Energy Efficient Residential Construction Volume 3: Heating, Ventilation, Air Conditioning

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Introduction

I'm not a "tin-bender" or a "tin-bender's" son. My father was a carpenter and builder as was his father, his grandfather and, as near as we can tell, his great-grandfather. My family has been involved in the building trades ever since we came to this country from Ireland during The Great Potato Famine.

I love houses. I love the way they are sited, the way they are framed, the way they are finished on the inside and out. They are works of sculptural art; some are cheap replicas of the great masterpieces, but they are all presenting a message as a form of public and private art. Sometimes, the message reflects the dichotomy of public beauty and private ugliness.

All homes form a symbiotic relationship with the occupant. The home shelters us from the elements, provides physical and psychological comfort, and connects us with our neighbors. A home that fails to provide the occupants with these benefits demonstrates that private ugliness. From the street the home looks beautiful but causes the occupant financial, physical and psychological discomfort. This should be criminal because it can cause a dysfunctional relationship between occupant and home; it doesn’t take care of us, so we don’t take care of it. Eventually the home becomes neglected to the point that it becomes part of substandard housing in a now substandard neighborhood. Neighborhood decline starts with the construction of poorly designed and constructed homes; it is simply a matter of time before the malignancy reveals itself. While there are many factors involved in the decline of a neighborhood, I believe that the most common is this dysfunctional relationship.

In the previous sections, I addressed the issues of quality construction for energy efficiency in Climate Zone 4, providing shelter from the elements and some psychological comfort. In this section, I will address providing physical comfort to the occupants through the heating, ventilation and air-conditioning (HVAC) systems.

Once the conceptual form and structure of the home have been developed, the comfort delivery systems need to be designed. There are 4 loads on a home: the structural, heating, cooling and moisture loads all have to be considered, designed for and addressed correctly. The earlier works addressed the structural and exterior moisture loads and this one will address the heating, cooling and interior moisture loads, all of which are handled by the comfort systems. We will see how the building envelope affects these comfort systems and how the comfort systems affect the occupants.

Homes are like a mobile, a suspended sculpture with balanced parts. Altering one part affects other parts, creating a cascade effect on the whole. The single most important system after creating the building envelope is the HVAC system. It is my contention that it can cause more damage to a home through poor design, selection, and installation than any other component because HVAC systems are a mystery to most builders and homeowners. We don’t understand how or why they work and never suspect them of creating conditions that damage our home and pocketbook. Hopefully, this booklet will educate you on this subject and allow you to make informed, intelligent choices on HVAC systems.

I would like to thank Dr. Carl Hite, President of Cleveland State Community College, for his visionary support of the residential energy efficiency program at the college. It is through the influence and support of people like him that mainstream building practices will be transformed for the 21st Century and beyond.

I would also like to thank some of the many HVAC contractors that I have worked with over the years for educating me on field practices and providing many stimulating discussions: Mike Jenkins and Cleo Heard of A-Tech Heating & Air, Jimmy Smith of J. Built Contracting, John Giles of ACS Services, Inc., and DeWayne Teague of D & N Heating & Air. These HVAC contractors have proven a willingness to do it right the first time and have helped build some of the first high performance homes in Chattanooga. I would also like to thank Gene Goff for educating me on what the field practices should be, and the good folks at TVA (John Proffit, Todd Thompson, John Shell, and Steve McMinn) and their distributors for being my friends.

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Basics of Energy

Thermodynamics

The first law of thermodynamics states that the total energy in the universe is constant and cannot be created nor destroyed, but transferred by heating, cooling or mechanical work.

The second law of thermodynamics states that systems in contact with each other that have differences tend to balance. Air, heat and water move from areas of high concentration to areas of less concentration (high pressure to low pressure, hot to cold, wet to dry).

Heat energy

There are three types of heat energy transfer: convective, conductive and radiant. Conductive heat flow is the flow of heat through a solid or from solid objects that are touching each other. Convective heat flow is the flow of heat through a liquid or gas (like air). Radiant heat flow is the flow of heat from a hot surface to a cooler surface. As long as the surfaces can "see" one another, heat will be transferred.

Just as pressure differences direct the movement of air, temperature differences direct the movement of heat. Nature is always trying to balance, always trying to maintain a balance and always takes the path of least resistance to achieve the balance.

Conductive heat transfer is the transfer of heat through a solid or between solids that are touching each other. Conduction is the heat transferred through the building assembly (floor, walls, ceiling) and insulation is used to slow it down. Examples of conductive heat transfer are heat loss/gain through the ceiling, through the walls, through the floor, through the windows and doors (all the building components that make up the building envelope). The resistance to heat flow is called the R-value and the conductance of heat flow is called the U-factor. These two are inversely related; the U-factor is 1 divided by the R-value and the R-value is 1 divided by the U-factor. R-value is for the resistance to heat flow and the U-factor is the conductance of heat flow.

Walls that have thermal mass (a phenomenon that delays the transmission of heat across the building envelope, caused by the material's higher capacity for heat retention) generally have lower R-values but perform much better in moderate climate zones that have decent temperature swings throughout the day. This gives the material a "mass-enhanced R-value", sometimes referred to as a higher "effective R-value".

Higher R-values provide more resistance to heat flow (are better) and lower U-factors conduct less heat (are better). Insulation works by trapping tiny air pockets which reduce the amount of surfaces touching each other. Insulation R-value is compromised by compression of the trapped air pockets and by air leakage around or through the insulation.

In a typical leaky home, ***convection*** is responsible for about 39% of the heating load on a home and about 28% of the cooling load. Air barriers slow down the convective heat transfer. Typical leakage areas include uncapped chases for ductwork, poorly sealed top and bottom plates of the framed walls, plumbing penetrations (you know, the tub drain rough opening that you could pass a keg through) and openings in the building envelope floors/ceilings) for ductwork. Most of the leaks occur overhead and underfoot. Generally, the exterior walls are fairly tight but the ceiling and floor get overlooked during construction. For example, if there are different ceiling heights on the sides of a wall, and blocking isn't installed between the studs at the lower ceiling height, a chase is created that can cause convective heat loss/gain to or from the attic space above.

There are air films that cling to all exposed surfaces. These actually help to resist heat flow and have an R-value assigned to them by ASHRAE. Typically, the inside air film of a vertical wall has an R-value of 0.68 while the outside air film has an R-value of 0.17 (depending on wind speed). These values can be found in the Handbook of Fundamentals, 2005 edition published by ASHRAE.

Natural convection is caused by a difference in density between warm air and cooler air. The warm air rises because it is less dense than the cooler air and the cooler air "falls" because it is denser than the warmer air. This can create convective loops within an un-insulated wall cavity. Forced convection is caused by external airflow (forced air-conditioning systems, vented attics, etc). Convection may reduce the effectiveness of loose-fill insulation up to 25%.

Radiant heat transfer is heat transfer between a warm surface and a cooler surface and doesn't require air movement or the two surfaces to touch. Solar radiation (heat energy radiated from the sun) happens in a perfect vacuum (space) every morning when the sun comes up and warms our side of the planet. Far-infrared radiation occurs in homes, usually in two locations: attics and windows.

Radiant barriers are usually shiny, metallic surfaces that have a low-emissive rating (they don't easily emit heat by radiation- they do conduct heat!). They are extremely conductive but do not release their heat through radiation. Metal playground slides were a shining example of radiant heat transfer. The playground would have a black asphalt walkway nearby and you could see the heat plumes rising off the surface. If you held your hand 6" away from it, you could feel the heat on the palm of your hand. Walk over to the playground slide and hold your hand ½" away from the surface- you couldn't feel any heat transferring to your hand. Sit down on that slide wearing shorts and boy, you could feel the heat!

Radiant barriers are found in thin coatings on windows, foil-faced bubble-wrap products, foil-faced papers, foil-faced foam board insulation and foil-faced plywood decking. For a radiant barrier to work, it needs to be in series with the hot surface and be separated from the cooler surfaces by an air space at least ¼" thick. On rooflines, it should be installed shiny side facing the attic and is best applied along the bottom of the rafters. Rolling the radiant barrier out on the attic floor will work until it gets dusty, then its performance drops off pretty quickly (unless you can talk your mother-in-law into vacuuming it on a regular basis!).

I have seen radiant barriers applied on basement walls. Since there usually isn't a lot of heat generated by the ground conducting through the concrete walls this is not the most cost-effective or efficient way to insulate the basement walls. Radiant barriers have no R-value to speak of; in order to get the claimed R-value on many products, it must be installed in the middle of a framed cavity that is enclosed on all 6 sides with no other insulation material. Since this application doesn't provide the code minimum R-values for walls in any climate zone in the US, it isn't recommended. I have even seen radiant barriers installed directly under the exterior siding on homes (again, radiation isn't the dominant form of heat transfer in walls and the fact that there is no air gap negates any benefit).

Radiant barriers in windows are called low-emissive coatings (low-e). Window manufacturers usually list the low-e coating on the label provided by the National Fenestration Rating Council (NFRC). The low-e coating affects the Solar Heat Gain Co-efficient (SHGC) by lowering the amount of radiant heat transferred through the window.

Measuring energy

A ***British thermal unit*** (Btu) is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit at sea level when the water is 39.2º F. While the United States uses British thermal units to measure the quantity of energy, most other countries use the term ***joule***. One Btu (about the amount of heat produced by burning a kitchen match) is equal to 1,055 joules, named after James Prescott Joule, an English brewery manager and amateur physicist whose discoveries in the mid-1800's led to the 1st Law of Thermodynamics. Like most major scientific breakthroughs, his ideas were scoffed at by the established academics of his day. A joule is the amount of work needed to produce one watt for one second (a ***watt-second***). In honor of its namesake, the joule is about 1/100th the amount of energy a person could get by drinking a single droplet of beer. A ***watt*** is named after James Watt, and is one joule of energy per second (a rate or quantity per time).

A ***kilowatt hour*** is the amount of energy spent by a 1,000 watt device over one hour. A *therm* is another quantity of energy that is equal to 100,000 Btu's (105,506,000 joules). One kilowatt hour (kWh) is equal to 3,412 Btu's (3.6 million joules) while 1 watt-hour is equal to 3.412 Btu's (3,600 joules).

To make this more complicated, these measurements are used by utility companies to sell energy. While we should probably be purchasing our energy by the joules (or ***megajoules***, 1 million joules), natural gas is usually sold by the therm while electricity is usually sold by the kilowatt hour. In order to compare pricing on a level playing field, they must be converted to a common measurement. Since the joule is a very small measurement of energy, we usually convert them to Btu's for cost comparisons. This method does not take into account equipment efficiencies and should not be relied upon for estimating annual costs or choosing fuel sources for HVAC equipment.

For example, if natural gas costs $1.22 per therm and electricity costs $0.0755 per kilowatt hour, the cost per Btu of natural gas is $0.0000122 and the cost per Btu of electricity is $0.000022. This would seem to indicate on the surface that natural gas is less expensive than electricity. To see how they actually compare, please see the example in "Equipment Selection".

Basics of Comfort

Comfort is highly individual and is a function of the surrounding air temperature, the relative humidity of the space, the temperatures of the surrounding surfaces (mean radiant temperature or MRT), and the airflow which affects the evaporative cooling rate from our skin. All of these work together to produce "comfort" and we all have different requirements for each of the different factors. Is it any wonder that comfort is a huge issue for both builders and homeowners?

The comfort zone is the space within a room that is 2' from the perimeter walls and 6' from the floor (my apologies to all who are taller than 6'). It is the air temperature, relative humidity, surface temperatures surrounding that space and air velocity within that space that we are mostly concerned with. People lose and gain heat primarily through convection, evaporation and radiation.

Surrounding air temperatures

The temperature of the air in a space is affected by the rate of heat transfer through the surfaces surrounding it, amount of heat energy produced by items within the space (people, pets, appliances), and the temperature and velocity of conditioned air supplied to that space. Load calculations are performed for heating and cooling seasons in order to determine how much conditioning (heating or cooling) energy needs to be supplied to a space to keep the air temperature at a certain level. The default design indoor temperature for the heating season is 70°F and the air within the comfort zone should be within ± 2°F of the thermostat setting. The default design indoor temperature for the cooling season is 75°F; the air within the comfort zone should be within ± 3°F of the thermostat for a single zone and within ± 2°F for a multi-zone design.

Relative Humidity

Relative humidity (RH) is the percentage of moisture held by the air in relation to the amount of moisture the air could hold if it were totally saturated.

Dew point temperature is the temperature at which the water vapor in the air changes into liquid. This process is called condensation and occurs on surfaces that are cooler than the surrounding air. Dew point temperatures can be found be reading the psychometric chart. It is a more reliable indicator of how comfortable the air is than relative humidity.

Relative humidity can also be determined by reading the psychometric chart and is not a reliable indicator of comfort since it is temperature dependent. When the temperature goes up, the RH goes down because the warmer air has a greater capacity to hold moisture (of course, this doesn't account for any additional moisture).

Most people find a RH range of 30% to 50% to be most comfortable. When humidity levels fall below that range, people tend to notice more dry sinuses and static electricity. When it is above that range, we tend to find higher concentrations of mold, mildew, dust mites, and material failure due to rot.

Surrounding surface temperatures

Building materials typically absorb some of the radiant heat from the sun, reflect some of the radiant heat back and transmit some of the heat through to the next exposed surface. At this point, there is no more solar radiation but now the building material emits that heat to cooler items within the comfort zone through far-infrared radiation. Our bodies also radiate heat from the surface of our skin to cooler surfaces surrounding the comfort zone.

If you were to stand in front of a north-facing window late at night, nervously watching strangers walk down the alley behind your home, you will feel colder than you did while sitting on the edge of your bed. This is because your body is much warmer than the glass of the window; you are losing heat to the glass (nature seeking a balance).

If you were to sit in front of a west-facing office window at 3:30 in the afternoon, contemplating why you are doing work that you don't enjoy, you will feel hotter than if you got up and moved to the file room. This is because the glass in the window is much warmer than your skin and you are gaining heat from the glass (nature seeking a balance).

Evaporation

People sweat. Some people sweat more than others and for different reasons. Everyone is losing moisture from their body all the time- from the lungs, mouth and skin. About 10% of the heat our bodies produce is dissipated through this constant evaporation. It is a cooling mechanism linked to our body's core temperature.

We are heat generating devices (about 350 Btu/hour) that use food and drink as fuel sources. Our core temperature is fairly constant, but the skin temperature fluctuates depending upon the surrounding environment and our metabolic rate. As activity increases, our skin temperature goes down and the core temperature rises slightly. As activity decreases, our skin temperature goes up and our core temperature goes down slightly.

