Advanced Space Conditioning

Design Trade-offs and Test Plan for High Performance Space Conditioning Systems

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Introduction

High performance building envelopes require controlled ventilation systems, sealed combustion appliances and allow the use of innovative air distribution systems.

The optimum controlled ventilation system in all climate zones is a supply ventilation system that allows for filtration of outside supply air and the pressurization of building enclosures to exclude environmental contaminants.

In very cold climates, this supply ventilation system is coupled with a high performance building envelope that has a high drying potential to compensate for the pressurization effects of the ventilation system.

In hot-humid climates, this supply ventilation system is coupled with supplemental dehumidification in order to address part load issues.

In all climates, air distribution systems are located completely within the conditioned spaces thereby minimizing the effects of duct leakage and air handler leakage. Additionally, all air distribution systems are air pressure balanced to prevent the pressurization or depressurization of rooms.

The high performance aspects of the building envelopes allow for the simplification of duct distribution systems. Single returns replace distributed returns. Supply registers no longer need to be located at building perimeters at window locations. All ductwork is fully sealed and "hard ducted". No building cavities are used as returns.

In hot-humid climates and hot-dry climates the construction of unvented, conditioned attics allows for the installation of air handlers and ductwork above ceilings – but still within conditioned spaces.

Advanced Space Conditioning

Advanced space conditioning involves the integration of a building's heating, ventilating and air conditioning (HVAC) system with the building enclosure or building envelope. This integration is dependent on the characteristics of the building envelope. High performance building envelopes have very different requirements for HVAC systems than standard building envelopes. High performance building envelopes also provide opportunities for HVAC systems that are not available with standard building envelopes.

The following discussion pertains to high performance building envelopes. A high performance building envelope is defined as a building envelope that meets both the EnergyStar thermal requirements and the air tightness requirements of the Energy Efficient Building Association (EEBA). Additional requirements relate to rain control, ground water control, and water vapor control. The specific metrics defining high performance building envelopes are contained in Appendix A.

Advanced space conditioning involves HVAC system innovations in the following areas:

- ventilation
- air distribution
- heating equipment
- cooling equipment
- water heaters

Each of these areas will be explored.

Background

Heating, ventilating, and air conditioning (HVAC) systems involve both thermal comfort (the heating and air conditioning components) and dilution of interior pollutants (the ventilating component). The HVAC system includes all heating, cooling, and ventilation equipment serving a building including their associated distribution systems.

The five principle functions of a HVAC system are as follows:

- maintain thermal comfort under operating conditions
- provide fresh air to the "head space" of occupants in sufficient quantity and quality to dilute pollutants generated by occupants, furnishings and the structure (outdoor air supply and ventilation effectiveness)
- facilitate source control of pollutants by providing adequate interzonal and interstitial pressure control (system operation, maintenance, commissioning/balancing)
- facilitate source control of pollutants by providing "capture at source" exhaust ventilation at pollutant generation locations and preventing reintrainment of this exhaust ventilation (local exhaust)
- facilitate source control of pollutants by providing air cleaning (filtration of particles, gases and dehumidification of airborne moisture)

The ability of a HVAC system to provide these functions is directly dependent on the characteristics of the building envelope and the climate.

Thermal Comfort

The indoor environment involves the interrelationship of comfort factors such as temperature and relative humidity, physical stressors such as noise, lighting and psycho-social factors (personal relationships, peer pressures, work stress, etc.) as well as chemical, particulate and biological concentrations.

The ultimate objective of a successful environmental system is to provide for the comfort and welfare of the occupants and prevent an accumulation of unpleasant and/or harmful pollutants.

Occupant comfort complaints constitute a significant portion of indoor environmental complaints. If occupants are uncomfortable, they will complain. Thermal comfort must be maintained within a building in order to provide for an acceptable indoor environment.

Many variables interact to determine whether occupants are comfortable. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 55-1992: Thermal Environmental Conditions for Human Occupancy describe the temperature and humidity ranges that are comfortable for most people under various activities. Some of the variables discussed in Standard 55-1992 are:

- uniformity of temperature (temperature stratification, convection)
- radiant heat transfer (cold or warm surfaces such as windows)
- relative humidity
- activity level, age and physiology of occupants
- clothing levels

There is considerable debate among researchers, building scientists, engineers and health professionals concerning recommended levels of relative humidity. Interior relative humidities which are too low are uncomfortable. Interior relative humidities which are too high are unhealthy. Consensus is emerging that the critical relative humidity for biological activity to occur on building envelope surfaces is 70 percent. Where relative humidities above 70 percent occur at surfaces, mold growth, dust mite growth, decay, corrosion, etc. can occur. Therefore, conditions should be maintained within a building such that the critical 70 (or higher) percent relative humidities at building envelope surfaces do not occur. Due to climate differences, interior conditions which must be maintained to avoid the critical surface relative humidities vary from region to region and time of year. They also vary based on the thermal resistance of the building envelope.

