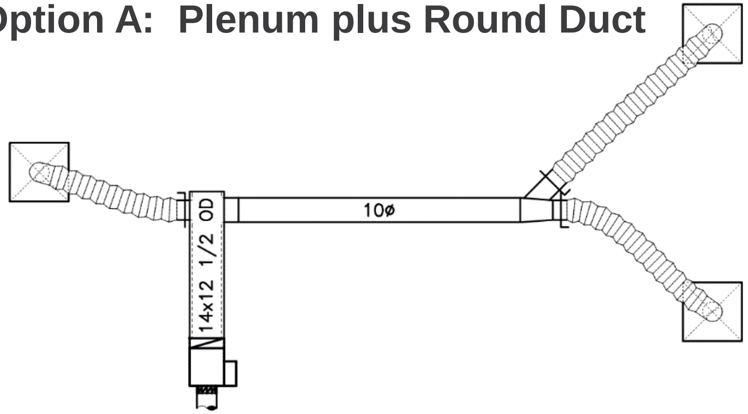
Option		A. Unlined Plenum	B. Lined Plenum, Constant OD	C. Lined Plenum, Constant ID	D. Unlined Plenum, Oversized HW Coil	E. Lined Plenum, Constant OD, Oversized HW Coil
						
Relative First Cost		Base	$55	$285	$90	$145
Total Pressure Drop (in.w.g.)	HW coil	0.30	0.30	0.30	0.15	0.15
	Liner edge	0.00	0.02	0.00	0.00	0.01
	Plenum	0.00	0.02	0.01	0.00	0.01
	Diff. Tap	0.05	0.09	0.05	0.03	0.05
	Total	**0.35**	**0.43**	**0.36**	**0.18**	**0.22**
Application Note		1	1	1	2	3

Application Notes:

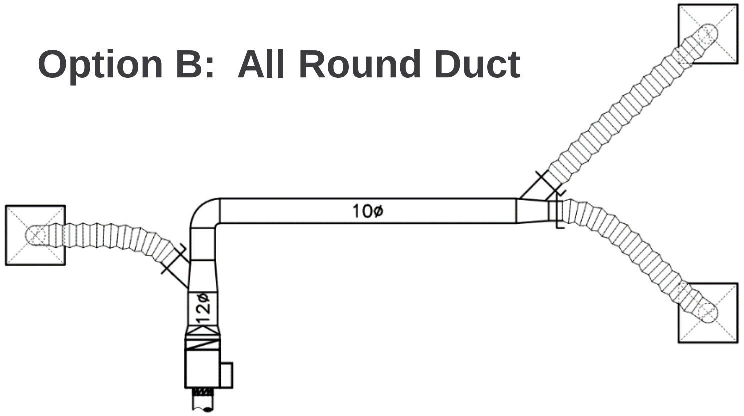
1. Not recommended
2. Recommended where acoustic considerations are met without liner or liner is not allowed/desired
3. Recommended where liner is required for acoustics and allowed by code and local practice