When our body's temperature increases, signals are sent to the sweat glands to increase their rate of production. When water evaporates, it takes heat with it (about 1,043 Btu's per pound of water evaporated). How much water do we evaporate per day? That depends on the amount and intensity of the activities we are engaged in and many other variables. Vigorous exercise can cause an average adult to evaporate between ¼ and ½ gallon per hour. Sitting on the sofa under the same ambient conditions, we can produce about 0.06 gallons of evaporated water. The rate of evaporation is dependent upon the relative humidity of the surrounding air, the velocity of the surrounding air and the area of the skin's sweat-soaked surface (also called skin-wettedness).

If there is a lot of moisture in the air, the rate of evaporation from our skin slows down. If the surrounding air moves faster, the rate of evaporation increases. The rate of evaporation also increases as the percentage of skin-wettedness goes up.

Mechanical systems affect the velocity of airflow; the velocity of the airflow affects our sense of comfort through increased evaporation and convection from our skin's surface.

We prefer to have air in the comfort zone move at around 25 feet per minute. When air within the comfort zone moves at less than 15 feet per minute, we feel like the air has become stagnant. When cooler air moves faster than 25 feet per minute, we tend to complain about drafts (particularly around the ankles and neck).

Load Calculations

According to the International Residential Code (Section M1401.3) and the International Energy Conservation Code, heating and cooling load calculations must be performed according to Manual J, ASHRAE Handbook of Fundamentals or other approved methods. Using rules of thumb are not approved! Some contractors have larger thumbs than others and no one's thumb actually takes into account the construction of the home- so don't use rules of thumb. Repeat after me: **"Rules of thumb are dumb".**

In one Colorado study conducted by a utility company, they found that the air conditioning equipment was typically oversized between 143% and 322%. The same study also found that the heating equipment was oversized between 106% and 234%.

Hank Rutkowski, PE, wrote the Air Conditioning Contractors Association (ACCA) manual for performing load calculations. He has been quoted as saying that only 5% to 10% of the residential HVAC systems installed have ever had a load calculation performed and the contractors typically tell him "I've never been sued for installing too large a system."

In a field study performed by Pacific Gas & Electric, they found that 53% of the cooling systems were oversized by a ton or more and Pacific Northwest National Laboratory found that a third of the systems were oversized by at least a ton!

Why would a system that is larger than necessary be a bad thing? Well, cooling systems that are larger than needed have a higher initial cost, are lousy at dehumidifying due to short cycling, create sudden temperature swings in the home, have lower efficiency ratings and higher operating costs, doesn't last as long as it should due to the increased wear and tear from the start-stop caused by short cycling, and ultimately creates discomfort for the homeowner. Combustion furnace heating systems that are oversized create additional issues like condensation in the flue pipe leading to rust and failure and corroded exchangers due to excessive airflow leading to condensation.

Unfortunately, most architects and builders assume that their HVAC contractor or mechanical engineer has properly performed an ACCA Manual J, 8th edition, load calculation to determine the heating and cooling load requirements, used ACCA Manual D to size the ductwork to deliver the right amount of conditioned air needed in each room, selected the equipment according to ACCA Manual S and has trained technicians who have properly installed the equipment and ductwork.

The reality is that of the 5% to 10% of the homes that have Manual J load calculations performed, most of them are performed incorrectly and generally will back out to a local rule of thumb for square footage per ton.

In Tennessee it is 600 square feet per ton, while in Texas it is about 450 square feet per ton. This is an industry wide issue that I have personally witnessed from Virginia to Texas and Kentucky to Florida. I have been told by colleagues that it also exists everywhere else in the country.

I spoke with an HVAC contractor in Texas who stated that he performed a 7th edition Manual J load calculation after he had already installed the equipment (using a square footage rule of thumb) in the first built model for a production builder. He did this on every new plan and never changed the size of the equipment to meet the “calculated” load and never updated the load calculation– not even after the builder upgraded to low-e windows, cellulose insulation with extensive airsealing, radiant barrier roof decking and joined the ENERGY STAR® program where every single home is inspected and tested for house and duct leakage by an independent 3rd party!

The production builder (~ 400 homes per year) was understandably upset after I pointed out that they had been paying between $2,000 and $4,000 per house more than they needed to in oversized equipment. They had initially asked me to look at meeting the tax credit, but after this exposé they realized that they could reap far greater financial benefit by simply right-sizing the equipment– which is required by the building code!

When HVAC contractors perform a Manual J load calculation, they usually alter the outdoor design temperatures to create greater temperature differences between the inside and outside; this creates greater heat losses and gains. They also like to use higher infiltration rates in the summer than winter so that they can boost the cooling load to deal with the extra dehumidification.

They tend to model windows without internal shading devices or external overhangs, increase the size of the windows facing east and west, increase the number of people that permanently occupy the home (you want to be comfortable when you have your holiday party!), increase the appliance loads on the home (honestly, I thought every floor had a kitchen!), model windows with lower performance than the installed windows, model lower insulation levels in attics, walls and floors and boost the grains of moisture difference to create greater humidity issues inside the home.

All Manual J load calculations should be performed using the latest edition (as of this writing, it is the 8th edition version 2). Manual J 8th edition has updated design temperatures and follows the ASHRAE standards for calculating the number of occupants (number of bedrooms + one) in addition to providing updated tables to reflect radiant barriers and low-e windows.

This is a chart I developed that shows the differences between the peak cooling load (only exceeded 1% of the time) calculated according to the 2005 ASHRAE Handbook of Fundamentals methodology and the cooling equipment installed by an HVAC contractor who relied upon “rules of thumb”.

As I dug further into the issue, I discovered that the reason the oversized equipment was installed was because the customers had been complaining to the HVAC contractor about being uncomfortable. The assumption on the part of the HVAC contractor was the equipment was too small to handle the load on the home. The reality was that the homeowners were uncomfortable because the distribution system (ductwork) was installed very poorly, resulting in the rooms not getting the airflow needed to condition the space.

It wasn't the size of the equipment causing the problem, but the poorly designed and installed distribution system! Naturally, the HVAC contractor proposed solving the problem with larger equipment which could potentially increase the airflow instead of fixing the ductwork. This is not a brilliant idea: spend an extra $3,000 to fix a problem caused by a subcontractor not meeting the code requirements for duct installation!

Size of home (square feet)	Peak Design Cooling Load Range (Best & Worst Case	Installed Equipment
1204	14.9 kBtuh – 15.1	30.0 kBtuh
1871	22.9 kBtuh – 25.5	42.0 kBtuh
2229	25.5 kBtuh – 27.3	42.0 kBtuh
2313	26.8 kBtuh – 29.0	36.0 kBtuh
2682	27.0 kBtuh – 29.6	48.0 kBtuh
2792	31.0 kBtuh – 31.5	60.0 kBtuh
3086	33.9 kBtuh – 37.0	66.0 kBtuh
3173	33.3 kBtuh – 34.4	60.0 kBtuh
3850	35.1 kBtuh – 37.2	78.0 kBtuh
4157	42.2 kBtuh – 45.6	72.0 kBtuh

The solution

The solution is to ensure compliance with Manual J by hiring a knowledgeable person to review the load calculations supplied by the HVAC contractor or mechanical engineer. Do not rely upon the guy selling you equipment "by the ton" to tell you how much you need!

ACCA has published a list of Do's and Don'ts for Manual J and I have adapted them here:

- Do not manipulate outdoor design temperatures.
- Do not ignore internal shade devices– assume the home will have blinds
- Do not ignore external overhangs
- Do not include intermittent fans (bath and kitchen) as ventilation fans
- Do not assume leaky ductwork and a leaky house
- Do not assume code ventilation rates are the default infiltration rates
- Do not assume worst case scenarios
- Do not design for record breaking weather conditions
- Do not add safety factors into the calculation

- Do not design for abnormally low or high outdoor temperatures or humidity
- Do not reduce known insulation levels to be safe
- Do not add internal loads for “entertaining groups of people”
- Do not add internal loads for special events
- Do not use “rules of thumb” based upon square footage
- Do verify all construction details prior to calculating Manual J
- Use the actual orientation
- Take full credit for insulation improvements to the building
- Take full credit for airsealing
- Follow the Manual J procedures for calculating ventilation and infiltration
- Use the outdoor design temperatures from Manual J or ASHRAE Handbook of Fundamentals, 2005
- Use the indoor design temperatures from the ASHRAE comfort chart
- Take full credit for sealed and insulated ductwork
- Match the duct location to the actual location as much as possible
- Match the duct system geometry as much as possible
- Take credit for documented window performance data
- Calculate the number of occupants as the number of bedrooms plus one
- Limit the number of appliances to those that would be on during peak load (usually around dinner time)

If Manual J is followed faithfully with any assumptions supported by building science and documented sources, the load calculation will be accurate without using any “safety factors” or fudging numbers because “that’s the way I’ve done it for 30 years”. At least this way, if a homeowner sues the HVAC contractor for sizing the system correctly it is completely defensible as opposed to trying to defend sizing based upon “rules of thumb” or “everybody does it that way”. We are already oversized 99% of the time and Manual J has an additional built-in safety factor of around 20% already- don’t add any more!

There are many reasons why we should be concerned about over sizing cooling equipment beyond the extra cost to purchase and operate, increased potential for mold growth, poor comfort due to lousy mixing of the conditioned air with room air– it also increases the peak demand for utilities leading to larger regional issues dealing with energy production, pollution production, and global warming. All because someone decided that 30 years of doing it wrong was better than following the International Residential Code, the International Mechanical Code, the International Energy Conservation Code and the ACCA procedures referenced by the code writing agencies.

The building envelope

The *building envelope* is an air barrier and thermal boundary that are continuous and touching and separate conditioned space from unconditioned space or the outside. It is sometimes referred to as the "thermal envelope". The envelope of a simple house may be the floor, the walls (including exterior doors and windows) and the flat ceiling.

There are many ways for a builder to define the building envelope (it can contain a conditioned basement, a sealed, insulated and conditioned crawlspace, a conditioned attic with insulation along the roofline) and even more ways for them to fail to define it properly.

The building envelope's function is to protect the occupants of the home from the elements (air, heat, cold, water). These outside conditions are called "ambient".

How loads are calculated

Heating loads are calculated by using the $Q = U \times A \times \Delta T$ formula over the course of the heating season for the climate where the house is built. Q is the heat flow in Btu's per hour (Btu/hr), U is the thermal transmittance factor, A is the area of building assembly with the same U-factor and ΔT is the temperature difference between the inside and outside.

The building envelope surfaces (the foundation walls, floor systems, exterior walls, windows, doors, attic kneewalls, and ceilings) are all sources of heat loss to the outside. Additionally, there is air infiltration and exfiltration plus intentional ventilation that must be accounted for as well as duct losses. Ducts conduct some heat through the insulation (R-6 or R-8) but lose more through leaking hot air to unconditioned spaces, or pulling in cold air from these unconditioned spaces. The internal loads of people, lights and appliances also generate heat and help offset some of the heat loss through the envelope and systems.

Cooling loads are calculated by using the $Q = U \times A \times \Delta T$ formula over the course of the cooling season for the climate where the house is built. Certain building envelope surfaces (exterior walls, windows, doors, attic kneewalls, and ceilings) are all sources of heat gain from the outside. Additionally, there is air infiltration and exfiltration that must be accounted for as well as duct gains. Ducts gain some heat through the insulation (R-6 or R-8) but gain more through leaks that pull in hot air from unconditioned spaces. The internal loads of people, lights and appliances also generate heat that must be removed by the mechanical equipment.

Cooling loads have to address two types of heat found in air: *sensible* which is the temperature of the air and *latent*, the hidden heat in the moisture in the air. The latent heat is released when the water vapor undergoes a phase change and condenses. Depending upon the moisture load on the home, the sensible-latent ratio may need to be adjusted. This ratio is called the sensible heat fraction (SHF) and is calculated by dividing the sensible load in Btu's by the total cooling load (Sensible + Latent) in Btu's. It is sometimes represented by the formula $SHF=S/S+L$.

Ventilation loads are created when we bring outside air in for the occupants. It is not created by the exhaust ventilation from kitchen range hoods and bathroom exhaust fans! Do not calculate those intermittent devices as part of the ventilation load of the home. The ventilation load is calculated by multiplying the number of occupants by 7.5 cubic feet minute (cfm) and adding 1 cfm per 100 ft^2 of conditioned space. This is the amount of air needed to be brought into the home every hour. This outside air will need to be heated in the winter and cooled and dehumidified in the summer, creating an additional load on the equipment.

The moisture load is calculated in grains. One pound of water vapor is equal to 7,000 grains at 70°F and sea level. One pound of dry air (at the same conditions) takes up 13.33 cubic feet (1 cubic foot weighs 0.075 pounds). The psychrometric chart shows the thermodynamic properties of moist air and can be used to determine the relative humidity, dew point, dry-bulb temperature, wet-bulb temperature, specific volume, humidity ratio, and enthalpy (Btu/lb of dry air).

Sizing the equipment capacity to match the heating and cooling load on the house is absolutely critical to achieving an energy efficient home.

If the furnace is oversized, the furnace and vent can become cool, causing condensation to form from the water vapor. This can lead to equipment failure due to rust. If there is too much airflow across the heat exchanger, the exchanger will stay cooler and may corrode from the condensation formed. If there isn't enough airflow across the exchanger, the exchanger may heat up too much and the repeated heating and cooling can cause the exchanger to deform or crack.

The airflow across the inside coil of the air conditioner or heat pump should be around 400 cubic feet per minute per ton (12,000 Btu's) of capacity. If the airflow is much less (± 50 cfm), distribution efficiency is lowered, compressor damage may occur, coils can freeze, latent cooling increases (reducing the Sensible Heat Fraction) and capacity is lowered.

If the airflow is too high, duct leakage increases, temperatures at the register during the heating season are too low, latent cooling capacity decreases (increasing the SHF) and the blower motor uses more electricity.

There also has to be at least 350 cfm (per ton) of airflow at the inside coil to make sure that the refrigerant leaving the evaporator is in vapor form and that the liquid refrigerant isn't evaporating in the line.

It is also critical that the ductwork be sealed properly when equipment is properly sized. Right sized equipment operates for a longer period of time (even though it is running longer, it costs less money to operate), potentially creating a situation where more duct leakage could occur. THINK LIKE A SYSTEM!

A proper load calculation will accurately reflect the heating, ventilation and air-conditioning (temperature drop and moisture removal) of the home based upon the outdoor design conditions, indoor design conditions, orientation, envelope components, and internal loads.

Outdoor design conditions

The winter outdoor design temperature is a temperature that the air is warmer than 99% of the time during the three coldest months. These design temperatures are found in ASHRAE's Handbook of Fundamentals, 2005 edition.

Heating Degree Days (HDD) are the total number degrees colder than 65°F (Base 65) during the heating season. For example, if the average daily temperature is 55°F, then 65 - 55 = 10 heating degree days.

