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DESIGN PROCESS FOR SIZING: COOLING AND HEATING SYSTEM CAPACITY, ROOM AIR FLOWS, TRUNK AND RUNOUT DUCTS, AND TRANSFER AIR DUCTS

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1.0 Introduction

A design process is described for sizing cooling and heating system capacity, for specifying the airflow and duct sizes to each conditioned space, and for specifying the free area needed to transfer air supplied to closed rooms back to the central return. This design process involves using a computerized version of the industry standard ACCA Manual J calculation procedure, with specific parameters specified to properly handle infiltration, ventilation, glazing, and airflow velocities for ducts. This process is particularly suited for Building America houses (also Environments for Living™ and Engineered for Life™ Platinum level).

The program RHVAC, version 8, from EliteSoft was used for this example (check the internet for the latest updates). An Excel worksheet was developed to collate the information from RHVAC and perform additional calculations to come up with final project specifications.

When setting up the building model, some specific parameters need to be input properly for evaluation of the Building America (BA) houses.

2.0 Infiltration

All of the BA houses are constructed to have a low building envelope air leakage rate and a controlled mechanical ventilation system. The ventilation system slightly pressurizes the house when the air handler unit blower is operating. During that time, a small amount of conditioned air leaves the building through unintentional leakage pathways to outside, restricting air exchange to exfiltration not infiltration. While the air handler unit blower is not operating, some air infiltration will naturally occur. Based on tracer gas measurements in many of the homes

constructed to the Building America standard, the infiltration rate should be input as 0.1 air changes per hour for winter and summer.

3.0 Ventilation

The design ventilation rate is input according to Equation (1). For three bedroom houses, using a 33% fan duty cycle, the intermittent outside air flow usually falls in a range of 60 to 85 cfm. We often specify 80 cfm for the design outside airflow. For large houses with high ceilings and relatively few bedrooms, the result of Equation (1) can be small or even less than zero; however, the minimum design ventilation rate should be 40 cfm for a three bedroom house. For houses with two systems, all 80 cfm can be put on one system, or it can be split up between systems.

The ventilation airflow rate is calculated according to the following equation, but limited to a minimum equal to $\dot{Q}_{cont}$:

$$\dot{Q}_{cfan} = \frac{(\dot{Q}_{cont}) - (\frac{I}{60} V(1-f))}{f} \qquad (1)$$

where:

$\dot{Q}_{cfan}$ = intermittent outside air flow rate through the central fan (ft^3/min)
$\dot{Q}_{cont}$ = continuous outside air flow rate required (ft^3/min)
I = estimate of natural air change when central fan is not operating (h^{-1})
V = volume of conditioned space (ft^3)
f = fan duty cycle fraction

4.0 Glazing

Use the National Fenestration Research Council (NFRC) rated and labeled U-value and Solar Heat Gain Coefficient (SHGC). The spectrally selective glazing used in BA homes often has a U-value of 0.35 and a SHGC of 0.35. Use Eq. 2 to convert from the older Shading Coefficient (SC) to SHGC if necessary.

$$SHGC = 0.86(SC) \qquad (2)$$

For cooling load calculations, interior shading should be selected as Drapes-Medium 100% closed. While this may not always be the case in actuality, we have found that system sizing will be too inflated if at least this interior shading is not selected, and this matches well with the new IECC Chapter 4 Reference Design internal shade specification of 0.7 for summer. Use no insect or external shade screens, and use ground reflectance equal to 0.20 except ground reflectance equal to 0.32 for glass adjacent to concrete areas such as a patio.

Exception: French doors and entry door side glass shall have None as internal and external shade. Bathroom windows shall have obscured or block glass.

5.0 Duct gain/loss

Because ducts are ducts are always located inside conditioned space for BA houses, duct gain and loss factors should be set to zero.

6.0 Appliance heat gain

One appliance will be equal to 600 Btu/h. Put one appliance in the laundry, and two appliances (1200 Btu/h) in the kitchen. If a Children's/Recreation Retreat, Theatre Room or other equivalent space exists, then put one appliance there.

7.0 People heat gain

Gain from people will be set at 230 Btu/h sensible and 200 Btu/h latent, per person. People will be placed around the house as follows:

- 2 people in the master bedroom and one person in each secondary bedroom;
- 2 people in the family room or in the living room if there is no family room;
- for houses with auxiliary recreation room, add one person there.

8.0 Indoor and Outdoor Design Temperatures

For the outdoor design temperature, use the 0.4% cooling drybulb temperature listed in the ASHRAE 2001 Handbook of Fundamentals. Indoor conditions will be set at 75 F drybulb and 63 F wetbulb (50% RH).