VAV Box / Branch Layouts

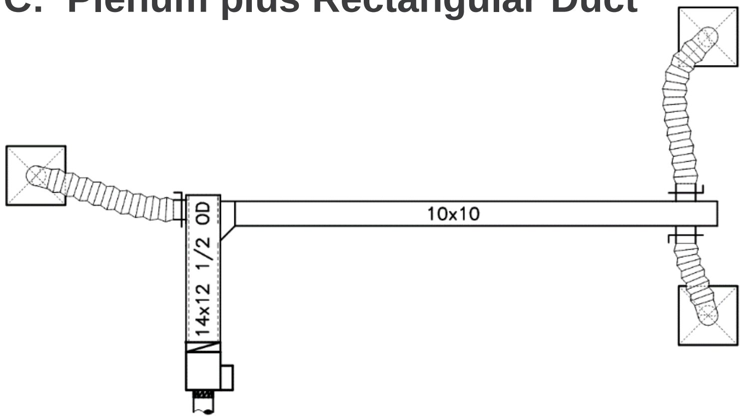
Option A: Plenum plus Round Duct



Option B: All Round Duct



Option C: Plenum plus Rectangular Duct



Return Air System Design

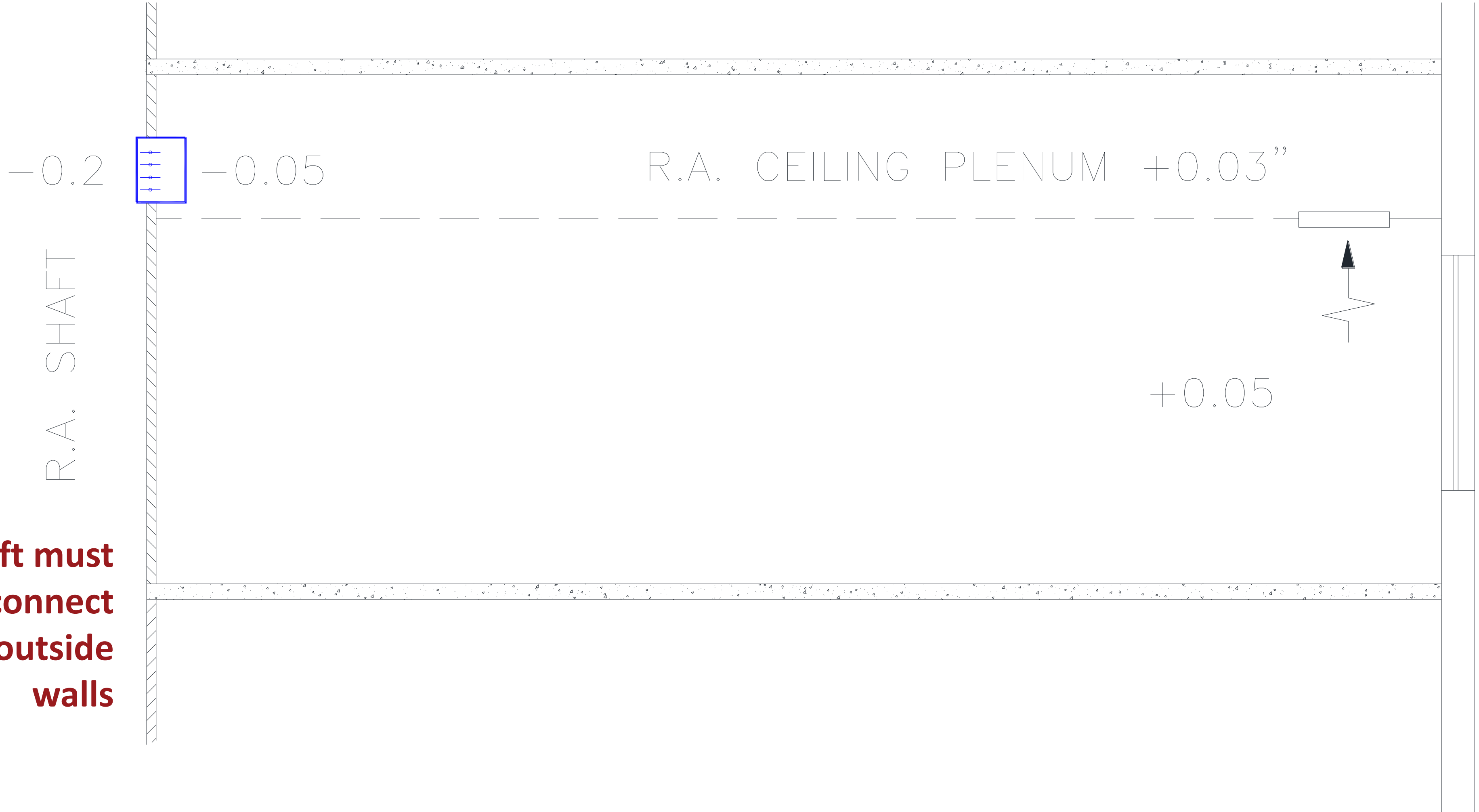
Return air system options

- Fully ducted
  - Seldom with return air VAV boxes except hospitals
- Architectural plenums
  - Ceiling cavities, drywall shafts, mechanical rooms
- Combination of ducted and architectural plenums