The summer outdoor design temperature is typically a temperature that the outside air is hotter than only 1% of the time during the three hottest months.

Cooling degree days (CDD) are the total number of degrees that the outside temperature is warmer than 65°F (Base 65).

Heating degree days and cooling degree days are usually used to estimate the amount of energy that will be needed over the heating and cooling seasons.

Outdoor design temperatures are affected by the location the home is going to be in. The values that should be used are the ones found in ASHRAE 2005 Handbook of Fundamentals. Manual J, 8th edition, was produced prior to the release of the latest ASHRAE Handbook; the design temperatures in the latest edition of Manual J have not been updated. These design temperatures are based upon data collected for over 20 years from over 4,000 weather stations around the world (even from Kazakhstan- take that, Borat!).

Latitude affects the angle of the glass in our windows and the amount of radiant heat gained through them; it also determines how much shading we need to have for passive solar design.

Elevation affects the load calculation due to the density of the air; the density of the air affects the moisture holding properties which are used to calculate values from the psychrometric chart. Elevation also affects the lapse rate of the troposphere. For every 1,000 feet you go up in elevation, the temperature in the troposphere drops about 5.9°F. If you know the elevation of the nearest weather station and you know the elevation for the home's site, you can calculate the actual design temperatures for that specific site based upon the difference in elevation and the calculated lapse rate.

Another component of the outdoor design conditions is the average number of degrees the temperature swings over 24 hours. A temperature range of 15°F or less is considered "low"; a temperature range of 15°F to 25°F is considered "medium", and a temperature range higher than 25°F is considered "high". This temperature range can be used to help design the building. For example, thermal mass walls are more effective in medium to high temperature ranges and should be considered a viable option under those ambient conditions.

Indoor design conditions

The indoor design conditions are the temperature and humidity levels that we want to maintain over the course of the heating and cooling seasons. We use an indoor design temperature of 70°F for the heating season and an indoor relative humidity level between 20% and 30%. We use an indoor design temperature of 75°F for the cooling season and an indoor relative humidity level between 25% and 50%. I personally use a cooling season RH design of 40% since most dehumidifiers have a ± 5% swing. This helps to keep us below the dust mite/mold thresholds, except in certain wet locations (bathrooms, laundries, leaky windows and doors).

An indoor temperature of 75°F with a RH level at 40% will give us a dew point of 49°F. Any surfaces cooler than that will result in condensation. An indoor temperature of 70°F with a RH level at 25% will give us a dew point temperature of 32°F, resulting in condensation (frost) occurring on any surfaces cooler than the indoor dew point.

Orientation

The orientation of the home affects solar gain through windows and the effect of thermal mass on the heating and cooling load of a home. If the home is designed with passive solar principles based upon orientation, these benefits need to be taken into consideration.

Foundations

Foundations are a crawlspace, a basement or a slab, or some variation or combination of them. The HVAC system designer must determine if the space enclosed by the foundation is conditioned (in the case of slabs, is the space over the slab conditioned), identify framed floors that are over unconditioned spaces, note the interior surface conditions (floor coverings), the floor area of slabs and the wall area of foundation walls, the thermal mass of the assembly if passive solar design is employed, whether the walls are insulated, the length of the slab perimeter and whether the slab perimeter is insulated.

Conditioned crawlspaces or basements are defined as having conditioned air delivered directly to that space (intentionally or unintentionally), with the walls insulated or not. They cannot be vented to the outside (vented crawlspaces are always considered unconditioned). Crawlspaces and basements can receive the conditioned air from connected spaces as long as the temperature is maintained near the set point.

Indirectly conditioned crawlspaces or basements are defined as having conditioned air delivered to them through heat transfer from the ceiling/floor above or unintentional heat transfer from the mechanical equipment located in that space. These spaces cannot be vented to the outside. Some software analysis programs indicate that these spaces should be considered unconditioned for their calculations to be accurate.

For unconditioned crawlspaces or basements that do not have insulation along the walls, vents may be present, any mechanical equipment located in there is insulated, and the ceiling/floor above is insulated.

There are two types of crawlspaces: open or enclosed (there are two types of enclosed crawlspaces, vented and unvented). An open crawlspace is a pier and beam foundation that has no curtain walls. They are commonly found in the South in areas of potential flooding (low lying ground next to bodies of water or swamps).

An enclosed crawlspace can be either vented or unvented. If vented, the temperature and humidity in the buffer zone is close to ambient conditions. If unvented, the space is mechanically ventilated, providing a buffer zone with a temperature and humidity level close to the conditioned space. An unvented crawlspace should be within the building envelope (insulated walls), following the rules laid out earlier for unvented crawlspaces.

It is important that the system designer first identifies if a crawlspace is present (must be 4' or less in height), and then identifies the type of crawlspace that has been built. Then, measurements of the area of the crawlspace must be taken (perimeter of the foundation walls, height above grade, height below grade) and the type and R-value of insulation on the walls (if any).

Basements are foundation walls that are taller than 4'. They may be vented, unvented and unconditioned, or unvented and conditioned. If the basement is included in the building envelope, it must be unvented (remember the continuous air barrier!) and should have insulation on the walls. Basements do not have to have a slab floor (although they usually do), but it is always a wise practice for there to be 100% coverage of the ground with polyethylene (seams overlapped and sealed, extending up and sealed to the foundation walls and piers). It makes no sense for anyone to build a vented basement, but sometimes they do!

Some basements have one or more walls that are framed above grade (usually found when the house is located on a hillside). These framed walls are not considered foundation walls, but are considered exterior above grade walls. Basements that have this feature are called "walk-out" or "daylight" basements.

Some pre-cast concrete panels already have insulation installed in them as part of the production process (Superior Walls, Dow's T-Mass), and some forms are insulated (Insulated Concrete Forms, ICF's). They have different R-values, but only the documented R-value of the insulation and materials can be used in the software. While a manufacturer may claim a higher R-value due to reduced convection or increased thermal mass, use the documented values (they can be found in ASHRAE's Handbook of Fundamentals or in the code approval documents available from www.icc-es.org). Phrases like "effective" R-value or "performs like" are marketing terms, not building science terms.

The designer must determine if a basement is present, whether that basement is inside the building envelope or not (is the insulation on the walls or ceiling and is it directly conditioned), and measure the perimeter and height of the basement walls. The area of the basement wall needs to be broken out into what that wall is separating the basement from (ground, crawlspace, ambient, conditioned space, etc.) in order for the software to calculate the proper heat flow of the assembly.

A concrete slab is created when concrete is placed in a form to create a flat surface upon which the home is built. Slabs can be on grade, elevated or below grade. An elevated slab has some advantages over the slab on grade (less ground moisture transfer potential). Slabs can be monolithic (footing and slab placed at the same time), or the slab may be placed after the footing and walls are installed. In all but the coldest climate zones, slabs mainly lose their heat off the exposed edges, so it is important that the amount of exposed edge is determined. The edges of slabs that join conditioned space and garages are considered exposed, even though the garage is a buffered zone.

Floors

Framed floors are found over unconditioned or outside spaces. A floor system built over a vented crawlspace, a floor system over an unconditioned basement, a cantilevered floor that extends over outdoor space, a floor system over the attached garage- all of these are considered framed floors. The designer must identify all the framed floors, the R-value of the insulation in that portion of the floor system, and the conditions on each side of the floor assembly (conditioned-enclosed crawlspace, conditioned-open crawlspace, conditioned-basement, conditioned-garage, conditioned-ambient) and the area of the floor system broken out by the differentiating conditions. They should also note the floor covering material- if the material is unknown, go conservative and select something like vinyl that has a high U-factor (instead of carpet which has an insulating effect).

Framed floors that are over conditioned spaces are not entered into the software since they are not considered to be part of the building envelope. A key concept- those areas are part of the calculated conditioned floor area, but are excluded from the building envelope calculations. Framed floors can be built using dimensional lumber, floor trusses, or engineered I-joists or SIPs.

Walls

The designer must determine the type of construction, the type of framing (if any), the insulation in the wall, the thermal mass of the wall and the conditions on each side of the wall. Location, location, location! The designer must also determine the surface area of the walls, broken out by the conditions on each side of the wall's location. Walls are generally located between unconditioned crawlspaces or basements, garages, ambient conditions or attics. In multifamily construction, walls may also be located between two conditioned units (called adiabatic- there is no temperature difference across them).

Wall systems are generally either wood frame construction, metal frame construction or masonry construction. Masonry construction can be aerated autoclaved concrete block (AAC), concrete placed in insulated concrete forms (ICFs), and in some older homes, double wythe brick. Other wall systems include structural insulated panels (SIPs) and log walls.

Wood frame construction usually has either siding or brick veneer (or stone) as the exterior finish material. The framing is usually either 16" or 24" on center and is framed with either 2x4 or 2x6 studs (1 ½"x3 ½" anand 1 ½"x 5 ½", respectively). The stud cavities are insulated with either a batt or spray applied insulation and sometimes has foam board sheathing on the exterior.

The HVAC system designer must determine the thickness of the wall system, the R-value of the insulation, the quality of the insulation installation, what the wall separates conditioned space from (any buffered zones like garages, attics, vented crawlspaces) and the surface area of the walls with similar conditions and construction.

Metal framed construction replaces wood with steel, allowing floor systems to span greater distances without support, and potentially providing more durability and structural integrity. However, steel is a super-highway for heat flow (it is very conductive) and there must be a means of compensating for that. The best way to do that is to provide a thermal break between the steel framing and the ambient conditions by sheathing the exterior with an insulated sheathing. While a 2x4 wood stud is about an R-4, a 2x4 steel stud is about an R-0 (I rounded up!). Heat will always take the path of least resistance, so applying a higher R-value in the cavity isn't effective when it can bypass the insulated portion of the wall and move through a highly conductive part.

Autoclaved aerated concrete (AAC) is a masonry product made from silica (flyash or sand), cement, aluminum, gypsum and lime. The aluminum and silica react together to create the millions of tiny hydrogen pockets found in AAC. These tiny hydrogen pockets give AAC its light weight, higher R-value than regular concrete blocks, sound absorption properties, and thermal inertia. It takes heat longer to transfer from one side of the wall to the other, allowing the HVAC equipment to deal with more even temperature fluctuations. It has an R-value of 1.03-1.25 per inch of thickness. AAC is usually covered with a stucco exterior finish.

Insulated concrete forms (ICFs) are forms created from foam blocks. The walls are built with these blocks and then the concrete is placed within the form. They provide continuous insulation on the exterior and interior of the wall (foam thickness varies with manufacturer), giving a continuous insulation R-value. A 10" concrete wall with 2 ½" of EPS foam on both sides would have an R-value around 21. The foam board can be treated with borate based termiticides for protection and can be installed below grade, as long as the walls are waterproofed (Tuff-N-Dri is a great waterproofing system for ICFs).

Double wythe brick walls are constructed of two brick walls that are connected by bricks turned perpendicular to the walls. These walls typically have large voids within them and are usually found only in older homes. In some cases, the brick walls also enclose a crawlspace or basement. These walls are very moisture permeable and they are very different than a wood-framed wall with a brick veneer.

Structural Insulated Panels (SIPs) are fabricated from straw or foam sandwiched between structural sheathing (usually OSB). The R-value depends upon the thickness of the foam panel, but the inherently tight construction and reduced framing lead to a higher performing wall than stick built construction.

Log walls have a certain amount of thermal resistance to them (and also thermal mass, if they meet the criteria) depending upon the thickness of the logs used. The designer needs to account for the thickness of the wall system and count any continuous insulation provided on the interior of the wall. The mass wall tables found in the IECC are an excellent source of information.

All load calculation software calculates heat flow through the building envelope ($Q = U \times A \times \Delta T$). This basic formula dictates the information the designer must provide the software. The designer needs to identify the construction of the wall assembly, the area of that type of construction and what conditions are on each side of the assembly in order to properly enter the wall assembly and get an accurate calculation of heat flow. Thinking about the end result allows you to figure out what information needs to be gathered and what is not relevant. When working from a set of blueprints, any assumptions should be documented and defensible.

Windows

The designer should determine orientation, area and location of the windows. The window orientation is obtained by using a compass on the site to determine which way the front of the home faces. The orientation of the other sides can be determined from there. Each window should be entered in separately so the actual load on each space can be calculated.

If a window is shaded by a porch roof or other significant overhang, the depth of the overhang must be noted as well as the distance from the top of the window to the bottom of the overhang and the bottom of the window to the bottom of the overhang. This allows the software to calculate how much shading is provided throughout the course of the year and factor in the reductions in solar heat gain.

Window area is calculated by measuring to the nearest inch or using the rough opening dimensions. Most windows are called out on plans as a “3-2 5-2”, indicating width and height. The designer must also determine the U-factor and SHGC of the window (the best source of information is the NFRC label!). If the values are not known, use the code default values found in the latest edition of the International Energy Conservation Code or enter a proposed performance number. If you know the client is going to use low-e windows, it should be factored into the load calculation. Manual J makes some horrible assumptions about the performance of low-e windows- use the values from actual low-e windows available in your market.

If there are skylights, determine the area, type of construction of the roof assembly, orientation, shading, SHGC, U-factor and degree of tilt. The degree of tilt is the pitch of the roof assembly and may require some math on your part.

Doors

Door areas are calculated by the size of the rough opening. They are typically called out as a 3-0 6-8 (3’ wide, 6’8” tall) or a 2-8 6-8. The area of the door is generally around 20 square feet for a single door and 40 square feet for double doors. Doors that are mostly glass should be treated as windows. Doors that are less than half glass should be treated as doors, measuring the glazing area and taking it off the area of the door (a 20 square foot door with a 2’ x 3’ pane of glass would be 14 square feet); the area of the glazing should be entered into the software as a window.

Doors are usually either wood, steel with a foam core or fiberglass. A solid wood door has U-factor around 0.36 – 0.47, a steel door with a foam core is usually around U-0.38 – 0.63, and a fiberglass door is usually around U-0.23. Remember that lower U-factors are better!

All doors that penetrate the building envelope must be accounted for and associated with a particular wall assembly. Heat flows at a different rate through a door between conditioned space and an attic (kneewall doors) than through a door between conditioned space and the garage or ambient conditions.

Ceilings & Roofs

Ceilings and roofs can be wood framed, metal framed, pre-cast AAC panels, and SIPs. Framed roof construction is usually either dimensional lumber framed 16" on center or engineered truss construction 24" on center. It is important to select the correct type of framing, since there is more conduction through 16" on center framing than there is 24" on center framing. The designer must also determine if the roof is part of the building envelope (vaulted ceilings, insulated rooflines) and the exterior color of the roof. We usually select "dark" as the exterior color if asphalt shingles are installed due to the nature of the material.