9.0 Cooling and Heating System Sizing

The building design load shall be calculated for the worst case elevation at the solar orientation that produces the highest heat gain.

For equipment selection, indoor and outdoor coils should be matched. The equipment will be selected to meet the design sensible load at the actual outdoor and indoor design conditions (not ARI standard conditions of 95 outdoor and 80/67 indoor). Count at least one-half of the unused latent capacity as additional sensible capacity according to ACCA Manual S .

HVAC designers and contractors often oversize cooling equipment to try to compensate for high occupancy, large thermostat setbacks, unusual loads, poor initial design, or inadequate distribution. Our experience has shown that typical air conditioner sizing generally results in cooling system over-sizing by about 40% to 50%. The following factors weigh against over-sizing:

- Humidity control is reduced
- The system short-cycles, which reduces efficiency and allows more air stagnation and stratification
- First cost is increased

In humid climates, a correctly sized system does a better job of humidity control than an oversized system. This is because the system runs longer and the evaporator coil remains colder. An oversized unit will short-cycle, sending a quick burst of cold air that will satisfy the thermostat before much moisture has been removed. Air conditioners are least efficient during the first few minutes after they start; short cycling increases the amount of time the system is operating at this lower efficiency. In addition, less air handler operation increases air stratification and stagnation. Although a fan cycling control will reduce air stagnation and stratification, we do not intend fan cycling to excuse poor design or poor workmanship. We intend to size the cooling system to appropriately to meet the design load, calculated according to ACCA Manual J, and to provide good air distribution for improved indoor air quality and thermal comfort.

Between building air tightening, getting ducts inside conditioned space, and using high performance windows, the system size can be reduced and pay for those upgrades. In no case, for the Building America program, should the cooling system total capacity be sized higher than 110% of the ACCA Manual J total load.

The size, or capacity, of cooling and heating systems should be specified based on the house orientation that creates the highest total load. This usually depends on the location of glazing. At minimum, the four N, E, S, W orientations should be considered. It may be advisable to also consider the four off-angle orientations of NE, SE, SW, NW as well, especially if there is a lot of off-angle, unshaded glass.

For non-heat pump systems, specifying the heating system capacity is straightforward; the output capacity of the heating appliance must match the calculated heat loss. Usually, the first available size in furnaces or boilers is well beyond the required heating capacity for energy-efficient homes. To get longer heating cycles, multiple stage heating equipment can be used. Heat pump sizing is more involved and is not covered here. Usually, the heat pump capacity is set by the more dominant cooling system size requirement.

For cooling systems, size the equipment based on 100% of the total cooling load (not the sensible cooling load) at the actual outdoor design condition (not the ARI rated condition) and for the realistically expected evaporator air flow (if you don't know then assume 125 Pascal [0.5" wc] external static pressure). The combination of indoor coil and outdoor units should be ARI rated.

Total external static pressure is defined as the pressure differential between the return side and the supply side of the air handler cabinet, and should not exceed the manufacturers specification, usually 125 Pa (0.5" water column).

System air flow should be between 400 and 425 cfm per ton of cooling for dry climates, and between 350 to 400 cfm per ton for humid climates. Dry climates are defined as those with 20 inches or less of annual rainfall, and where the evaporator coil rarely removes much moisture from the air. These are also referred to as dry-coil climates. Humid climates, or wet-coil climates, have more than 20 inches of annual rainfall.

If the total cooling load is more than 15% of the way toward the next larger cooling system size, then specify the larger size. Major manufacturers produce cooling systems in the following tonnage increments: 1.5, 2, 2.5, 3, 3.5, 4, and 5. One ton of cooling is equal to 12,000 Btu/h which is the heat rate required to melt one ton (2,000 lb) of 32 F ice in 24 hours.

Especially for dry climates, most excess latent capacity converts to sensible capacity, so sizing by total load helps avoid a common mistake of over-sizing. In dry climates, system efficiency can be improved by increasing the size of the indoor unit (blower and evaporator coil) relative to the outdoor unit (compressor and condenser) by one-half ton. Upsizing the indoor unit increases the air flow per ton of cooling and raises the evaporator coil temperature, usually increasing the rated efficiency. For systems with a fixed metering device (non-thermal expansion valve system), this one-half ton mismatch usually requires a change in the orifice size according to the manufacturers specification. More than a one-half ton mismatch is not recommended even for dry climates, and for humid climates, do not upsize the indoor coil relative to the outdoor unit.