In general relative humidities should be kept as low as comfort levels and HVAC equipment will allow. People are rather insensitive to relative humidity variations between 25 percent and 60 percent. However, relative humidity variations within this range do affect perception of temperature. In other words, interior relative humidities should be maintained as low as possible, and interior temperatures adjusted within the parameters specified in Standard 55-1992 to maintain thermal comfort. Relative humidities below 20 percent are uncomfortable to most people and should be avoided. Relative humidities below 50 percent during air conditioning periods in hot, humid climates may not be economical/practical to achieve. During heating periods interior relative humidities should range in the 25 percent to 35 percent range. During air conditioning periods interior relative humidities should range in the 50 to 60 percent range (if equipment allows).

Outside Air Supply

One principle focus of a healthy indoor environment is on concentrations of pollutants. In simple terms, the greater the concentration, the greater the risk. Pollutant concentrations are determined by two factors (Figure 1):

- source strength; and
- rate of removal

HVAC systems impact both the source strength of pollutants and the rate of removal of pollutants.

Source strength is determined by the rate of pollutant entry into a conditioned space from the exterior, the rate of pollutant generation within the conditioned space, and the rate of pollutant off-gassing from the building products comprising the building assemblies, components, elements, sub-systems and furnishings (Figure 1).

Removal or dilution is typically determined by air change, air cleaning and storage. Air change can be considered a combination of natural ventilation (infiltration/exfiltration) and mechanical (controlled) ventilation. Air cleaning usually occurs through the filtration of particulates (and some gases) and by the removal of moisture (dehumidification). Storage of pollutants involves furnishings and surface coverings absorbing pollutants and/or becoming receptors for particulates (carpets) (Figure 1).

In general, if the rate of entry, generation and off-gassing of pollutants exceeds the rate of removal, concentrations will rise. In general, if the rate of removal exceeds the rate of entry, generation and off-gassing, concentrations will fall. The key is to maintain pollutant concentrations at levels sufficiently low to avoid problems.

One simplistic approach is to provide mechanical ventilation to control pollutant concentrations. The greater the source strength, the greater the mechanical ventilation required. The problem with this approach is that this ventilation air must come from the exterior. This exterior air must be heated or cooled and humidified or dehumidified depending on climate. In some locations this air must also be cleaned (filtered) prior to use within a conditioned space. The conditioning of this air consumes energy and increases operating cost.

The greater the rate of dilution by mechanical ventilation and infiltration/exfiltration, the greater the operating cost and capital cost for equipment to provide this dilution and conditioning. Furthermore, dilution is very inefficient. Any powerful pollutant source will overpower even large ventilation rates. Dilution is not the solution to indoor air pollution. At least not by itself. In hot, humid climates, dilution can become the problem. The greater the rate of dilution in these climates, the greater the rate of entry of moisture. Moisture is a major indoor air pollutant. Mold and other biological agents can quickly multiply out of control. In heating climates, high dilution rates during the heating season can lead to excessive loss of interior moisture and in order to compensate, humidification may be necessary.

Another simplistic approach is to provide source control to control pollutant concentrations. If pollutants are prevented from entering conditioned spaces, are not generated within conditioned spaces, and are not off-gassed from building materials and furnishings, then dilution by mechanical ventilation and infiltration/exfiltration is not required. The problem with this approach is that one of the major pollutant sources in a building enclosure happens to be people.

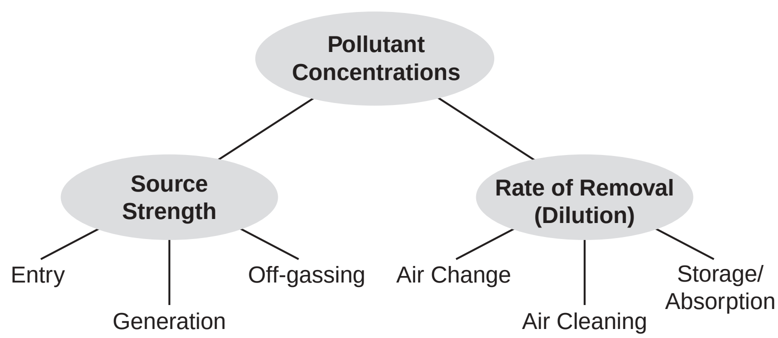


Figure 1: Pollutant Concentrations

People can be considered as evaporatively cooled, unvented combustion appliances. They burn a hydrocarbon fuel (food) and generate three principle by-products of combustion, carbon dioxide, moisture and odors depending on diet and activity. When deodorants, perfumes, clothes, and hair sprays are added, people become thermal cracking towers and analogies can be made to petroleum distillation. It has been said that if people were not allowed into buildings we wouldn't have problems. It is also obvious that source control for people is not practical.