Flat ceilings are either framed 16" or 24" on center (depending usually upon the roof framing). It is the designer's job to determine the dimensions of the framing material and the thickness of the insulation (this allows for a certain amount of the insulation to be cavity and a certain amount to be continuous).

Insulating along the roofline, turning what would have been an attic space into one that is not vented with outside air has proven to be effective and code approved. The insulation material (such as an open or closed cell foam) must be air impermeable and installed directly against the underside of the roof decking. Additionally, there cannot be a vapor retarder installed on the attic floor, and in warm humid counties (Table N1101.2.1, 2004 IRC) a vapor retarder of 1 perm or less must be installed under asphalt shingles to prevent moisture problems. In climate zones 3-8, enough insulation must be installed to keep the monthly average condensing surface (interior side of insulation) temperature above 45°F.

By definition, these spaces must also be conditioned. This strategy has a performance advantage over a vented attic system, particularly if there are mechanical systems installed in that space.

I had it driven home to me about the importance of verifying insulation R-values. I had two homes that were about 5 miles apart and built in coastal Georgia. One home had a roofline insulated with open cell spray foam (has an R-value of about 3.6 per inch) and was installed to a depth averaging 6" along the roofline, about an R-21. The other house had a roofline insulated with closed cell spray foam (has an R-value around 7 per inch) and was installed to an average depth of 2" along the roofline, yielding about an R-14. The builder had been told by the salesman that the closed cell foam had an effective R-value of 20 per inch and so he thought he had an R-40 roof insulation. He wasn't' very happy when I told him that his home didn't even meet the minimum requirements for the State of Georgia, and his heating and cooling loads were much higher than anticipated!

Ductwork

Ductwork installed in a conventional attic can drop the efficiency of the system by 50%. When that ductwork is installed in a semi-conditioned buffer zone (unconditioned basements inside the building envelope, inter-floor spaces), the efficiency ranges between 50-100% of the system. Ductwork and air handlers installed in a cathedralized (unvented, insulated along the roofline) attic use about 45% less energy than systems installed in conventional (vented) attics.

Ducts outside conditioned space should be insulated to at least R-8, and ducts inside conditioned space should also be insulated to avoid condensation issues (usually R-4 or R-6).

The efficiency of the unit is cut in half and capacity is reduced by 30% with just 15% duct leakage as a fraction of fan flow and research clearly indicates that the installation has more to do with duct leakage than the design. Duct leakage averaged an almost 0.15 $ACH_{Natural}$ increase in building envelope leakage in one study and around 0.20 $ACH_{Natural}$ in another.

When performing a load calculation, the duct leakage should be accurately estimated and the location of the duct accurately defined. Do not assume that all ductwork is leaky, especially in a high performance home that is getting inspected and tested! If the contractor uses appropriate sealing measures, the load calculation should give credit for that and be lowered accordingly. I know that it is hard to guess if the ductwork is going to be in conditioned space or not, but having conversations with the builder, architect or homeowner should give you the information you need to make a defensible assumption.

Air infiltration

Air leakage through the building envelope accounts for about 1/3 of the heating and cooling loads on a home. In the winter, air that leaks in is cold and dry and must be heated; in the summer, the air sneaking in is hot and humid and must be cooled and dehumidified. The air infiltration rate has a huge impact on the peak design loads because of this. If the client is building a high-performance home, use the least amount of infiltration possible. If the homes built by this builder have been tested with a blower door before, use the values from the tests to ensure that air infiltration is not overestimated. Some programs, such as ENERGY STAR®, require that the air infiltration be modeled as the tightest default available.

Internal loads

Internal loads are generated by people, pets, plants and appliances. People give off heat (some of us are regular furnaces) and moisture that needs to be accounted for. The safe and defensible assumption is that the number of occupants of the home will be equal to the number of bedrooms plus one. Do not add additional people to account for holiday parties! If you know the client likes to entertain, an additional unit may be installed to deal with the extra load, one that is sized for the appropriate number of guests. This unit would not be operating most of the year and will only be used during the special events. Do not oversize the unit(s) for the entire home for the entire year to account for those parties!

People are assumed to give off 230 Btu/hour sensible and 200 Btu/hour latent loads. This accounts for the moisture generating activities we usually engage in (washing clothes, taking baths, brushing teeth, cooking, etc).

Pets give off heat and moisture as well. A 22 pound dog will give off about 68 Btu/hour when resting and about 105 Btu/hour sensible and 56 Btu/hour latent when active. A 50 pound dog will give off about 124 Btu/hour when resting and around 230 Btu/hour sensible and 124 Btu/hour latent heat when active. To give a rough estimation of the heat produced by an animal, the metabolic rate is calculated by multiplying the weight of the animal in pounds by 6.6. The average total heat gain is then calculated by multiplying the metabolic rate by 2.5. The sensible heat gain is calculated at 67% of the total heat gain and the latent heat gain is calculated at 33% of the total.

This has led to an interesting question: how many dogs does it take to heat a home? The answer is usually calculated after several of us building science geek-types go out drinking. One time we calculated the number of wiener dogs (I know, technically they are Dachshunds) needed to heat a 1200 ft^2 house in Atlanta. Assuming an average standard weight wiener dog (I'll use 22 pounds for simplicity), we came up with 120 wiener dogs! The reason I bring this up is because there are some folks who, in their pursuit for a home that uses no purchased energy, have actually suggested that people use their pets for heat sources. Unfortunately, that may work in a cold climate but it certainly won't work in all climate zones. Additionally, in the summer time the animals will have to go outside where that number of animals at a single home will definitely draw the attention of Humane Society workers and neighbors. The cost of their food should be taken into account as well and the increased need for ventilation (sorry, Sturmi!).

The only time I would calculate the effect of a pet on the heating and cooling loads of the home would be if it were being built for a known animal lover who intends to keep the critters inside. Other than that, leave pets out of the equation!

Plants give off latent heat (moisture) that should be accounted for. Small plants (less than 12" high) are assumed to release about 10 Btu/hour, medium plants (12" to 24" tall) release about 20 Btu/hour and large plants (taller than 24") release about 30 Btu/hour latent heat. If you know for a fact that the home is going to have plants in it, factor this into the load calculation. Otherwise, don't mess with it- you need to use the smallest defensible load that you can accurately calculate!

Appliances and other activities also generate sensible and latent heat. The default assumption is that 1,200 Btu/hour can be added to the kitchen to account for a refrigerator and a range hood that is vented to the outside. The next default option is to assume 2,400 Btu/hour for a refrigerator, range with vented hood, clothes washer and dryer and a TV or computer. Break this load up so that 1,000 Btu/hour is added to the kitchen, 500 Btu/hour added to the laundry area and 900 Btu/hour added to the area likely to contain the TV or computer.

The third default option is to use an appliance load of 3,400 Btu/hour; this load is caused by a refrigerator plus a stand-alone freezer (or 2 fridges), dish washer, cooking range with a vented hood, clothes washer and dryer and a TV or computer. Add 2,000 Btu/hour to the kitchen, 500 Btu/hour to the laundry area and 900 Btu/hour to the space likely to have the TV.

If the cooking range isn't vented to the outside (the ACNE 3000, extra special forehead greaser and fire hazard model), add 850 Btu/hour sensible and 600 Btu/hour latent to the kitchen area.

A 75 Watt ceiling fan will add 250 Btu/hour to a space and a water bed heater will add 450 Btu/hour to a bedroom. IF you know these items are going to be installed, they should be accounted for. Never assume the highest possible appliance load!

Determining the heating and cooling loads on the home accurately prior to selecting equipment is absolutely critical to building a high performance home that is comfortable. Not only is it required by law in many cases, it is the only way you will be able to select a piece of HVAC equipment that will provide the comfort we crave.

System Selection

The equipment should be selected based upon the load calculation performed according to Manual J and sized according to Manual S. The capacities and efficiencies of the cooling equipment are affected by the outdoor design conditions. In the case of geothermal heat pumps, they are most affected by the ground temperature (or the water loop temperature) in late summer.

When selecting equipment, the things to pay attention to are first, the efficiency ratings of the equipment; second, the fuel and type of equipment; and third, the capacities of the equipment. Once these options are determined, an economic comparison can be made in order for the most cost effective solution to be brought to bear on the comfort challenge.

Efficiency ratings

Each type of equipment has a different efficiency rating category. Gas furnaces use the annual fuel utilization efficiency (AFUE), air source heat pumps use the heating season performance factor (HSPF) for heating and the seasonal energy efficiency ratio (SEER) for cooling, and geothermal heat pumps use a coefficient of performance (COP) for heating and an energy efficiency ratio (EER) for cooling.

AFUE: Fuel output in Btu's per hour / fuel input in Btu's per hour

HSPF: Average annual Btu's of heating / annual average watt-hours of electricity used

COP: Total heating capacity in Btu's per hour / (total electrical input in watts x 3.412). This is a steady state efficiency rating.

SEER: Average annual Btu's of cooling / annual average watt-hours of electricity used

EER: Total cooling capacity in Btu's per hour / total electrical input in watts (btuh/watt)

The efficiency ratings are typically found using the Air-conditioning and Refrigeration Institute (ARI) database, found at www.ahridirectory.org. As a word of caution: the ARI numbers don't really mean much.

The published numbers are from data that was collected at temperatures much different than indoor design and actual climate. We use 75°F for the indoor design cooling temperature, but ARI uses 80°F for their indoor design temperature when rating equipment. We use an indoor wet bulb temperature around 64°F, but ARI uses an indoor wet bulb temperature of 67°F. The ARI outdoor design temperature for cooling is 90°F, not the actual climate conditions where your equipment is going to be installed.

On the heating side, ARI publishes their information based upon an outdoor design of 47°F, although they give capacities at 17°F as well.

This is a critical distinction to make: do not use ARI information for determining capacity! The information can be used for determining efficiency ratings, but not the capacity. For actual capacity, use the manufacturer's data (which has been approved by ARI) and interpolate between the given design temperatures.

Furnaces

Furnaces heat the air through the combustion of fuel. They have an electric motor driven fan that moves the air through the distribution system (ductwork), pulling cool air from the house and pushing the heated air back into the home. While the minimum efficiency rating of furnaces is currently 78% AFUE, they are typically found with either an efficiency rating of 80% AFUE or a 90% + AFUE. Efficiency ratings for furnaces can be obtained from the Gas Appliance Manufacturers Association (GAMA, www.gamapower.org). NOTE: GAMA has merged with ARI to form AHRI.

An 80% AFUE furnace is most easily distinguished by the metal flue pipe and the need for combustion (or make-up) air to be supplied to the furnace for the combustion process. The combustion air may be supplied from the space containing the furnace or from the outside.

The 90% + AFUE furnace (also called a condensing furnace) is usually identified by the non-metallic flue pipe and often is a direct vent appliance, bringing in combustion air through one PVC pipe and exhausting flue gases through another. Sometimes, these pipes are combined in what seems to be a single pipe; it actually is a pipe within a pipe. They are efficient and provide protection from combustion gases that may backdraft, causing indoor air quality problems. The condensing furnace achieves its higher efficiency rating by taking back the heat found in the water vapor produced by combustion. This latent heat is released when the water vapor condenses.

If a furnace has an input capacity of 45,000 Btu's and has an efficiency rating of 80% AFUE, the output capacity will be around 36,000 Btu's (80% of 45,000). Always size furnace equipment based upon the output capacity at the selected efficiency rating. If the furnace is oversized, the furnace and vent can become cool, causing condensation to form from the water vapor. This can lead to equipment failure due to rust.

Over sizing furnaces does not make the home more comfortable. It only takes about 20 minutes to route all the air in a typical home through the furnace (if everything is designed and installed correctly). Over sizing the furnace by 100% may cut that time in half, but the sense of comfort will be restored with a right sized piece of equipment in the same amount of time. We reach our comfort level in about ½ the time it takes to reheat the thermal mass of the home, well before the furnace has completed its cycle.

The output capacity of the furnace must be between peak load and 40% more than peak load. If the cooling load requires a larger indoor coil than is compatible with a right-sized furnace, you should probably be looking at heat pumps instead.

If the 80% AFUE furnace is located in an unconditioned space of the home (outside the building envelope), it can use the air within that space for combustion as long as the space has at least 50 cubic feet of volume for every 1,000 Btu's of input rating.

If the 80% AFUE furnace is located within a conditioned part of the home (like a basement), the requirements change depending upon the air infiltration rate (in air changes per hour, ACH). If less than 40% of the air exchanges with the outside (0.40 ACH) and the furnace is atmospherically vented (no fan), the required volume is calculated by the formula:

$$Volume_{Req} = 21\ ft^3 / ACH \times (input\ rating/1{,}000\ Btu/hr)$$

If the furnace has fan assisted venting (and less than 0.40 ACH infiltration), the formula for the required volume is:

$$Volume_{Req} = 15\ ft^3 / ACH \times (input\ rating/1{,}000\ Btu/hr)$$

If it turns out that the space doesn't have the correct amount of volume, that confined space can be connected to other spaces in order to provide the correct amount of combustion air. Those openings must be sized according to code requirements, and may not take air from bedrooms, bathrooms, toilet rooms and storage closets.

USING THESE CODE-APPROVED MEANS OF PROVIDING COMBUSTION AIR FOR FUEL GAS APPLIANCES INSIDE CONDITIONED SPACE IS A REALLY BAD IDEA… sort of like having a place where you could buy beer, gas and fireworks! Just because it is legal to do so, does not make it right (or like Grandpappy would say "Bein' legal ain't always right!").

If the 80% AFUE furnace is located within the conditioned space of the home, it should be contained within a specially constructed chamber called a combustion closet. This combustion closet is considered outside the building envelope and will have insulated and air sealed walls, a solid door with a threshold and weatherstripping, and may require an insulated ceiling. Combustion air is going to be supplied to this chamber through openings that are ducted to the outside or unconditioned spaces freely connected to the outside (like vented attics or crawlspaces). There are two ways to do this: using 2 permanent openings or 1 permanent opening.

The two permanent openings method requires that one opening be installed within 12" of the top and one opening installed within 12" of the bottom. This could be, in a single story home, a duct into the vented attic and a duct into the vented crawlspace (or two ducts from the vented attic). If vertical ducts are used, the openings must provide a free area of 1 square inch per 4,000 Btu/h of the total input rating for all the fuel gas appliances in that chamber. If horizontal ducts are used, the openings must provide a free area of 1 square inch per 2,000 Btu/h of the total input ratings.

The one permanent opening method requires a single opening at the top of the chamber that is either directly connected to the outside or is ducted to spaces that are, such as a vented attic. The opening must provide at least 1 square inch of free area per 3,000 Btu/h of the total input ratings AND must be at least as large as all the vent pipes added together. The size requirement does not change for vertical or horizontal ducting.