Ceiling Return Air Plenums

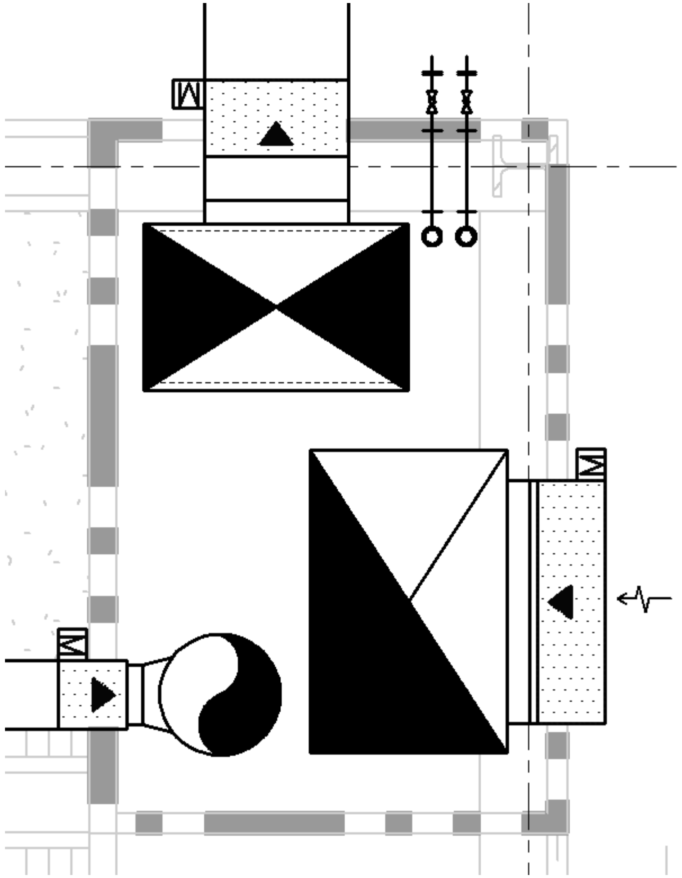
- **Advantages:**
  - Reduced HVAC system costs ($3 to $5/ft2)
  - Reduced costs to other trades to accommodate the congestion
  - Reduced fan energy costs of about 20%
  - Reduced fan energy in systems with outdoor air economizers due to the ability to use non-powered relief or relief fans in lieu of less efficient return fans
  - Little or no balancing costs
  - For VAV systems, balance is better maintained as supply airflow rate varies as loads vary
  - Reduced noise transfer between rooms unless return air ducts are lined
  - Enhances use of fan-powered terminal units (no return air ducts, ventilation benefit)
- **Disadvantages:**
  - Possibility of IAQ problems in humid climates if plenum is negatively pressurized to the outdoors
- **Note:** Claims that ducted return air mitigates COVID transmission are not based on any research.
  - Only related research on issue (Bahnfleth et al 2009) found "plenum return resulted lower space concentration peaks, and delayed attainment of peak concentration than ducted return" based on a contaminant release in the space.

To avoid moisture issues, return air plenums with outside walls must be design to be positive vs. outdoors