Combining source control and removal is the preferred approach. Source control and air cleaning can be provided for all the pollutant sources except for people. Ventilation is then provided for the people. This can be rephrased as: "You ventilate for people not for buildings". Ultimately, this provides the most cost effective and energy efficient approach. Since the higher the ventilation rate, the higher the operating and energy costs, a great incentive exists to reduce ventilation rates to save operating costs and energy. However, ventilation rates should not be lowered beyond those required by people to control the pollutants generated by the people themselves (carbon dioxide, moisture and odors). All other pollutant sources can be controlled by source control and air cleaning. There is a great economic incentive to provide source control and air cleaning for all other sources, since ventilation (the only other alternative) to control these other sources increases operating costs and the capital costs for installation and maintenance of systems.

Building Envelope Leakage

Relying on random leakage openings and the effects of wind and stack to provide air change through infiltration/exfiltration does not ensure constant dilution or dilution when required. Controlled mechanical ventilation is a requirement in all buildings, regardless of tightness, for health reasons.

Maintaining an acceptable indoor environment by natural means such as wind, is unacceptable by today's standards. In the past, energy was inexpensive and natural means, such as wind, was relied upon to bring fresh air into buildings. Building envelopes were leaky and indoor moisture and other indoor pollutants were able to move outdoors (in heating climates) through the leakage openings around windows and doors without causing serious problems. In cooling climates, air conditioning was not common and extensive natural ventilation was required for minimal comfort. The introduction of air conditioning in cooling climates resulted in a significant reduction in natural ventilation.

Building enclosures have become significantly tighter over the past several decades and mechanical cooling and heating is common in all climate zones. At the same time, the introduction of hundreds of thousands of new chemical compounds, materials and products occurred to satisfy the growing consumer demand for goods and furnishings. Interior pollutant sources have increased while the dilution of these pollutants through air change by natural ventilation has decreased.

Ventilation is the process of removing and supply air by natural (infiltration/exfiltration) or mechanical (intake, exhaust) means to and from any indoor space. Controlled ventilation is defined here as a combination of mechanically exhausting indoor air and mechanically or passively supplying outside air to maintain adequate indoor air quality.

Natural ventilation, or infiltration/exfiltration driven by the stack effect and wind through random openings or through deliberate, discrete openings such as operable windows, doors, ductwork or holes is not adequate to remove pollutants and odors from an enclosure on a continuous basis due to the lack of the consistency of the stack and wind driving forces. However, this inconsistency does add significantly to the annual space conditioning (heating and cooling) energy consumption. Natural ventilation reduces the ability of occupants to control ventilation rates and seldom provides ventilation effectively to the critical “breathing zone” or head space.

Natural ventilation may be adequate at a certain instant in time, but may not be adequate at another instant in time when there is no wind, or when there is a change in wind direction, or when an insufficient interior to exterior temperature differential exists. In typical building envelopes, the normally random distribution of leakage openings influences the exfiltration/infiltration process which is responsible for the rate of natural ventilation. This random or accidental distribution of leakage openings resulting in accidental leakage does not provide assurance that adequate air change can take place.

The random distribution of leakage openings in a typical building causes the instantaneous infiltration/exfiltration rate in the building to vary substantially due to the influences of wind pressures, stack pressures and pressures induced by air consuming devices. Thus, a building or areas of a building can have adequate natural air change at one point in time and not have adequate natural air change at a subsequent point in time. The variation can be so substantial that the infiltration/exfiltration rate may be on the order of several hundred cubic feet per minute during a wind gust, and moments later zero if the wind suddenly dies down and the majority of the randomly distributed leakage openings accidentally and temporarily happen to fall along the neutral pressure plane. Furthermore, there is seldom provision under natural ventilation for air change to be “effective” in that the air quality in the breathing zone improves.

Controlled ventilation involves the provision of a controlled driving force to remove and supply ventilation air through deliberate, discrete openings. This driving force can be provided on a continuous basis or, as necessary, based on the level of pollutants and odors within an enclosure.

Controlled Ventilation

The principles behind acceptable indoor air quality and providing controlled ventilation to achieve it are very basic.

- ventilate for occupants; and
- provide source control for everything else.

This is the single most energy efficient and cost effective approach. Occupants produce carbon dioxide, odors and moisture. Ventilate for the carbon dioxide, odors and moisture generated by occupants.

How much air must be supplied to accomplish this? ASHRAE Standard 62.2: Ventilation for Acceptable Indoor Air Quality recommends a rate of between 10 cfm and 20 cfm per person.

Once a ventilation rate is determined by occupancy the basic requirements of ventilation systems should be applied:

- provision for air exhaust
- provision for air supply
- provision for continuous operation during occupancy
- provision for distribution

One of the key requirements is the quantity of exterior air supplied to the "head space" of a room. "Head space" terminology refers to the zone in each room where occupants "heads" are likely to be located. For example, while seated at a desk, the "head space" location is between 3 feet and 5 feet above floor level. "Head space" zones are the locations where occupants obtain their "fresh" air for respiration. Test and balance information typically determines the flow rate of air (including fresh air) into rooms, spaces and common areas, but does not determine flow rate of exterior supply air to the "head space" region. The amount of fresh air delivered to the "head space" compared to the amount of fresh air delivered to the room is referred to as the "ventilation efficiency".