This combustion closet concept is a great one for all combustion appliances. A negative pressure zone could still be created, but it would be outside the building envelope in this buffered zone. It is extremely important that the air handler cabinet and the supply and return plenums are well-sealed, since negative pressure (a leak in the return side) could cause backdrafting of the fuel gas appliances. This could potentially cause combustion gases (CO, CO_2, NO_x, SO_x) to enter the duct system and be distributed throughout the home. The advantage of the well-sealed combustion closet is that it removes all the other mechanical causes for pressure differences (kitchen exhaust hoods, clothes dryers, bath exhaust fans, whole house fans) from the equation. It also provides less likelihood (if the mechanical system is also well-sealed) of dangerous combustion gases entering the home.

When sizing furnaces, the equipment capacity should be at least equal to the calculated heating load (in Btu/h) and not be greater than 40% more than the calculated load. If the furnace air handler is also acting as the air handler for the air-conditioner, the blower must be able to handle the amount of air needed to meet the cooling load.

Blower

When a heating only system is installed, the system pressures are lower because there is no indoor coil for the supply air to pass through. The amount of air flowing across the heat exchanger has a direct effect on the temperature rise (creating the temperature difference between supply air and room air). The flow rate needs to be calculated so that the temperature rise falls within the manufacturer’s temperature rise range.

When a furnace and cooling system are installed, the system pressure is higher at the blower because the supply air must pass through the indoor coil. The indoor coil can drop the pressure between 37 Pascals (Pa) and 62 Pa. A Pascal is a measurement of pressure equivalent to 0.004 inches of water column (IWC), and is used to measure duct leakage among other things.

The blower also has to meet the airflow requirements of the indoor coil and peak cooling load; this is usually much higher than just for a heating system. A cooling coil usually drops the temperature between 17°F and 21°F, requiring a greater amount of airflow than needed for just crossing a heat exchanger (which creates a temperature rise between 25°F and 45°F).

This may require a more powerful furnace air handler than would normally be needed for just heating the home. If this means over sizing the furnace by more than 40%, check out heat pumps instead.

Heat exchanger

The heat exchanger is the device that transfers the heat from burning the fuel to the air stream. Manufacturers typically have a range of temperature rise that the heat exchanger can perform; outside of that range, bad things can happen!

Temperature rise (°F) is equal to the output capacity in Btu/hr divided by the heating airflow requirement multiplied by 1.1. The formula is Rise = Output Capacity / (1.1 x Heating CFM).

If there is too much airflow across the heat exchanger, the exchanger will stay cooler and may corrode from the condensation formed. If there isn’t enough airflow across the exchanger, the exchanger may heat up too much and the repeated heating and cooling can cause the exchanger to deform or crack.

Air Conditioners

Air conditioners work using the concepts of refrigeration. Refrigeration is taking heat from a place you don’t want it and placing it in a place you do want it. In our case, we don’t want the heat in the home and we do want the heat outside.

Air conditioners have four basic components: a compressor, an expansion valve and two heat exchanger coils (evaporator and condenser).

Air conditioners work by pulling warm house air through the return side of the air handler and across the indoor evaporator coil. The heat in the air is moved to the cool, low-pressure vapor refrigerant that loops through the indoor coil. The longer the air moves across this coil, the greater the moisture removal (as the air cools down, the moisture condenses on the coil's fins and drains to the outside). This is an advantage that slightly undersized systems and variable speed motors provide: more dehumidification.

As the cool, low-pressure vapor refrigerant heats up, it is compressed into a hot, high-pressure vapor by the compressor. This hot vapor is looped through an outdoor condensing coil, causing the heat to transfer to the cooler "heat sink" (outside air). As the vapor refrigerant cools down, it becomes liquid and goes through the expansion valve where it is transformed back into the cool, low-pressure vapor refrigerant.

By changing the pressure and temperature of the refrigerant, we can use it to move the sensible and latent heat from inside the home to outdoors. Sensible heat is heat that is added or removed that changes the temperature, but not the state (solid, liquid, and vapor). Latent heat is heat added or removed that causes a change in state (solid, liquid, vapor) but not a change in temperature. We do not want the refrigerant to solidify, so we must design a process that keeps the temperature of the refrigerant above that point and use a refrigerant that stays in liquid or vapor form under our equipment design conditions. We also want the refrigerant to be in very specific phases at certain points of the refrigeration cycle; it needs to undergo phase changes at the evaporator coil and condensing coil in order to function properly.

The ***saturation state*** is when a refrigerant is both liquid and vapor; the liquid and vapor have the same temperature- this occurs when a refrigerant is undergoing a phase change and when it has reached equilibrium.

Superheat is the amount of heat contained in a vaporized refrigerant above the saturation point. If superheat doesn't exist within the refrigerant cycle, the refrigerant can enter the compressor in liquid form and potentially tear the compressor up. If too much superheat exists, the evaporator will only have a small amount of liquid refrigerant; this causes a decrease in the efficiency of the system. Measuring superheat can allow you to check the refrigerant charge on systems that do not have a thermal expansion valve (TXV).

Subcooling is the temperature removed from the vaporized refrigerant when it is condensed back into a liquid. Because a TXV device keeps superheat at a constant level across a wide range of operating conditions, measuring superheat on a system with a TXV is completely inaccurate. Instead, measure the amount of subcooling.

Lower subcooling temperatures provide greater heat removal capacity and ½% increase in efficiency is obtained with every degree of subcooling. Use a subcooling calculator to determine what the subcooling temperature should be for the installed piece of equipment.

If the refrigerant hits the compressor in liquid form, it increases the amount of energy used by the compressor, overheats the compressor, breaks down the oil, reduces the capacity of the equipment, causes increased wear and tear due to decreased lubrication, and makes the compressor noisier.

The ***compression ratio*** has an effect on energy efficiency and superheat. Higher compression ratios reduce the efficiency of the unit. The compression ratio compares the discharge pressure with the suction pressure. Measure the pressures in the lines with the pressure gauges (PSIG) and convert them to Absolute Pressure (PSIA) by adding 14.7 to the gauge pressure. Then, divide the discharge pressure by the suction pressure to get the compression ratio (Discharge PSIA / Suction PSIA = Compression Ratio).

The ***metering device*** takes high temperature, high pressure liquid refrigerant from the condenser and sends a low temperature, low pressure saturated refrigerant (liquid and vapor) to the evaporator. It lets the liquid refrigerant enter the evaporator at the same rate the evaporator can vaporize it. It also drops the pressure to a point that allows the refrigerant to reach a low enough temperature to absorb heat during vaporization. This pressure drop also allows the refrigerant in the condenser to liquefy at a temperature high enough to reject heat.

The ***evaporator coil*** is a refrigerant-based heat exchanger. It takes low-temperature, low-pressure saturated refrigerant and vaporizes it into a low-temperature, low-pressure vapor. It is important for it to have the right amount of airflow across it. It sends the vapor refrigerant to the compressor which discharges it to the condensing coil as a high pressure, high temperature refrigerant.

The ***condensing coil*** is another heat exchanger within the system. It takes the high-temperature, high-pressure vaporized refrigerant and condenses it to a medium-temperature, high-pressure liquid. It does this in three steps: de-superheating, condensing, and subcooling. De-superheating removes the superheat from the refrigerant, changing the temperature without changing the state and accounts for about 14% of the reduction in the heat content (enthalpy) that occurs in the condenser. Condensing removes the latent heat (changing the state without changing the temperature) from the refrigerant. This takes care of about 81% of the reduction in heat content occurring in the condenser. The last step is subcooling; the temperature of the liquid refrigerant is dropped without changing the state and is sent to the evaporator coil.

Because the state of the refrigerant is so important at these very specific points during the cycle, any refrigerant line that runs longer than 80’ equivalent length or travels more than 20’ vertically needs to be designed according to the HVAC manufacturer’s long line set installation instructions. This typically involves adding devices to the system that help to maintain the correct refrigerant state.

With air conditioners, duct leakage becomes critical since hot or humid air that is drawn in on the return side can murder the efficiency rating.

Air Source Heat Pumps

Heat pumps work by moving heat instead of converting it from a fuel (electricity or gas). It is essentially a two-way air conditioner that heats by reversing the refrigerant flow, causing the heat to be transported from the outside to the home.

Heat pumps are very efficient but the efficiency can vary depending upon the source of the heat. Air source heat pumps have two rated heating capacities: one at 47°F and one at 17°F, reflecting the lowered capacity for moving heat at the lower outdoor temperatures.

Sometimes, the outside coil collects ice (in heating mode, the outdoor coil is about 20°F to 25°F lower than the air temperature) and the heat pump switches to cooling mode, moving heat from the house to heat up the outside coil to melt the ice. The heat pump then uses electric resistance heating (strip heat) to heat the cold air, compensating for cooling the home in the winter. This is like heating the home with a toaster oven and loses the efficiency of moving heat. It is very important that heat pumps have an outdoor thermostat set at a proper temperature (the heat pump's balance point) to avoid using strip heat when it isn't necessary.

The heat pump's balance point is the outdoor temperature at which the heating capacity exactly matches the heating load needed by the house; above the balance point, the heat pump can always satisfy the thermostat. Below the balance point, the supplemental electric resistance heat (or gas furnace in a dual fuel heat pump) must turn on in order to satisfy the heating requirements of the home.

Heat pumps do not heat the air to as high a temperature as furnaces do. A heat pump will generally heat the air to about 20°F higher than the temperature pulled from the home at the return, perhaps a few degrees more when the strip heat comes on. A furnace, on the other hand, can heat the air to between 40°F and 70°F higher than the temperature of the air pulled from the house.

Heat pumps should have the inside and outside coils matched and rated by the Air-Conditioning and Refrigeration Institute (ARI, www.ahridirectory.org) in order to verify the actual installed equipment efficiency.

If the refrigerant charge is too low, the cooling capacity is reduced and the compressor motor may overheat (due to lowered suction pressure). If the refrigerant charge is too high, condensation may form on the compressor housing as a result of refrigerant "flood back" and, in severe cases, lead to failure of the compressor.

Geothermal Heat Pumps

Geothermal heat pumps use the earth instead of the air. The earth has a fairly constant temperature all year long, while the air temperature fluctuates seasonally. This constant temperature provides greater efficiency for heating and cooling when using a heat pump.

There is about 20 times more geothermal energy available than what we can get from burning coal and about 300 times more than what we have available in oil and gas. Geothermal heat pumps are a technology that is suited for all climate zones; the earth's temperature is stable at a range of 45°F to 75°F (colder in the north, warmer in the south).

Some of the challenges are a lack of skilled trade contractors who can assemble the systems, a higher initial cost (offset by lower operating costs), and a lack of consumer education. The geothermal industry has been content to duke it out amongst themselves instead of working together to promote their technology to the public.

In spite of this, around 40,000 geothermal heat pumps are installed every year in the United States and even more in Canada, where they are experiencing a growth rate of nearly 100%.

Geothermal heat pumps can also provide domestic hot water (DWH) through using the de-superheating that takes place during the refrigerant cycle and do not suffer from cyclic output like wind and solar water heating technologies.

Geothermal heat pumps have the same components and work on the same principles as air source heat pumps. They use a refrigeration cycle to discharge heat from the home to the ground in the summer and discharge heat from the ground to the home in the winter. System design depends upon the geology of the site, the hydrology of the site (if using an open loop system), and the amount of land available for installing the piping.

The refrigerant used in geothermal heat pumps varies. Most systems are designed with two refrigerant loops. The underground piping uses a mixture of water and 15% propylene glycol which is pumped through the heat exchanger. A refrigerant in the secondary loop within the unit transfers energy with the underground piping through the heat exchanger. This is often called the “water-antifreeze” system. A direct expansion system (DX) eliminates the heat exchanging process by using a single refrigerant loop that continues through the underground piping.

In the heating cycle, heat is picked up from the ground by the water-antifreeze solution in the piping and is pumped through the heat exchanger. The refrigerant receives the geothermal heat and is vaporized into a low-pressure, low-temperature refrigerant vapor. It goes through the reversing valve to the compressor. When compressed, the low-pressure, low-temperature vapor becomes a high-temperature, high-pressure refrigerant vapor and passes through the reversing valve to the condensing coil. At this coil, it is condensed from a high-temperature vapor to a medium-temperature liquid, transferring the heat to the air stream blowing across it. It then goes through a thermal expansion valve which lowers the pressure and temperature even more; the low-temperature, low-pressure refrigerant is sent back to the evaporator coil to pick up more geothermal heat.

During the cooling cycle, the reversing valve is used to switch the evaporator and condensing coils. Now the refrigerant is picking up heat from the return air stream blowing across it and is rejecting it through the ground loop-refrigerant heat exchanger.

The capacity of the equipment is determined by the temperature of the water-antifreeze mix entering the system. The late summer water temperature is calculated by subtracting 10°F from the extreme summer temperature and the late winter water temperature is calculated by adding 40°F to the extreme winter temperature. The entering water temperature is used with the manufacturer's data to select a piece of equipment suitable for the heating and cooling loads on the home.

There are two main types of geothermal heat pump systems. The ***open loop*** system (Ground Water Heat Pump, Surface Water Heat Pump) pulls groundwater from a well or body of water and uses it instead of the water-antifreeze solution through the underground piping. This water is then discharged to either the surface of the ground, another well, or back into the pond or lake. There are a couple of serious challenges with this system; the water tends to be corrosive due to the hydrogen sulfide content and shortens the life span of the heat exchangers, and there are valid concerns over introducing contaminants into the water supply. If the water is hard (more than 100 ppm) or if you know it contains hydrogen sulfide, don't even consider an open loop system. I don't recommend open loop systems. The ***closed loop*** system (Ground Coupled Heat Pump, Surface Water Heat Pump) uses the water-antifreeze solution (which is environmentally safe) or a refrigerant as described above.

There are different ways of configuring the underground loops as well. The loops can be in ***vertical*** bores or in ***horizontal*** trenches. Additionally, the loops in horizontal trenches can take a ***spiral*** form which shortens the length of the trench needed.