For humid climates, sizing by total cooling load will tend to cause the system to have longer runtimes, which is good for humidity control. However, using this sizing methodology, at design conditions and steady-state operation, we don't expect the system to operate more than 80% of any given hour. Of course for this to be true, the system must be installed and maintained properly, meaning proper refrigerant charge and proper air flow (see our other guideline, "Refrigeration System Installation and Startup Procedures").

10.0 Air Flow Velocity and Duct Size

When setting up criteria for the mechanical system, some velocity constraints and duct size constraints should be set to obtain appropriate duct sizing from the program, as follows:

1. Set the supply trunk minimum velocity to 500 ft/min and the maximum to 750 ft/min.
2. Set the supply runout minimum velocity to 400 ft/min and the maximum velocity to 500 ft/min.
3. Set the runout duct type to round flex and the minimum runout duct diameter to 4".
4. Set the maximum runout flow to 120 cfm (see below for splitting up flow for closed rooms).
5. Set the return air trunk minimum velocity to 250 ft/min and the maximum velocity to 550 ft/min.
6. Set the duct size schedule for supply runouts to 4" through 8" ducts in one inch increments.

For community scale homebuilding, it is not practical to specify the cooling and heating system size and duct layout based on actual orientations for each house, although that would be ideal. It

is standard practice to use the orientation that creates the largest load to size the systems for that house plan. However, a common mistake is to use that same orientation to size the supply ducts. The orientation that creates the largest system load is not useful for sizing the supply ducts, because a given room that may face north for the largest system-size orientation may face west for any given constructed house. In that case, depending on the amount of glass, the design air flow may need to double, but the installed supply duct would not be capable of providing that. Our experience has shown that using the average of all four cardinal orientations is better for sizing supply ducts. That way, when doing any necessary air balancing, adjustment is possible up or down from the middle instead of from one extreme to another. In some cases, informed judgment is needed when comparing the maximum required duct size to the average duct size for a given room, and it may be prudent to slightly increase the specified supply duct based on that comparison. One such case is where the glazing to floor area ratio is greater than 18%. However, too much adjustment can be a problem since moving extra air to one place lessens the air flow available to other places.

For example, a room facing west with a 20% glazing to floor ratio may require 200 cfm, while if it faced north it may require only 100 cfm. That is a 2-times factor, or about the difference between an 8" and 6" supply duct. Using the average orientation method, the flow would have been specified at about 150 cfm and a 7" duct. Depending on the actual orientation of the constructed house, adjustment of registers would be required to increase or decrease the air flow 50 cfm. However, if the room air flow was sized based on the house orientation that created the highest system load, and that orientation happened to cause that bedroom to face north, then the flow would have been specified at 100 cfm. Then, if the house was built with that room facing west, it would be nearly impossible to make enough register adjustments to get 200 cfm to that room (i.e. one extreme to the other).

The worksheet in Figure 2 lists each room/space for an example house with the respective air flow and duct size for each orientation. If the builder wants only one mechanical plan per house plan, the ducts should be installed for the average of all four orientations, when the house is balanced, the technician should refer to the worksheet to get close to the flows listed for the actual orientation.

Another alternative is to specify two mechanical plans for each house plan, one for the front of the house facing north or south, and one for the front facing east or west. In that case, the room flows and duct sizes would be specified separately for the average of the north/south-facing orientations and the east/west-facing orientations. There are often only two or three duct size differences compared to the average of all orientations, but in some cases, those differences can be important. It is therefore ultimately left up to the designer to know his climate and market.

Often, HVAC contractors only want to stock flexible duct sizes in two-inch increments (4”, 6”, 8” and so on). This is a mistake for energy-efficient, low-load houses because the gap between 4", 6", 8" is too large to properly dial in the air flow. Top-notch contractors should be willing to stock and install 5" and 7" ducts. For energy efficient houses with cooling systems that are not over-sized, it can be important to use the less common 5” and 7” duct sizes in order to accomplish the desired air balance.

Whole-house ventilation is relatively new in residential buildings. Therefore, some homeowners will question what the fan cycling ventilation system is doing. The home sales consultant probably explained it to them, but with so much on their mind at the time, some people won't remember. If needed, a timely and proper re-explanation of the system designed to provide ventilation air distribution for improved indoor air quality, and whole-house mixing for reduced temperature variation, will usually be sufficient.