Air Pressure Control

In order to have an air quality problem four requirements are necessary:

- a pollutant is necessary
- a receptor (occupant) is necessary
- a pathway is necessary (connecting the pollutant to the occupant)
- a pressure difference is necessary (to push the pollutant down the pathway to the occupant)

HVAC systems often are involved in three of these requirements. First, the HVAC system itself may be contaminated with pollutants such as mold growing in duct lining or bacteria growing on coils and in filters. Second, the HVAC duct distribution system is often the most common pathway for pollutants within a building. It is sometimes referred to as the "pollutant interstate". Finally, the HVAC system is often instrumental in creating air pressure relationships between zones and building cavities that facilitate the movement of pollutants.

Air pressure differentials are of major significance with respect to the transfer of pollutants from special use areas as well as radon ingress and spillage and backdrafting of combustion appliances. Determining air pressure relationships allows the determination of the effectiveness of the HVAC system in containing pollutants to the direct vicinity of where they are generated and exhausting them from the building without permitting them to impact other areas.

If more air is supplied to a room than is exhausted, the excess air leaks out of the space and the room is said to be under a positive air pressure. If less air is supplied than is exhausted, air is pulled into the space and the room is said to be under a negative air pressure. Individual rooms can have differing air pressures. Entire buildings can be under a negative or positive pressure. Finally, building cavities such as floor cavities, interior partition walls, exterior wall cavities can also be under a negative or positive air pressure.

The tighter a building envelope or enclosure, the less air required in order to pressurize or depressurize the conditioned space. Leaky buildings require a great deal of air from the exterior in order to achieve pressurization. In the humid south, pressurization of conditioned spaces is desirable in order to exclude exterior humid air which can lead to mold growth. However, the air which is brought in from the exterior in order to achieve pressurization must be dehumidified and cooled. The more air which is brought in, the greater the cooling load and the greater the operating cost. It is therefore desirable to build tight building envelopes in order to minimize the amount of air required to provide pressurization.

Many building enclosures have exhaust systems and air consuming devices such as dryers and cook tops which extract air from a building. This air must be replaced with "make-up" air. If it is not, depressurization of the conditioned space occurs, resulting in infiltration.

Building mechanical systems can succeed in pressurizing building enclosures relative to the exterior with conditioned air. However, duct leakage from return systems and air handlers enclosed in building cavities and service chases can succeed in depressurizing demising walls and other interstitial cavities. If these cavities are connected to the exterior they become pathways for infiltrating pollutant laden air.

Building enclosures should be built tight, not just to eliminate openings and pathways, but to make it easy to control air pressures with minimum air flows. An ideal level of tightness would be that level at which the ventilation air flow requirements from human occupancy are sufficient to provide air pressure control. This is typically not possible unless building envelopes are constructed to high levels of tightness.

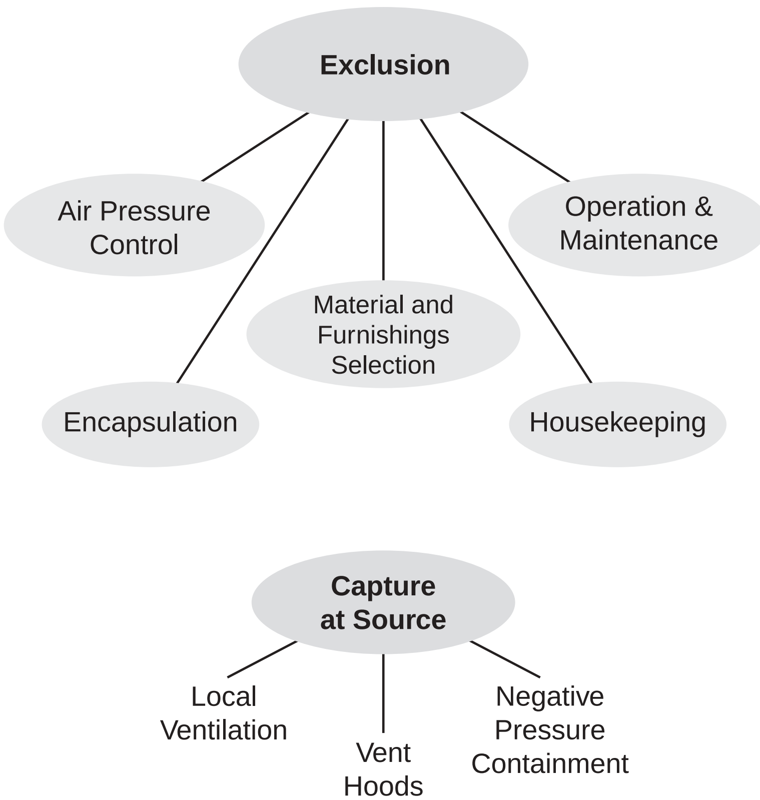


Figure 2: Source Control Strategies

Control of Pollutants

The major pollutants in conditioned spaces (exclusive of the moisture, carbon dioxide and odors generated by occupant respiration), in order of impact are as follows:

- combustion products
- microbial contaminants
- radon
- formaldehyde and other volatile organic compounds (v.o.c.'s)
- particulates
- heavy metals (mercury, lead)

All of these pollutant categories respond to source control. A properly installed gas or oil furnace and fireplace can eliminate combustion products entering conditioned spaces. A correctly designed and constructed basement, crawl space, and slab will reduce the presence of moisture. A tight foundation coupled with air pressure control will prevent radon infiltration. Formaldehyde can be eliminated or reduced by using building products with zero or low formaldehyde emission ratings. Client education (don't store cleansers and cleaning agents under the kitchen sink) addresses the presence of V.O.C.'s and introduces rules for combustion products (don't heat your house with unvented heaters). Asbestos, lead and mercury can be removed from conditioned spaces or encapsulated.

However, source control cannot be used to deal with carbon dioxide and moisture generation from people. People vent carbon dioxide and moisture from the respiration process directly into living spaces. Dilution is the only practical approach to deal with carbon dioxide and moisture generated by people.

Source control of pollutants involves the following strategies (Figure 2):

- exclusion (control of air pressures and moisture, material and furnishings selection, encapsulation, housekeeping, maintenance and operation)
- capture at source (fume hoods, local ventilation and negative pressure containment rooms such as bathrooms, spas, etc.)

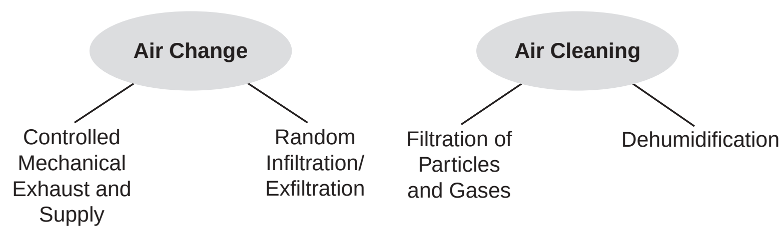


Figure 3: Removal Strategies

Removal (dilution) of pollutants involves the following strategies (Figure 3):

- air change (controlled mechanical exhaust and supply)
- air cleaning (dehumidification, and filtration of particles, gases)

Combustion Products

Exclusion and capture at source are the most effective methods of dealing with combustion products.

Negative pressures created within conditioned spaces as a result of duct leakage, closing of interior doors, and competition for air from air consuming devices (exhaust fans, range hoods, clothes dryers) can lead to the spillage and backdrafting of traditional chimneys when they are used with gas and oil fired furnaces and water heaters. These types of chimneys and the combustion appliances which use them should not be installed in conditioned spaces (exclusion).

Sealed combustion and power-vented gas, oil and wood appliances (capture at source) eliminate concerns about spillage and backdrafting of combustion appliances.

No unvented combustion appliances of any kind (kerosene heaters) should be installed within conditioned spaces (exclusion).

Capture at source is an effective method of dealing with kitchen appliances. Gas cook tops should be installed in conjunction with exhaust range hoods.

Environmental tobacco smoke (ETS) is classed as a known human carcinogen. ETS constitutes such a strong pollutant source that often the only practical control strategy is source control. Don't smoke inside.

Microbial Contaminants

Controlling indoor moisture levels, surface temperatures and moisture movement will provide source control of biological agents such as mold, bacteria and dust mites. In heating climates the major moisture sources in buildings, exclusive of occupants, are foundations. A correctly designed and constructed foundation (exclusion) has a major impact on indoor air quality issues linked to moisture related biological agents.

In cooling climates the infiltration of hot, humid air is the single largest moisture source, including occupants and foundations. Infiltration of moisture laden air below grade in all climates, infiltration of hot, humid air above grade in cooling climates (or during cooling periods) and the exfiltration of interior, warm, moisture laden air in heating climates (or during heating periods) are major concerns. Accordingly, it is desirable to control air pressures (exclusion) within buildings in order control air transported moisture.

Furthermore, all moisture producing appliances such as clothes dryers should be vented directly to the exterior in all climates (capture at source). Unvented space heaters and other unvented combustion appliances generate significant amounts of moisture as well as other pollutants and should never be installed within conditioned spaces (exclusion). Bathrooms, washrooms and any other moisture generation rooms should be mechanically vented directly to the exterior in all climates (capture at source). Firewood should never be stored indoors (exclusion).