Closed Loop Geothermal Heat Pump, Ground Temperature 56°F - 59°F				
	Capacity			
	2 ton, 5-6 gpm	3 ton, 7-9 gpm	4 ton, 10-12 gpm	5 ton, 12-15 gpm
	Feet of Pipe			
Horizontal 6-pipe	320	480	640	800
Horizontal 4-pipe	360	540	720	900
Horizontal 2-pipe	560	840	1,120	1,400
Vertical U, ¾" pipe	340	510	680	850
Vertical U, 1" pipe	320	480	640	800
Vertical U, 1 ¼" pipe	300	450	600	750
	Number of Parallel Loops			
Horizontal 6-pipe	3-4	4-6	6-9	8-10
Horizontal 4-pipe	2-3	4-6	5-8	6-9
Horizontal 2-pipe	2-4	3-5	4-6	5-8
Vertical U, ¾" pipe	2-3	3-5	4-6	5-8
Vertical U, 1" pipe	2-3	2-4	3-5	4-6
Vertical U, 1 ¼" pipe	1-2	1-2	2-3	2-3
	Header Diameter, High Density Polyethylene			
Trench < 100' long	1 ¼"	1 ¼"	1 ¼"	1 ½"
Trench > 100', < 200'	1 ¼"	1 ¼"	1 ½"	1 ½"
	Number & Size of Pumps			
	(1) 1/12 hp	(1) 1/6 hp	(1) 1/6 hp	(2) 1/6 hp

Vertical loops are usually 2 pipes that are shaped like a U and are inserted into a 4" wide bore that is between 100' and 400' deep. These bores are grouted with bentonite or a thermally enhanced grout to ensure better heat exchanging with the earth. Depending upon the size of the unit required you may need a number of bores; multiple bores should be at least 20' apart. These pipes are connected together by a single header pipe that runs to the indoor unit. The pipes used in geothermal systems are at least a series 100 high density polyethylene (HDPE) pipe that has the connections thermally fused, making the joints stronger than the pipe itself. While the indoor components of the geothermal system have a life expectancy of 25 years, the pipe system generally has a life expectancy of at least 50 years.

Horizontal loop systems remind me of double barreled shotguns: they can be over-under or side-by-side. If the 2 pipes are over-under, they are usually buried with one 6' below grade and one 4' below grade inside a 24" wide trench. Whenever trenching, follow the safety rules! If you don't know the rules, don't dig the bloody trench. Hire a professional. The pipes should be kept at least 6" from the sidewalls of the trench, backfilling carefully over the lower pipe before laying the upper pipe. If you use the side-by-side configuration, the 2 pipes should be buried at least 5' below grade and about 2 feet apart. Keep them at least 6" away from the side walls (meaning the trench will need to be at least 3' wide). If you need multiple trenches, they need to be at least 5' apart and have the pipes connected to a header pipe that runs into the indoor unit.

These trenches need to be back filled carefully, using something that conducts heat fairly well. Historically, clay or sand was used as backfill. One of the challenges is the effect moisture has on soil conductivity. Wet soil has greater conductivity than dry soil, but discharging heat into the ground causes water to move away from the piping which reduces the conductivity (reducing the capacity). Also, the conductivity of the ground around the piping needs to be considered since it has an effect on the capacity of the pipe to move heat as well.

The length of the pipes depends upon the soil conductivity, the load requirements of the home, and the pipe configuration (2 pipe, 4 pipe, or spiral).

U-factor of Soil Types, Btu/hour/ft/°F	
2% Dry sand	0.34
7% Damp sand	0.87
12% Wet sand	1.27
2% Dry, sandy soil	0.75
5% Damp, sandy soil	1.45
8% Wet, sandy soil	1.62
2% Dry clay or silty clay	0.21
10% Damp clay or silty clay	0.46
20% Wet clay or silty clay	0.64
Granite	1.97
Limestone	1.97
Shale	1.39

If the soil conductivity is around 0.40, horizontal length should be multiplied by 1.22; around 0.60, use the length given; around 0.80, multiply by 0.89; and around 1, multiply the length by 0.82.

For vertical installations, if the soil conductivity is around 0.80, multiply the vertical depth by 1.23; if the conductivity is around 1, multiply the depth by 1.1; if around 1.4, multiply the depth by 1.3; if around 1.6, multiply the depth by 0.87; if around 1.8, multiply by 0.83; and if the soil conductivity is around 2, multiply the depth by 0.79. This is assuming that the grout used has a U-factor of 0.85. If the grout has a U-factor around 0.40, multiply the depth by 1.2; if the grout U-factor is around 1.1, multiply the depth by 0.95.

The flow rate of the water-antifreeze mix is determined by this formula: Flow Rate (gpm) = Load / (500 x Water Temperature Drop). The water temperature drop is found in the manufacturer's data, which also provides the air temperature drop (cooling) and rise (heating).

Geothermal heat pumps have an initial higher installation cost, with an average installed price around $2,500 per ton for the equipment. However, they use about 30% to 40% less energy than an air source heat pump and have a 95% homeowner satisfaction rate. They can also reduce the amount of energy purchased for heating water. This is one technology that I highly recommend, providing the site conditions are economically favorable.

Economic comparisons

To accurately compare energy costs between furnaces and air source heat pumps, several calculations have to be performed.

Cleveland, TN, affordable housing	
Heating Degree Days	3,883
Cooling Degree Days	1,235
Winter design tem-perature	21° F
Summer design tem-	92° F
Design peak heating load	13,200 Btu/hr
Design peak cooling load	10,200 Btu/hr
Cost per therm	$1.22
Cost per kWh	$0.0755

Heating load hours: (Heating Degree Days x 24) / (65 – Winter Design Temperature)

Cooling load hours: (Cooling Degree Days x 24) / (Summer Design Temperature – 65)

Heating and cooling design loads (Manual J load calculation, discussed later)

The calculation for estimating furnace costs take several additional steps

1. Burner Btu/year = (0.77 x heating load hours x heating design load) / equipment efficiency rating
2. Pilot light Btu/year = ((8,760 – ((0.77 x heating load hours x heating design load) / (equipment efficiency rating x burner input in Btu's per hour)) x pilot light input in Btu's per hour)
3. Auxiliary electrical consumption (available from manufacturer) in kWh
4. Add Steps 1 & 2 together
5. Multiply Step 3 by rate per kilowatt hour
6. Divide Step 4 by 100,000
7. Multiply Step 6 by rate per therm
8. Add Steps 5 and 7

The calculation for estimating heat pump heating costs is:

1. Heating kWh = (0.77 x heating load hours x design heating load) / (1000 x heating season performance factor)
2. Heating kWh x rate per kWh

The calculation for estimating heat pump cooling costs (and cost for air conditioning for furnaces) is:

1. Cooling kWh = (cooling load hours x design cooling load) / (1000 x seasonal energy efficiency ratio)
2. Cooling kWh x rate per kWh

For furnace costs, add the results from the furnace calculation with the cost of cooling.

For heat pump costs, add the results from heat pump heating and cooling together.

Suppose an affordable housing provider in Cleveland, TN, wants to know if an 80% efficient furnace with a code minimum air conditioner is more cost effective than a code minimum air source heat pump (7.8 HSPF, 13 SEER).

Heating load hours = (3,883 x 24) / (65° F - 21° F) = 93,192 / 44 = 2,118

Cooling load hours = (1,235 x 24) / (92° F - 65° F) = 29,640 / 27 = 1,098

Manual J heating load = 13,200 Btu/hr; Manual J cooling load = 10,200 Btu/hr

Furnace estimated annual heating cost

1. (0.77 x 2,118 x 13,200) / 0.80
2. (21,527,352 / 0.80) = 26,909,190
3. Furnace selected has electronic ignition (no pilot light)
4. 465 kWh (from manufacturer's data)
5. 26,909,190 Btu's
6. 465 x .0755 = $35.11
7. 26,909,190 / 100,000 = 269.0919
8. 269.0919 x 1.22 = $328.30
9. $35.11 + $328.30 = $363.41

Heat pump estimated annual heating cost

1. (0.77 x 2,118 x 13,200) / (1,000 x 7.8)
2. 21,527,352 / 7,800 = 2,759.92
3. 2,759.92 x 0.0755 = $208.38

Heat pump (or air conditioner) estimated annual cooling cost =

1. (1,098 x 10,200) / (1,000 x 13)
2. 11,199,600 / 13,000 = 861.51

3. 861.51 x 0.0755 = $65.05

Estimated furnace / air conditioning costs, per year = $363.41 + $65.05 = $428.46

Estimated air source heat pump costs, per year = $208.38 + $65.05 = $273.43

Performing these calculations allows one to provide fairly accurate advice to the client that separates utility company marketing hype from fact.

Ductwork

These are also called “thermal distribution systems” and are perhaps one of the most critical components of the HVAC system. It is also the most overlooked. The distribution system includes the air handler, ductwork and registers. Ductwork should be designed to supply the needed amount of conditioned air to the zones in the home. Duct design, duct material (metal, flex, and ductboard), duct diameter, duct installation and duct leakage all affect the capacity for the ductwork to deliver the amount of air needed to satisfy the heating and cooling load.

Ductwork must be properly designed and installed for it to be effective and efficient. Installing a $7,000 piece of HVAC equipment and spending $600 on the ductwork installation is ridiculous, since the ductwork installation is probably the primary factor in determining the comfort of the people inside the home.

Duct design

First, try to get the ductwork inside the building envelope. This reduces the duct leakage to the outside (which has an energy penalty) and generally improves performance. While there is no blatant energy penalty for duct leakage to the inside of the building envelope, it can create a comfort penalty (air not getting where it should) and may create indoor air quality issues by creating specific pressure zones that may draw air from bad sources. Well-sealed ductwork within the building envelope is a priority issue. Getting the ductwork inside the building envelope may simply require redefining the building envelope to include an attic, crawlspace or basement. Perhaps a drop ceiling can be installed in a hallway or a soffit built around the edges of the room. Maybe a special truss design can be used that allows the ductwork to be installed within a conditioned zone of the attic. There are many creative ways (exposed ductwork) to get ductwork inside the conditioned space (and some of them are less expensive than others!)

Sheet metal elbows should be used for making tight turns. Sheet metal has a lower friction rate than flex duct, making it easier for the proper amount of airflow to reach the register. Flex duct turns should be gradual, with the radius of the turn greater than the diameter of the flex duct. In terms of reducing airflow, every 90° bend is the equivalent of adding 30’ or more of straight length to the duct run.

Duct runs should not originate within 1 foot of the plenum cap or from the plenum cap itself. Ducts shouldn’t originate within 1 foot of the end of a trunk line or from the end of the trunk line. Duct run take-offs should be spaced at least 1 foot apart on the plenum or trunk line.

Layout

Duct layout involves designing a system that accounts for zone loads, the home’s structural materials and locations, the framing orientation, occupant comfort and ensuring the delivery of the right amount of conditioned air.

The duct layout needs to take into account the size of the duct (including the insulation) needed to heat or cool each space. This also means that the trades need to work together to make sure that there is enough space for the ductwork to be installed. This is tricky and requires coordination between the building superintendent and his mechanical, plumbing and electrical subcontractors. I always prefer having a project kickoff meeting where they all sit down and look over the plans, discussing where their lines are going to run and start off with a coordinated effort to respect the ductwork.

The structural material also needs to be considered; each type of framing system requires a different approach. Dimensional floor joists between floors cannot be altered enough to run ductwork across them and may require a perimeter soffit and chase system to do a single unit, multi-floor system (zoned system). I-joists can be altered, but not willy-nilly and must have an engineer's approval if the alteration goes beyond the manufacturer's recommendations. Laminated veneer lumber (LVL) beams cannot be altered in any way without an engineer's approval. Open web floor trusses provide the greatest versatility for all the trades; the critical component is making sure that the plumbing layout does not have a drain coming through the floor truss.

While this may seem simple enough, I once worked with a mechanical contractor and a builder on the duct layout for a home; the builder said he was going to use floor trusses for the second floor and we designed accordingly and the HVAC contractor estimated his labor costs based upon that information. After construction started, the builder found out that he could save less than $100 by switching to I-Joists- and he did! However, the duct installation labor costs nearly tripled and forced an extremely convoluted design. The HVAC contractor and his crew worked very hard and managed to get all of the airflows within 15% of the design, but it would have been easier and more cost effective if the builder had simply followed our advice and used the trusses- even though they had a higher purchasing price!

The orientation of the floor framing will also affect the design. Ducts should run between the floor framing members, not across or through them (unless it is an open web truss).

The system should be laid out in a way that provides comfort to the occupants. Don't terminate a duct at the only place in a bedroom where they can put a bed, don't terminate one next to the bathtub or shower, and don't terminate one under the place where their desk will go!

The layout should be designed to deliver the right amount of air needed for each space. This is achieved through duct sizing calculations and flow balancing dampers. Flow balancing dampers are inexpensive and allow the amount of airflow into a room (or zone) to be altered. They should be installed in the duct at an accessible location upstream of the duct supply register. This may be at the take-off from the trunk or plenum, or may be in-line on the duct run itself. The key is to have the damper installed in an accessible location.

Distribution geometry

Duct systems usually take the shape of a trunk and branch, perimeter loop, spider system or radial system. Trunk and branch systems are the best type to be installed if the architecture and construction materials support it, using sheet metal trunks and flexible duct branches.

The ***trunk and branch system*** can have a trunk that is one size (extended plenum), a trunk that reduces in size over its length (reducing plenum) or multiple trunks (primary-secondary trunk). The air handler should be centrally located on the trunk; however, it is possible to have it off-set and still get the performance needed. It simply requires more work because there are large differences between the effective lengths of the ducts at the air handler and end of the trunk.

The ***reducing plenum system*** addresses that issue by equalizing the fitting losses of the branch take-offs, helping to move air into the ducts closer to the air handler. The reduction should take place when the velocity in the trunk drops to about ½ the velocity of the first part of the trunk. Velocity is calculated by dividing the air flow rate (cfm) by the cross-sectional area of the duct in square feet.

Imagine we have a 12" diameter round trunk system delivering 525 cubic feet per minute that has 5 take-offs and the first take-off delivers 266 cubic feet per minute, the second take-off 86 cfm, the third 81 cfm, the fourth 36 cfm and the fifth 56 cfm. The velocity of the air entering the trunk will be around 670 feet per minute (surface area = Pi x R^2, convert square inches to square feet = 0.785; 525 / 0.785 = 668.78 feet per minute). After the first take-off, the velocity will be around 330 feet per minute (fpm), calculated by subtracting the take-off cfm from the total cfm and dividing by the surface area of the trunk cross-section. Since this is less than 50% of the initial velocity, the trunk should be reduced after the first take-off.

How far down should it be reduced? The answer is that you want to reduce it to a size that will maintain the initial velocity (or close to it). A 10" duct will give you a velocity of 475 fpm, a 9" duct will give you a velocity of 587 fpm, and an 8" duct will give you a velocity of 744 fpm.

If we reduce it down to a 10" duct, will we need another reduction? Well, we are now delivering 259 cfm through the duct at 475 fpm; the next take-off drops us to 173 cfm with a downstream velocity of 317 fpm (66%) and the third take-off drops us to 92 cfm and a downstream velocity of 168 fpm (35%).