Here are some design considerations that should be followed by the installing contractor to further reduce the risk of cool air complaints when using fan cycling. Do not feed a supply register with a duct larger than 8" diameter, except possibly for high ceilings in open areas. Do not feed a supply register in a bedroom with a duct larger than 6" and keep the duct velocity below 500 ft/min, which should keep the volume flow below 100 cfm. Reasonable care should be taken to avoid blowing air directly on beds. This will prevent cool air complaints in winter when fan cycling occurs without heat. This is especially important for master bedrooms, so focus there first. For example, use two supply registers in the master bedroom as opposed to one large register; always split an 8" duct into two 6" ducts for master bedrooms.Do not use 9" or larger ducts for supplies, except for high ceilings in open areas and for trunk lines. Also, do not use larger than 6" duct in a bedroom and keep the duct velocity below 500 ft/min, which should keep the register velocity much lower. Reasonable care should be taken to avoid blowing air directly on beds. This will prevent cool air complaints in winter, due to fan cycling without heat, which is integral to our ventilation air distribution and whole-house mixing strategies. This is especially important for master bedrooms, so focus there first. For example, use two supply registers in the master bedroom as opposed to one large register; always split an 8" duct into two 6" ducts for master bedrooms.

As a guide, Table 1 shows air flow in ft^3/min as a function of flexible duct diameter (in) and air velocity (ft/min).

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Table 1 Air flow, velocity and duct sizing guide

		CFM of round flex duct at given velocities					
		ft/min for supply run-outs (blk) and return ducts (brn)					
area (in^2)	inch dia.	250	300	350	400	450	500
12.6	4	22	26	31	35	39	44
19.6	5	34	41	48	55	61	68
28.3	6	49	59	69	79	88	98
38.5	7	67	80	94	107	120	134
50.3	8	87	105	122	140	157	175
63.6	9	110	133	155	177	199	221
78.5	10	136	164	191	218	245	273
113.1	12	196	236	275	314	353	393
153.9	14	267	321	374	428	481	535
201.1	16	349	419	489	559	628	698
254.5	18	442	530	619	707	795	884
314.2	20	545	654	764	873	982	1091
380.1	22	660	792	924	1056	1188	1320
452.4	24	785	942	1100	1257	1414	1571
530.9	26	922	1106	1290	1475	1659	1844
615.8	28	1069	1283	1497	1710	1924	2138
706.9	30	1227	1473	1718	1963	2209	2454

General branching conventions:
1-5" goes to 2-4"
1-6" goes to 2-5"
1-8" goes to 2-6"

Where possible, an extended supply plenum with enough room to make mostly homerun runouts is the preferred duct layout method. In that way, final air balancing is not dependent on the limitations and difficulties of cascading supply branches.

There are a variety of commercially available duct calculator tools (also known as ductulators) that are easy and accurate to use for sizing ducts if you know the flow rate and friction loss or velocity. To size by flow rate and friction loss, use the following guidelines in Table 2:

Table 2 Friction loss guidelines for sizing ducts with duct calculator tool

Type of duct	**Friction loss per 100 ft of duct** (inch water column)
Supply run-outs	0.08
Supply trunk or plenum	0.05
Return ducts	0.02

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As an example to illustrate the design process, the results for a production builder plan are given in Figures 1 and 2.

	Orientation of Front of House									
	N	NE	E	SE	S	SW	W	NW	max	avg
	RHVAC program output									
Heating Load (kBtu/h)	27.9									
Sensible Cooling Load (kBtu/h)	26.0		28.2		25.5		28.3			**Spec**
Latent Cooling Load (kBtu/h)	3.7		3.7		3.7		3.7			
Total Cooling Load (kBtu/h)	29.8		32.0		29.2		32.0		32.0	30.8	3.0 ton
Room Air Flow (cfm)										
Foyer	75		103		83		103		103	91	
Dining	75		112		86		112		112	96	
Kitchen	89		80		89		76		89	84	
Breakfast	128		123		122		118		128	123	
Great Room	165		215		143		215		215	185	
Master Bedrm	138		178		121		178		178	154	
Master Bath	39		22		39		27		39	32	
Master Closet	13		13		13		13		13	13	
Laundry	14		14		14		14		14	14	
Game Rm	58		75		63		75		75	68	
Bedrm 2	75		61		75		55		75	67	
Hall, 2nd	21		21		21		21		21	21	
Bath 2	35		49		29		49		49	41	
Bedrm 3	77		57		77		63		77	69	
Bedrm 4	75		56		75		62		75	67	
Bedrm 4 Closet	10		10		10		10		10	10	
Totals:	1087		1189		1060		1191			1132	1132