In heating climates or during heating periods, dilution by controlled ventilation (air change) can be utilized to remove moisture from building enclosures. In cooling climates during cooling periods, dilution by controlled ventilation (air change) cannot be utilized to remove moisture from building enclosures. Dilution by dehumidification through air conditioning (air cleaning) and by the use of ventilating dehumidifiers should be used during cooling periods or where exterior vapor pressures are high.

Radon

In order for radon to enter a space the following three requirements are necessary:

- radon must be present in the soil surrounding the building
- an opening or pathway must be present
- a driving force must be present (an air pressure difference or a concentration gradient)

It is safe to assume that radon will always be present in the surrounding soil. It is also reasonable to assume that openings and pathways will be present in all building enclosures notwithstanding the best attempts of builders, designers, and contractors to control them. Accordingly, control of the air pressure driving force constitutes the best approach at control of radon entry.

Below grade spaces should be pressurized with respect to the surrounding soil (exclusion). At the very least, air handling systems, combustion appliances and exhaust systems should be prevented from depressurizing below grade spaces due to duct leakage, make-up air and combustion and draft control air requirements.

Sub-slab depressurization is also recommended in all climate zones. Passive radon vents should be installed with the option of continuous mechanical exhaust. This air pressure control strategy for radon source control is fully consistent with the air pressure control strategy recommended for air transported moisture in all climate zones.

Formaldehyde and Other Volatile Organic Compounds (V.O.C.'s)

Formaldehyde is one of the most common industrial adhesives utilized. It is a volatile organic compound and typically used in two forms:

- urea formaldehyde
- phenol formaldehyde

Phenol formaldehyde is much more stable than urea formaldehyde and is not water soluble. Accordingly, phenol formaldehyde is typically used as an adhesive in exterior rated building materials such as plywood, waferboards and oriented stran boards (O.S.B.) which are exposed to rain. Urea formaldehyde is water soluble and off-gases readily at room temperatures. Increases in interior relative humidity and temperature significantly increase urea formaldehyde off-gassing. Urea formaldehyde is used in the manufacture of particle board and particle board is typically found as floor underlayment, in cabinetry and furniture. It is also a key component in many surface finishes and commonly used as a preservative. It is a potent human irritant and an animal carcinogen. It is a suspected human carcinogen and has been linked to multiple chemical sensitivity as a sensitizing agent.

Urea formaldehyde containing products should not be used within building enclosures (exclusion), or if used, the urea formaldehyde should be sealed or encapsulated to reduce emission source strength. For example, using paint as a sealer on the interior exposed surfaces of particle board used in cabinetry and furniture.

Urea formaldehyde based products should be replaced with phenol formaldehyde based products and phenol formaldehyde based products should be replaced with urethane based products and so on.

Carpeting rarely contains formaldehyde. However, some carpeting contains numerous other volatile organic compounds which may pose risks to susceptible individuals. Most of these v.o.c.'s have a rapid decay rate and pose little risk several months after installation. Unfortunately, problems can occur within those first few months of installation or if defective products (carpets with high v.o.c. loading) are installed. Of considerably more concern are the adhesives which are used in adhering carpets and floor coverings to traffic surfaces. More often than not, the carpet or floor covering gets blamed for a pollutant source problem created by a highly toxic adhesive used in conjunction with a relatively "clean" floor covering.

One of the most serious concerns arising from volatile organic compounds comes not from the building products or furnishings themselves, but how the building and furnishing are maintained and cleaned. It has been said that in North America we clean for appearance not for health. In other words, the surfaces may look clean but we may have "poisoned" the surfaces to do so. Many cleaning agents are extremely toxic and these substances are almost always stored inside in kitchen or bathroom cabinets. Off-gassing from cleansers has been linked to corrosion of stainless steel heat exchange surfaces in high efficiency combustion appliances and severe reactions in people. In many cases occupants choose to use more powerful substances than are necessary for the task. For example, ammonia to clean window glass when vinegar diluted with water would be adequate. Source control in these cases involves client education (match the strength of a cleaning agent to the strength of the task) and the storage of cleaning and maintenance agents outside of conditioned spaces (in a garage or shed).

Many air fresheners are volatile organic compounds which perfume the air or coat the linings of the respiratory/olfactory system to mask the offending odor. Deadening of the senses is a typical outcome. Air fresheners are not the solution to indoor pollution.

Synthetic, Natural and Benign Materials

It has been said that there are no bad materials, only bad uses. The use of a material has to be put into the context of a system. "The appropriateness of use" takes on a critical meaning. There are really no truly benign materials, only degrees of impact. There may be no alternative material to a particularly toxic material in a specific system, but the use of that material may pose little risk when used in that system and provide a significant benefit to that system. For example the use of bituminous dampproofing on the exterior of a concrete foundation wall enclosing a pressurized basement.