We are now carrying the air in the reduced trunk at less than 50% of the velocity; we should have another reduction, probably between take-offs two and three. Reducing to an 8" duct between take-offs 2 and 3 will give us a trunk velocity of 497 fpm. Since the 3rd take-off doesn't drop us below 50% of this section's velocity, we don't need another reduction after it.

Take-off 4 will bring us to a downstream velocity of 161 fpm (32%), so we should have another reduction in the trunk between take-offs 4 and 5. Reducing to a 6" trunk will give us a velocity of 285 fpm, about 57% of the initial velocity in that section of the reduced trunk.

The supply trunk should be sized with enough capacity to handle all of the airflow needs for all of the supply ducts for that conditioned zone.

The ***perimeter loop system*** is the most expensive to install and is usually used for in-slab installations in cold climates. Under those conditions, it has better performance for delivering warm air into the comfort zone than perhaps the others during the heating season.

The ***spider system*** is a system of flexible ducts that are connected by rectangular or triangular ductboard boxes, eventually terminating at a supply boot. When you see this system, you will be reminded of the spider plant, sending out its many little plantlets. There are many more connections that can fail with this system and they typically take up more space in attics. While testing one of these systems, the inspectors found much more leakage than normal and started looking for obvious culprits. When everything appeared normal, they ran the test again- and it failed again. This time, one inspector ran the duct pressurization fan and the other went to look at the system. As the fan ramped up, he noticed that the top of one of the connection boxes lifted up. Upon closer inspection, he discovered that the top of the box had never been sealed with mastic, only tape; as the tape failed, the lid would lift up from the pressure and leak.

The ***radial system*** looks great on paper but is generally a very bad idea. Every duct run is a home run from the plenum to the supply boot. Most HVAC contractors never build the plenum large enough to handle the number of duct take-offs and the air distribution is compromised.

Sheet metal ducts

Sheet metal ductwork has a lower friction loss rate than the other types of ducts. Fungi typically won't grow on metal ductwork (although they will grow on the dust and trash that can accumulate in the ductwork!), the installation is usually more expensive, the joints and seams leak unless they are well-sealed, and it must be insulated.

Duct insulation board ducts

Rigid duct insulation board is also used to create ducts by field fabrication. Usually, the pieces are attached to each other by some form of tape and are used to create plenums, trunk lines, and distribution boxes. Duct insulation board is a dense, glass fiber mat that has a shiny foil on the outside. Some manufacturer's make a product that has an inner liner as well that is treated with a mildew and fungi retarder. It must be carefully sealed in order to be airtight, but provides excellent noise control. An ideal duct board would have the foil on both the outside and inside.

Flexible ducts

Pre-fabricated flex duct took the craftsmanship away from duct design and installation and replaced it with a Dadaistic art form. Now, it can be left to the installer to interpret where the duct should go, what size should be used, while rejecting standards in favor of chance and randomness. The odds are stacked against a proper flex duct installation from the beginning because the main advantage of the material (it's cheap) is also the main disadvantage (it's cheap). Flex duct has no seams but tends to leak at the joints- a lot! It is fairly fragile and is easily compressed, pinched, crushed and otherwise abused if it is not respected. Flex duct contains an inner pressure liner and an outer layer of insulation covered with a vapor retarder (usually a shiny foil that also acts as a radiant barrier). In order for flex duct to operate properly, it must be installed properly (straight runs; supported every 5' with at least a 1" wide strap; sag no more than ½” per foot of run; be cut to the proper length; and not be pinched to change direction or make a connection).

Building cavities as ducts

The last category of duct material is actually not duct material- it is a building cavity that is used as a duct! This can lead to all kinds of issues, such as extreme amounts of duct leakage (wood shrinkage due to temperature and humidity differences), poor insulative characteristics, positive or negative pressure zones may be created within these cavities (driving an increase in house exfiltration or infiltration), and sometimes, other trades don’t realize that it is a duct. Many times we find plumbing lines and cable or electrical wires pulled through a site built return (Honestly, I thought it was a chase!), or multiple holes drilled through the “duct” before it became a duct! Panned joist returns and panned studs are not an approved duct system, not by the Air Conditioning Contractors Association or building science. BUILDING CAVITIES SHOULD NEVER BE USED AS DUCTS!

Manual D duct sizing & design

Manual D is the residential duct design manual that is published by the Air Conditioning Contractors of Association (ACCA). It covers duct types, applications, selections, principles of multi-speed and variable speed blowers, pressure loss, operating point, duct sizing calculations, duct leakage and conduction losses. Ducts should be sized according to the highest load for that zone and laid out in a way that accounts for load zones, structural material, framing orientation and occupant comfort (have you ever had a ceiling register pointed at the bed?). The ducts also must be sized so that the static pressure drop over the length of the ducts is equal to the static pressure produced by the selected air handler delivering the required airflow.

Supply duct sizing

Supply duct sizing starts with the room-by-room load calculation results. This will tell us the amount of air (cubic feet per minute, cfm) needed to maintain the indoor design conditions during the heating and cooling seasons. The amount of airflow needed depends upon the load in that space and the temperature difference between the supply air and room air. According to ASHRAE, supply air should not generally be below 64°F for cooling (although the typical default for air conditioning is 55°F, a 20°F difference).

The cooling supply air design temperature is driven by the sensible heat ratio, calculated by dividing the sensible load by the total load. If the sensible heat ratio (SHR) is below 0.80, the temperature difference between the room air and supply air should be around 21°F. If the SHR is between 0.80 and 0.85, the temperature difference between room and supply air should be around 19°F. Finally, if the SHR is above 0.85, the temperature difference should be about 17°F.

If a room requires 4,537 Btu/hr sensible cooling, and the home has a SHR of 0.87, the temperature difference between the room air (75°F) and the supply air should be 17°F; the air supplied through the duct should be around 58°F.

The amount of air needed in that space (cfm) is calculated by: sensible load / (1.1 x temperature difference).

- 4,537 / (1.1 x 17) =
- 4,537 / 18.7 =
- 243 cubic feet per minute (cfm)

Heat pumps generally spit out air between 90°F and 100°F while furnaces can deliver the supply air at a temperature range of 110°F to 140°F. Using the same room as above, the number of Btu/hr required for heating is 3,387; with a design indoor temperature of 70°F, the temperature difference between the room air and the supply air delivered by an average heat pump would be around 25°F and an average furnace would be 55°F (which is why the air supplied by a heat pump during the winter feels cooler than a furnace).

The amount of air needed in that space (cfm) is calculated by: heating load / (1.1 x temperature difference).

- 3,387 / (1.1 x 25) =
- 3,387 / 27.5 =
- 124 cfm for a heat pump
- 3,387 / (1.1 x 55) =
- 3,387 / 60.5 = 56 cfm for a furnace

The ducts should be sized for the largest required airflow; in this example, the amount of air required for cooling is much larger than the amount needed for heating.

Now that we know how much air we need, we need to figure out the size of the duct needed to deliver it. This is calculated by determining the friction rate of the duct. The friction rate is equal to the pressure loss over a specific distance. Friction rate charts and duct slide rules all use 100' of duct as the reference and is measured in inches of water column (IWC). To determine the friction rate of the duct, we must know the pressure loss and the total effective length of the duct run.

The pressure loss is normally assumed to be 0.10 IWC as a default for this calculation. The total effective length is equal to the lengths of straight duct run plus the additional lengths of any fittings between the air handler and the duct termination boot. Each fitting has a default effective length assigned to it and can be found in Appendix 3 of Manual D. For example, a round wye adds 15' to the length of the duct run while a branch adds 25' to the duct coming off the main line and 5' to the main line. A sheet metal elbow adds 30' to the duct length and a 90° supply air boot fitting for flex duct adds about 80'.

If we have a duct run that is 20' long, but has a 90° elbow and terminates at a 90° boot, the total effective length will be 130' (20' + 30' + 80'). The friction rate for that run would be calculated as follows:

  - (Pressure drop x 100) / total effective length
  - (0.10 x 100) / 130 =
  - 10 / 130 = 0.077

Look up the duct size using a duct slide rule; find the friction rate and the required airflow- the slide rule will give you the size of the duct (usually you have a choice between round and rectangular).

In the case of our example room, the required airflow was 243 cfm; with our calculated friction rate of 0.077, the size of the duct required to deliver that will be between 8 & 9 inches. The best recommendation I can give would be to service that room with two 7" ducts with dampers.

The air should be delivered to the room at a velocity less than 500 fpm and at a volume less than 250 cfm per supply outlet.

Tons at the register

It is the heating or cooling capacity of the delivered air that keeps us comfortable. This is different than the capacities found in the manufacturer's data book; that only tells us the potential of the equipment to meet the load. The more accurate assessment is measuring the amount of cooling and heating actually delivered to the space, taking into account duct leakage and installation practices. It should be measured after the equipment has been running for at least 30 minutes.

It is the tons at the register that affect ***pulldown*** times. This is the amount of time needed to bring the space to a comfortable temperature. Homeowners often view pulldown time as a measure of the efficiency of their HVAC equipment- and shorter pulldown is better! Using correctly sized equipment will generally only lengthen the amount of pulldown time by 15 minutes versus the typically oversized equipment. However, installing ENERGY STAR® certified HVAC equipment typically results in cutting the pulldown time in half (a 54% reduction over the normal efficiency unit).

Return duct sizing

Another consideration of good duct design is designing the return airflow path. The return grille should be sized according to the amount of airflow needed (if it is too small, the air handler can be "starved" for air) and the lower velocity requirements on the return side of the air handler. The return trunk velocity should be around 350 fpm in order for there to be adequate return airflow (return grille face velocity should be less than 400 fpm). The return duct should have at least a 90° bend between the grille and the air handler to help with sound control.

There must be a low-resistance return path. Under cutting the doors doesn't work and is not recommended by ACCA. What I recommended is a ducted return or transfer grilles in every room.

A filter grille should be sized to permit 2 cubic feet per minute per square inch of grille surface area, and non-filter grilles sized for 2 ½ cubic feet per minute of square inch of grille surface area. If a 2 ½ ton system is installed (~ 1,000 cfm), a filter grille would need to be at least 500 square inches (about 3.5 ft^2) and a non-filter grille would need to be at least 400 square inches (about 2.8 ft^2). In addition to grille sizing, the return duct should be sized to accommodate the needed airflow. The return duct should be greater than the sum of all the supply ducts serving the same zone (a good rule of thumb is 120% larger than all the supply ducts added together). If the home has a single central return, a system must be designed that prevents the bedrooms from becoming pressurized when the doors are shut and avoid the creation of a depressurized zone in the space containing the return duct.

In one home I worked on, when the bedroom doors were closed with the air handler on (a central return system) pressure imbalances were caused ranging from +2.7 Pa to +5.0 Pa with respect to the main body of the home. This drives up infiltration in the main portion of the home and exfiltration in the bedrooms. It also increases the amount of duct leakage on the return side as well as the other problems already mentioned earlier with pressure imbalances. These zones needed to be equalized.

This pressure equalization can be done by constructing high-low transfer grilles (a grille high on the bedroom side and low on the hallway side) that are connected through a sheet metal or duct board lined stud cavity in an interior wall. This system can have the problem of not being recognized as a duct, so it should be labeled.

Alternatively, a jumper duct can be used to connect the bedroom with the other zone. A register is installed in the ceiling and is connected to a flex duct that terminates at another register in the ceiling of the hallway zone. The flex duct has sound-absorptive properties for those concerned about privacy and should be sized larger than the sum of the supply ducts to the bedroom zone. One contractor I know has connected multiple jumper ducts to a single sheet metal barrel containing a baffle system; this was then connected to a single large duct to the hallway. This could be replicated by using duct insulation board boxes as well (a spider system).

Of course, the ideal solution to obtain pressure equalization among the zones is for there to be a properly sized return duct connecting each zone with the return plenum on the mechanical system.

Comfort

The conditioned air delivered to the space provides us with a sense of comfort. We like the air temperature to be at a certain level, we like air that isn't stagnant, we don't like drafts and we don't like rooms that have different temperatures depending upon where you are.

Within the occupied comfort zone (that space 2' from the walls and 6' from the floor), we like it if the air is not stratified or in layers with different temperatures. Through much research, we have determined that we should have less than a 5°F difference between the temperatures 4" and 67" off the floor.

The last component of the distribution system has a direct effect on our comfort level. It is the grille that covers the duct termination boot. We also call them registers or diffusers, but they are designed to throw the air into the room in a way that maximizes our comfort.

Actually, there are differences between grilles, registers and diffusers. A grille is a louvered or perforated cover that fits over the duct boot. The vanes can be fixed or adjustable. A register is a grille that has a damper on it that can regulate the amount of air coming through the grille. A diffuser has more mixing ability than the other two and can throw higher volumes of air into a room without causing drafts. Diffusers are usually installed in ceilings and throw the air parallel to the ceiling or down toward the floor.

The distance the air from a duct travels into a room until it slows down to a specific velocity is called ***throw***. We like for the air in the occupied zone to be moving less than 50 fpm, so that is the assumed default when doing "throw" calculations.

Depending upon the temperature difference between the room air and the supply air, the air may fall more quickly. This is called ***drop*** and it shortens the throw. Colder air drops more than warmer air.

If the supply air is warmer than the room air, the air tends to ***rise*** above the grille. This also affects the throw, depending upon whether the air stream is projected horizontally or vertically.

An open air stream expands in all directions at a 22° angle. If that air stream is located near a wall, floor or ceiling, the natural distribution pattern is disrupted. If the grille is within 1' of that disruptive surface, a low pressure region is developed between the grille and the surface (wall, floor or ceiling). This pulls the air stream toward that surface and lengthens the throw.

Residential Comfort		
	Heating	Cooling
Thermostat set point	70°F	75°F
Relative Humidity	25%	40%
Temperature @ T-stat	68°F – 72°F	72°F – 78°F
Temperature in any room	± 2°F of set point	± 3°F of set point
Room – Room or Level – Level temperature differences	± 4°F	± 6°F
Floor temperature over slab or unconditioned space	> 65°F, 4" above floor surface	
Filtration	≥ MERV 8	≥ MERV 8
Outside ventilation air	7.5 cfm/person + 1 cfm per 100 ft^2	7.5 cfm/person + 1 cfm per 100 ft^2
Duct leakage	< 6%	< 6%
	Minimum	Maximum
Supply trunk velocity, fpm	500	750
Supply runout, fpm		500
Supply flow, cfm		250
Return trunk velocity, fpm		350

The shape of the air stream discharged from the grille also affects the throw. Using vanes in the register or grille, the shape of the air stream can be adjusted. This shape is called ***spread***; the wider the spread, the shorter the throw.

If the duct terminates in the floor system, the throw should be at least to the ceiling. During the heating season, the rise helps the discharged air to travel to the ceiling and drop into the occupied zone. During the cooling season, the discharged column of air tends to fall on itself and create stagnant zones within the room.