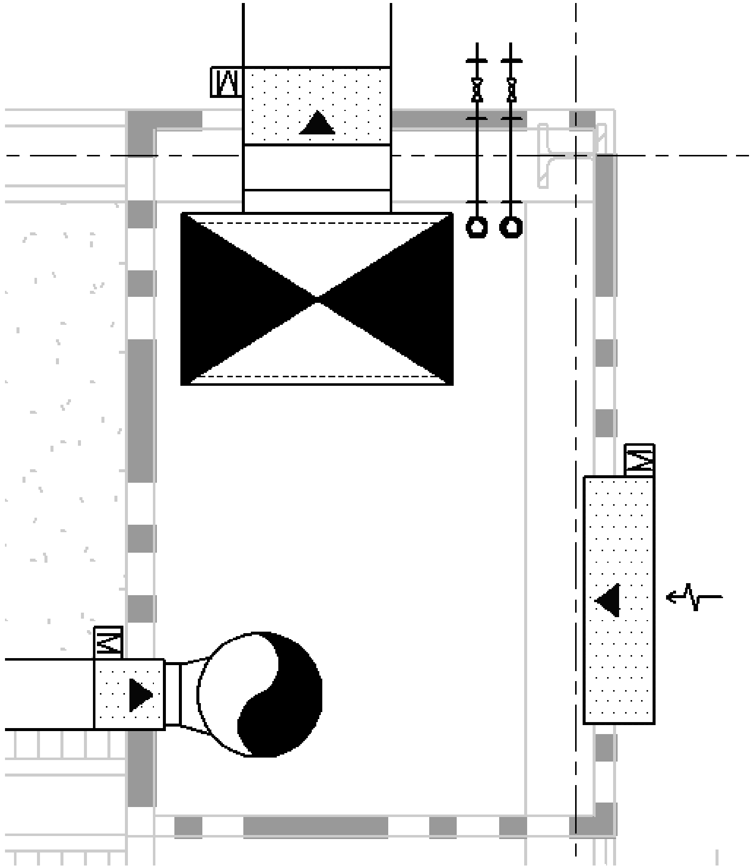


Shaft must not connect to outside walls

Ducted or Unducted RA Risers

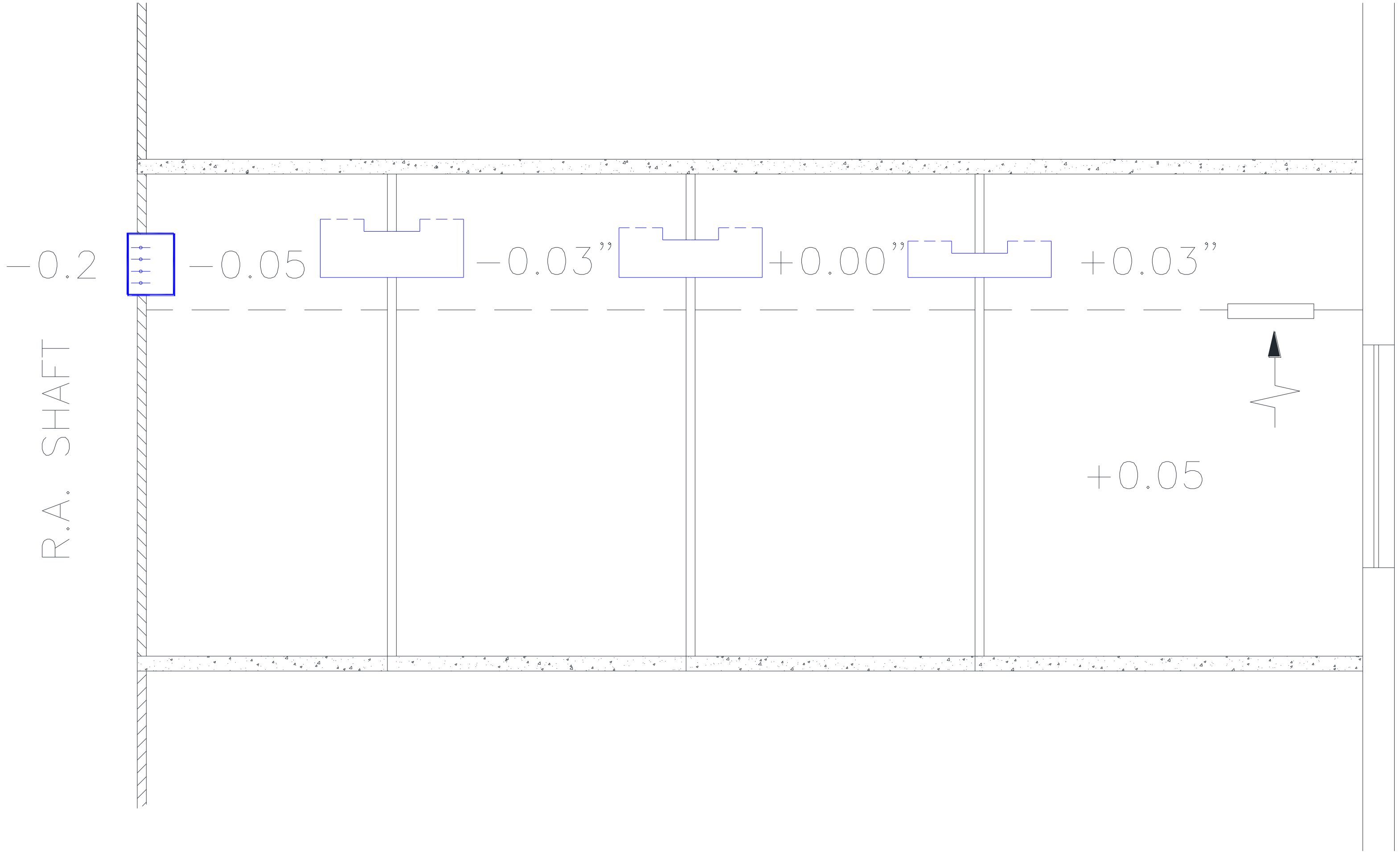


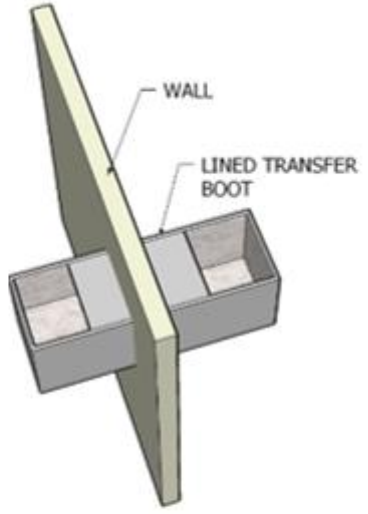
Shaft not negatively pressurized (humid climate IAQ issue if walls connect to outdoors)



Lower first costs
Lower pressure drop
Self-balancing

Care must be taken with full height walls and return air boots in series





Return System Sizing Rules of Thumb

No.	Inlet Location	Discharge Location	Application	Duct sizing rule of thumb fpm
1	Return air plenum	Return air plenum	Lined 5 foot boot	800
2	Return air plenum	Return air plenum	Flex duct both sides	750
3	Return air plenum	Return air plenum	Single elbow (no turning vanes)	700
4	Return air plenum	Return air plenum	Double elbow both sides (no turning vanes)	575
5	Ceiling grille	Return air plenum	Flex duct to perforated face grille	500
6	Ceiling grille	Ceiling grille	Flex duct to perforated face grilles	350
7	Return air plenum	Ceiling grille	Toilet makeup. Flex duct to perforated face	325

The velocities are intended to result in a 0.08 in.w.c. pressure drop across the transfer assembly including pressure drop of entrance, exit, duct, and grilles. Return air plenum is assumed to be 0.02 in.w.c. relative to the space for Application 5 and 0.05 in.w.c for Application 7. Note that these are for a single return air transfer – for multiple boots in series (e.g. cascading from one room to another before it gets to the shaft), velocities must be even lower so the total pressure drop does not exceed 0.08" from furthest room to shaft or fan room to ensure exterior plenum walls are positively pressurized relative to the outdoors.

Conclusions

- **Sizing VAV Duct Mains**
  - Use Friction Rate Reduction Method to size mains starting with ~0.3”/100’ friction rate
    - Start fast, end slow
- **Sizing VAV Boxes**
  - Select standard VAV reheat boxes for 0.5” ΔTP
  - Use oversized reheat coils (factory option)
- **VAV Box Inlet & Outlet Duct Design**
  - Do not use flex duct at VAV box inlets
  - Oversize inlet duct for obviously critical zones and where duct main velocity is low
  - Use a rectangular discharge plenum, then all round duct
- **Return Air System Design**
  - Use return air plenums and unducted return air shafts where allowed by code
  - Carefully and conservatively size return air transfer boots

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