Supply Duct Diameter (in)	**RHVAC program output**				**Spec**
Foyer	1-6	1-7	1-6	1-7	1-7
Dining	1-6	1-7	1-6	1-7	1-7
Kitchen	1-6	1-6	1-6	1-6	1-6
Breakfast	1-7	1-7	1-7	1-7	1-7
Great Room	2-6	2-7	1-8	2-7	2-7
Master Bedrm	1-8	2-6	1-7	2-6	2-6
Master Bath	1-4	1-4	1-4	1-4	1-5
Master Closet	1-4	1-4	1-4	1-4	1-4
Laundry	1-4	1-4	1-4	1-4	1-4
Game Rm	1-5	1-6	1-5	1-6	1-6
Bedrm 2	1-6	1-5	1-6	1-5	1-6
Hall, 2nd	1-4	1-4	1-4	1-4	1-4
Bath 2	1-4	1-5	1-4	1-5	1-5
Bedrm 3	1-6	1-5	1-6	1-5	1-6
Bedrm 4	1-6	1-5	1-6	1-5	1-6
Bedrm 4 Closet	1-4	1-4	1-4	1-4	1-4

Figure 1 System and duct sizing worksheet based on ACCA Manual J calculations

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Air Transfer Free Area (in ²)	Orientation of Front of House									
	N	NE	E	SE	S	SW	W	NW	max	avg
Foyer										
Dining										
Kitchen										
Breakfast										
Great Room										
Master Bedrm	87		99		77		102		102	91
Master Bath										
Master Closet										
Laundry										
Game Rm	15		24		18		24		24	21
Bedrm 2	24		17		24		14		24	20
Hall, 2nd										
Bath 2										
Bedrm 3	26		15		26		18		26	21
Bedrm 4	24		14		24		17		24	20
Bedrm 4 Closet										

Jump Duct Diameter (in)										**Spec**
Foyer										
Dining										
Kitchen										
Breakfast										
Great Room										
Master Bedrm	10		11		10		11		11	11	10
Master Bath										
Master Closet										
Laundry										
Game Rm	4		6		5		6		6	5	6
Bedrm 2	6		5		6		4		6	5	6
Hall, 2nd										
Bath 2										
Bedrm 3	6		4		6		5		6	5	6
Bedrm 4	6		4		6		5		6	5	6
Bedrm 4 Closet										

Main System Duct and Grille Sizing

	Width	Height		
Supply trunk	32.91	7		**33x7 Main Trunk**
Return grille	0.00	20		**0x20 Return Grille**
Main ceiling transfer grille	13.19	16		**13x16 Ceiling Grille**
Condensing unit size (nominal)				**Outdoor Condensing Unit**
Airhandler size (nominal)				**95 Ton Airhandler**
Total air flow by load (cfm)			1132	
Total airflow at 400 cfm/ton (cfm)			1200	
Return grille design velocity (fpm)			350	
Return grille free area (%)			80%	
Supply trunk design velocity (fpm)			750	
Total transfer airflow (cfm)			411	

Figure 3 Transfer area and jump duct sizing

11.0 Air Transfer Area and Jump Duct Size

In order to keep supply air from pressurizing closed rooms by more than 3 Pa, transfer grilles or jump ducts are installed to allow supply air to flow back to the central system return. The transfer areas and ducts are sized based on Equation (3). To calculate the finished grille size, no more than 80% free area should be assumed, requiring that the transfer area be divided by at least 0.8.

$$A = \frac{\dot{Q}}{1.07\sqrt{3}} = \frac{\dot{Q}}{1.853} \qquad (3)$$

where: A = area in square inches
$\dot{Q}$ = air flow rate (ft^3/min)

As a general rule of our own, no room will have less than a 6" diameter jump duct, and master bedrooms usually will have between a 10" and 12" diameter jump duct, or equivalent transfer area. Master bedrooms are the hardest to transfer from since they have the largest air flow, including air flow to the master bath and walk-in closet. If more than 250 cfm needs to be transferred back to the main return area, it may be advisable to run a dedicated return duct to that area instead.

12.0 Central Return Duct and Grille Sizing

Central return ducts should have at least one 90 degree bend between the air handler unit and the central return grille, and the air speed at the face of the return grille should be designed at 350 ft/min. This keeps noise in check while allowing enough negative pressure in the return box to draw in outside air with the central-fan-integrated supply ventilation system. To size the return grille, use Equation (4) and divide the result by 0.8 to account for about 80% free area, which is normal for stamped return grilles.

$$A = \frac{\dot{Q}}{v} \qquad (4)$$

where: A = area in square feet
$\dot{Q}$ = volumetric air flow rate (ft^3/min)
v = air speed (ft/min)