The return duct should be placed within the stagnant zone. For heating only systems, the stagnant zone is on the floor at the opposing side of the room from the duct. For cooling only systems, the stagnant zone tends to be at the ceiling on the opposing side of the room from the duct. This way, the air that has the greatest temperature difference to the supply air will be removed first, helping in a small way to relieve any stratification comfort issues. If the system is doing both heating and cooling, figure out where the largest stagnant zone is going to be and place the return there. This is particularly useful when doing jumper ducts to a central return.

System Installation

Duct leakage costs the American consumers around $5 billion per year, wasting the equivalent energy used by 13 million cars per year, and is equal to the estimated annual oil production from the Arctic National Wildlife Refuge. It takes about 7 billion trees to offset the carbon dioxide released by the production of this wasted energy. This is why duct sealing is so important. It has been estimated that by retrofitting duct sealing measures and testing all new duct systems to verify a lower leakage rate, the State of California may be able to prevent having to build a 1 GigaWatt power generation plant.

Connections

Ducts are usually sealed with either cloth duct tape, foil tape, foil tape with a UL181 rating, or mastic.

Cloth duct tape should not be used to seal duct work. It doesn't work in the lab, it doesn't work in the field, and it just doesn't work anywhere. It may be used to temporarily hold pieces of ductwork together, but cannot be relied upon to seal ductwork. Cloth duct tape should never be found holding ductwork together in new construction, particularly in locations that have adopted the International Codes which require the use of duct tape with a UL181 rating.

Plain foil tape is also often used ("You can't pull that tape off if you tried!") by contractors who are unaware of the requirements for a UL181 rating. The foil tapes must be attached to clean, dry surfaces and pressed to remove tiny air bubbles. If they are not installed correctly, leakage can (and will) occur.

Foil tape that has a UL181 rating has had to pass an adhesive test for 24 hours and meet flame and smoke spread requirements. There are different types of UL181 listed tape; the UL181A tape is for duct insulation board and UL181B tape is for flex duct. Within those designations are specialties: for duct board there are UL181A-P (pressure sensitive), UL181A-M (butyl adhesive, also called mastic tape), and UL181A-H (heat sensitive) while flex duct has UL181B-FX (pressure sensitive) and UL181B-M (butyl adhesive). Over time, these tapes will fail (the grand lesson is that all tapes are temporary), generally due to the exposure to heat from the surrounding environment (like attics). In order to receive the UL181B rating, the tape must have a mechanical hose clamp installed over it. This rarely happens in the field, but will help prevent delamination and shrinkage of the tape. Even the "mastic" tape will start to lose its effectiveness over time (7-8 years). The best sealant is water based mastic.

Mastic is an adhesive that can be applied with a brush, hand applied wearing rubber gloves or with the bare hands. When applied properly (the key to all sealants), it forms an airtight barrier and "glues" the components together. Mastic (like all duct sealants) should be applied to the pressure barrier of the duct system, not the insulation. On metal ductwork, it is the sheet metal. On duct insulation board, it is the shiny foil exterior surface. On flex duct, it is the inner plastic core liner. On building cavities used as ducts, mastic should be applied everywhere (especially to the person who installed that system!). It is absolutely critical that the sealant is applied to the pressure boundary! Mastic is faster, less expensive, more durable and messier than tape.

The way to apply mastic for flex duct:

1. Apply mastic to the sheet metal fitting
2. Slide the pressure liner over the mastic on the fitting
3. Apply mastic over the pressure liner and fitting
4. Install a mechanical clamp over the mastic on the pressure liner and fitting
5. Cover the connection with the duct insulation and install a mechanical clamp over the insulation (or use tape- it doesn't matter!)

Mastic application over duct insulation board joints and seams is very similar, but the installer may use tape to hold the pieces together. Then, the mastic is brushed on over the tape and the width of the tape on each outer edge (so the mastic is 3x as wide as the tape). If it is just applied over the tape, when the tape fails, the mastic fails (not really, but the leakage will occur).

The key places to seal the thermal distribution system are the air handler (where pressures are highest), air handler-plenum connections, plenum-take off collar connections, duct-collar connections, duct-splitter connections, duct-duct connections and duct-boot connections. For metal ductwork, the longitudinal seam must be sealed as well as the duct joints. It is also important to seal the seams in metal elbows. I know one contractor who has his crew paint the sheet metal connections with mastic whenever they have down time. This way, the time in the field is reduced and he can visually inspect at least part of every job.

Duct leakage has a huge impact on operating costs, comfort levels, efficiencies, peak electricity demand, pollution prevention- and did I mention COMFORT levels? It is inconceivable to me how an HVAC contractor can sell someone a high-end unit and spend no time at all on ensuring that what was sold (energy efficiency and comfort) was delivered.

System Commissioning

After the system has been installed, it needs to have the duct system tested for leakage, the refrigerant charge checked and the airflow measured and balanced.

Duct leakage

Duct leakage can be measured as total leakage or leakage to the outside. Total leakage measures all duct leakage and can be useful for testing the system after the rough-in is complete and the system has been installed, but before the ductwork is concealed by gypsum board. For total leakage, the ducts are pressurized to + 25 Pa and the fan pressure is converted to airflow.

Since duct leakage to the outside of the building envelope is the leakage with the direct energy penalty, it is measured by pressurizing the house to a + 25 Pa pressure difference with respect to the outside. With all the supply and all but one of the return registers sealed off, the duct testing apparatus (duct blaster) is attached to the unsealed return. The air from the house will flow through the duct pressurization fan and will pressurize the ducts as well. When the pressure in the ducts is measured at the nearest supply register, it will be less than or equal to 0 Pa. If it is 0 Pa, the duct system is really tight (meaning the ducts are maintaining the same pressure difference as the house w.r.t. the outside). If it is less than 0, the duct system is showing leakage to the outside (not able to maintain the house pressure). By turning on the duct pressurization fan and carefully pressurizing the duct system, the ducts can be brought to the same pressure as the house (zero pressure difference between house and duct). The amount of fan pressure needed to do this can be converted to flow (cfm_{25}, for a 25 Pa pressure difference) and the amount of duct leakage can be established from charts. Some folks prefer to depressurize the ductwork- please RTFM (Read The Friendly Manual!) if you choose to perform duct depressurization (I call people who do that “duct suckers”!).

A high performance system should have less than 5% duct leakage normalized by conditioned floor area. The target is calculated by multiplying the conditioned floor area served by the system by 0.05; once the leakage has been determined from the test results, divide the test result by the conditioned floor area and multiply that answer by 100 to get the actual duct leakage percentage.

Refrigerant charge

For units that do not have a thermal expansion valve, use the superheat method. To measure ***superheat***, you will need a pressure gauge and a digital thermometer.

Let the system run for at least 20 minutes

Read the pressure on the suction line

At the same time, take the temperature of the suction line within 6” of where you are reading the pressure

Use a pressure-temperature chart and convert the pressure reading to a temperature

Subtract the converted pressure temperature from the actual temperature

The result is the amount of superheat

Look up the ideal superheat value from the manufacturer's table or slide rule. If the superheat is less than the manufacturer's value, remove 2 to 4 ounces of the refrigerant, following all of the EPA rules.

If the superheat is higher, add 2 to 4 ounces of refrigerant. Let the system run for 10 minutes to establish normal operating conditions and test the superheat again. Repeat this procedure until you are within 1°F of the manufacturer's value for ideal superheat (obviously, you will have to vary the amount of refrigerant added or removed each time).

In order for this to be accurate, you must have correct airflow across the coils, the outdoor temperature has to be above the minimum specified by the manufacturer, the equipment needs to be past the initial pull-down time (see the section on ductwork), there should be a temperature drop across the indoor coil between 15°F and 25°F, and there shouldn't be any leaks in the refrigerant lines.

To measure refrigerant charge in systems with a TXV, measure the ***subcooling***. You will need the same tools used to measure superheat and follow the same procedure. Instead of measuring the suction line, measure the temperature and pressure on the liquid line.

If the measured subcooling is higher than the manufacturer's ideal value, remove some refrigerant. If the subcooling is lower than the ideal value, add refrigerant. Let the system run for 10 to 20 minutes to establish the new operating conditions and run the subcooling test again. Repeat this procedure until the subcooling matches the manufacturer's ideal value or is between 10°F and 15°F (if you don't have the manufacturer's value).

The ideal method for measuring refrigerant charge is to weigh it. This is done by recovering the refrigerant from the unit and recharging the system with refrigerant. Follow the manufacturer's recommendations and try to get the charge within 1 ounce of their recommended charge. This ***refrigerant weigh-in*** method can be used when superheat or subcooling cannot (when outdoor conditions are outside the scope of those tests).

With the compressor turned off, add the liquid refrigerant to the liquid line. If the liquid refrigerant stops flowing before the correct charge is established, turn the compressor on and add the remaining refrigerant to the suction line as a vapor. Before opening the suction line service valve, make sure that the cylinder pressure is higher than the suction pressure by checking your low-pressure gauge.

Airflow measuring and balancing

Proper airflow is critical to providing comfort to the people who are going to live in the home. It needs to be measured and balanced in order to make sure the system is installed and operating correctly.

To measure airflow, you can use a flow hood or a velometer. You can place the flow hood over the return and measure the amount of air that moves through it. This is the airflow entering the system. To measure how much airflow is being delivered, you can use the flow hood over each supply and total them up. The amount of air delivered should be very close to the amount of air that entered the system through the return.

In order to accurately use the velometer, you will need to know the size of the ducts to calibrate the device. Each duct size has a different cross-sectional area which affects flow rate and velocity. The flow rate is equal to the area multiplied by the velocity (Q = A x V), when area is measured in square feet.

Round Duct Cross-Section Surface Area, ft^2	
4"	0.087
5"	0.136
6"	0.196
7"	0.267
8"	0.348
10"	0.545
12"	0.785
14"	1.068
18"	1.766
24"	3.14

The commissioning of the system is the fine tuning of the comfort system and ensures that the installed system is operating correctly. Will it guarantee no complaints? Of course not! But will you be able to defend your installation practices and demonstrate that this system was installed correctly- the answer is “YES!” The reality is that performing commissioning on the system goes a long way to reducing comfort call-backs. Those call-backs can eat up every bit of profit made at the sale and performing commissioning work is simply a means of ensuring profitability over the long haul.

Conclusion

I certainly hope that you can understand why I feel so strongly about the importance of getting the HVAC system right. There are so many opportunities for our technology to fail us when things are done properly, and there are a lot of opportunities for failure with HVAC.

This is the single most important system installed in the home, providing us warmth in the winter, coolness in the summer, controlling humidity levels for indoor air quality and comfort, keeping us healthy through controlled ventilation and making sure that we aren’t paying more for these benefits than we have to.

But I really think that it is so important because it gives us control over our environment. We have proven time and again that we cannot master Nature, but in our homes we are kings! This sense of control that we all enjoy is part of the psychological comfort owning a home brings. Without it, we begin to feel helpless and defeated. Study after study has demonstrated the clear link between comfort and work production and comfort and health.

I hope that you will take what little information I have given you and use it to make the lives of those around you better by delivering comfort.

References

American Society of Heating, Refrigeration and Air-Conditioning Engineers. *2005 ASHRAE Handbook of Fundamentals.* ASHRAE, 2005.

International Code Council. *2000 International Residential Code for One– and Two-Family Dwellings.* ICC, 2000.

2000 International energy Conservation Code. ICC, 2001.

2003 International Residential Code for One- and Two-Family Dwellings. ICC, 2004.

2003 International Energy Conservation Code. ICC, 2004

2004 International Residential Code for One– and Two-Family Dwellings. ICC, 2004.

2004 International Energy Conservation Code. ICC, 2004

Dillon, Brett. Home Energy Rater Manual. Dillon Consulting. Chattanooga, TN. 2006.

"GSHP Design Recommendations– Residential and Light Commercial"

Karg, Rick and Krigger, John. "Specification of Energy-Efficient Installation Practices for Residential HVAC Systems". Consortium for Energy Efficiency. Boston, MA. 2002.

Rudd, Armin. "Design Process For: Sizing Cooling and Heating System Capacity, Room Air Flows, Trunk and Runout Ducts, and Transfer Air Ducts". Building Science Corporation. Westford, MA.

Rutkowski, Hank. Residential Duct Systems Manual D. Air Conditioning Contractors Association. Arlington, VA. 1995.

Comfort, Air Quality, and Efficiency by Design Manual RS. Air Conditioning Contractors Association. Arlington, VA. 1997.

Heat Pump Systems: Principles and Applications Manual H. Air Conditioning Contractors Association. Arlington, VA. 1984.

Residential Equipment Selection Manual S. Air Conditioning Contractors Association. Arlington, VA. 1995.

Air Distribution Basics for Residential and Small Commercial Buildings Manual T. Air Conditioning Contractors Association. Arlington, VA. 1992.

Residential Load Calculation Manual J, 8th edition Version 2. Air Conditioning Contractors Association. Arlington, VA. 2006.

About the author

A native of Southern California, Brett is a 4th generation carpenter & builder. Raised in a traditional construction background, he started to apply the principles of building science to the homes he built as the Construction Director for the Habitat for Humanity affiliate in Chattanooga, TN. As a result of those efforts, this affiliate was one of 16 affiliates worldwide that earned an energy efficiency award from Habitat for Humanity International at the 25th anniversary conference in Indianapolis in 2001.

Brett has extensive field experience performing Home Energy Rating System ratings, residential commissioning, energy audits, mold and moisture assessments, building envelope pressure tests, and duct system pressure tests in addition to his experience in construction management and techniques. He has been a licensed contractor in Tennessee and has over 15 years of experience in the residential construction industry, working in both land development and construction. He now owns Dillon Consulting, specializing in the integration of building science, design and best construction practices.

Brett currently teaches many seminars and workshops on high performance home building, the International Energy Conservation Code, moisture control and homeowner education to groups as varied as the American Institute of Architecture to affordable housing providers. A former program manager at Southface, he was the point person for expanding the EarthCraft House program regionally into Alabama, South Carolina and Tennessee. He is a nationally certified Home Energy Ratings System (HERS) Rater in addition to being a Residential Energy Services Network (RESNET) certified HERS Rater Trainer and Quality Assurance Designee, the highest level of national certification available in the residential energy efficiency field. He also provides building science-based training to builder groups and utility companies, including teaching the Certified HERS Rater Course.

Brett has served on the Advanced Rater Task Force for RESNET, the Affordable Housing Task Force for LEED for Homes and has conducted workshops for the Building America Program (DOE) and State Energy Offices throughout the Southeast.

Brett is married, enjoys classical foil fencing with his wife and four sons and resides in Chattanooga, TN.