Society has benefited immeasurably through the use of tens of thousands of materials, compounds, chemicals, agents and products many of which have been developed in the last half century. It is impractical to avoid the use of manufactured and synthetic agents in construction. Concerns have been raised about the use of these products with respect to their impact on indoor environments (off-gassing, etc.). It is felt by many that synthetic materials should be avoided, that "natural" or "green" materials should be used. Natural materials are somehow felt to be safer. Many "natural" materials contain volatile organic compounds and are also potent irritants and pose hazards to human health. Allergic reactions to the odors emanating from "cedar" closets and chests are common. In fact, what does "natural" or "green" mean? Radium and radon are natural materials. We doubt that any rational human being would suggest that these two "natural" materials be used in construction even though radon gas would prove an excellent insulator in sealed glazing systems in place of argon gas and radium could be used on thermostat dials to make them easy to read at night.

The guiding principle to employ is that it is acceptable to use a particular synthetic or natural agent in a building product as long as that particular agent remains in that building product during its useful service life and does not enter or affect the human system through respiration and physical contact. Products which do not off-gas are preferable to those that do. Products which off-gas a little are preferable to those which off-gas a great deal. Less toxic alternatives should be used in place of more toxic materials and all of these material choices need to be placed in the context of the system or assembly the material is a part of.

When considering volatiles, the off-gassing decay rate also needs to be considered. For example, most interior latex paints contain significant quantities of volatile organic compounds. They are usually the vehicle for the pigment and the resin in the paint. They off-gas or evaporate very rapidly as they dry and leave behind a relatively "benign" surface finish which off-gases very little after several weeks. These volatile organic compounds dissipate very quickly and typically pose very little real "risk" to most occupants over the useful service life of the paint finish. However, they may pose a real "risk" to the painters as an occupational hazard. Accordingly, if a product containing a volatile organic compound which off-gasses is used, it is preferable that the off-gassing occur in a short time frame and that occupational risks be considered as well as risks to early occupancy.

The principle of product substitution should be employed wherever possible. Products containing compounds and chemicals which are volatile should be replaced with products containing less volatile agents. Volatile organic compounds should be replaced with semi-volatile organic compounds and semi-volatile organic compounds should be replaced with non-volatile organic compounds. If a compound or product does not contain any volatile agents, it is likely that the constituent materials will not exit the product and enter the human respiratory system or be absorbed through the skin. Finally, if volatile agents are used, it is preferable that they have very rapid decay rates and their "dwell" time in a particular product be limited.

Particulates

Particulates can be controlled by air cleaning (filtration) and by exclusion (encapsulation or product substitution). Of particular concern are "respirable" particles, or materials which can enter the lower reaches of the human respiratory system.

Particles which can be inhaled are typically smaller than 20 microns. Particles between 10 and 20 microns are typically deposited in the upper respiratory system (nasopharyngeal region). Particles which can reach the lower respiratory tract (tracheobronchial and pulmonary regions) are in the less than 10 micron size range and are classed as "respirable".

Respirable particles can pose a health risk when they interfere with the lungs' ability to exchange gases and when they cannot be easily removed or broken down by body defenses.

Asbestos fibers meet this criteria and as such are believed by some to pose a serious health risk. Fiberglass fibers used in cavity and attic insulation and as a lining on mechanical system ductwork do not. Part of the concern with asbestos fibers is their aspect ratio. They resemble tiny "spears" of diameter 1 to 2 microns and lengths of 4 to 6 microns. Once these tiny spears become embedded in the mucous lining of the lower respiratory system they become very difficult to clear and can not be broken down by the body. This is in contrast with fiberglass "twigs" or "rocks" which are typically 15 microns in size or larger and as such can not access the lower repiratory system. They can also be cleared more readily by the body and can be broken down or dissolved.

However, fiberglass fibers can become aerosolized for many reasons and can be a significant irritant for sensitive individuals. Cavity insulation “encapsulated” by gypsum board and insulation above gypsum board ceilings typically pose little risk unless they find there way into a mechanical system or into the conditioned space. Fiberglass fibers in ductboard and acoustical lining do not readily become aerosolized, but these products can become a host for dust and biological agents especially should “wetting” or condensation occur. Careful cleaning protocols must be employed with such products. Should they become contaminated or wet and biological growth occur, removal and replacement may be the only option.

Carpeting is typically the major source for particulates in indoor environments. Vacuuming and traffic aerosolize particles collected by carpeting as well as the carpet fibres themselves. If house dust mite infestation is also present, dust mite feces and the dust mites themselves also become aerosolized. Installation of central vacuum systems with extraction fans located in garages are an effective method of source control as is the use of HEPA vacuum systems (high efficiency particle arrestance) which capture respirable particles. Finally, use of other floor coverings such as wood floors and tiles are also effective source control.

Carpets should be maintained with periodic steam extraction in accordance with professional standards. Owner conducted carpet “shampooing” can create more problems than it solves. “Shampooing” can result in a perfuming of the carpet and provide moisture to facilitate dust mite growth. Dust mites can be killed and removed if steam accesses deep into carpet piles and particulates are removed under high suction. Dry extraction and cleaning methods should be considered. To prevent reinfestation and growth of dust mites, carpet micro-climates should be maintained at below 70 percent relative humidities.

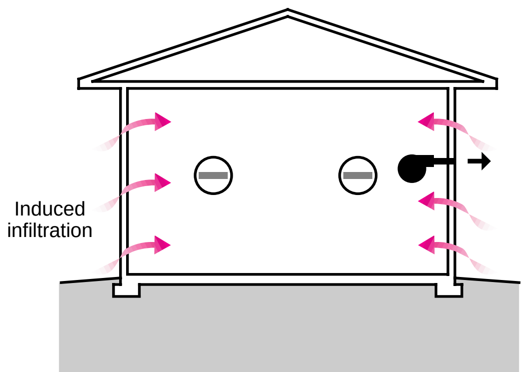
Filters installed in most air handling systems are installed to protect equipment not people. Typical filters are “bolder catchers” capturing 50 to 100 micron and larger particulates which can clog and contaminate fans and heat exchange surfaces. Dust mites are in the 30 to 40 micron size range and dust mite feces are in the 15 to 30 micron size range.

Electronic or electrostatic filters tend to be very efficient. However, they can contribute to ozone production at very low air flows, and require regular cleaning to remain effective. Their principle attraction, aside from their effectiveness, is that they do not restrict air flows as much as HEPA filters. The new generation of HEPA filters, about to be introduced for use in residential and commercial systems, promise to address this flow restriction issue.

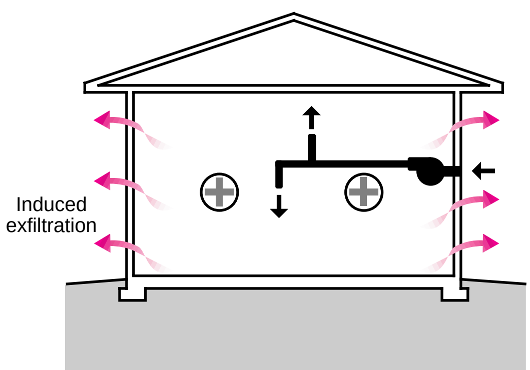
Air flow through a filtered system can be as important a consideration as filter efficiency. The air in a room with a given volume circulated through a low efficiency filter more frequently can be as “filtered” as the air in a comparable room circulated through a more efficient filter less frequently. Air flow rates can be used, in some cases, to compensate for less efficient filtration. A high circulation rate helps improve the capture of large particles. However, higher efficiency filters will capture particles which are so small they may never be arrested in lower efficiency filters.

Heavy Metals

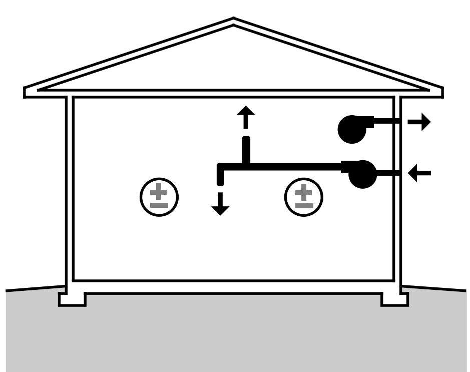
Mercury, lead and cadmium are commonly referred to as “heavy metals” and are recognized as extremely toxic substances. Cadmium is not typically found on construction sites. However, mercury has a long history of use as an effective mildecide or biocide in paints, gypsum board joint compound and many other products. Lead was similarly used in paints as well as being considered a pigment. Lead was a key constituent of solder used in plumbing systems for many years. The use of mercury and lead as mildecides and biocides is strictly regulated and it is not likely that these two agents will turn up in new products and materials. However, their prior widespread use make them a concern when rehabilitation of existing structures takes place and when recycled materials are used in new construction.



Exhaust Ventilation System



Supply Ventilation System



Balanced Ventilation System

Figure 4:
Ventilation Systems

Ventilation

Providing controlled mechanical ventilation in high performance building envelopes can be accomplished with exhaust systems, supply systems or balanced systems (Figure 4). Exhaust systems have the advantage of low cost but the disadvantages of negative pressures and the inability to filter incoming air. Supply systems have the advantage of filtration and positive pressurization and the disadvantage of lack of heat recovery. Balanced systems have the opportunity for energy recovery and the disadvantage of cost and the inability to pressurize building enclosures.

Supply ventilation systems are arguably the best approach to controlled mechanical ventilation since they provide both the ability to filter incoming air and the opportunity to positively pressurize the building enclosure. Pressurization of the building enclosure excludes exterior environmental contaminants.

Since supply ventilation systems create slight positive pressurization in building enclosures, building envelopes constructed in cold climates must be designed to be sufficiently forgiving to handle the pressurization moisture load.

Cold Climates

The greater the air change or ventilation rate, the greater the moisture removal rate. Excessive air change or ventilation leads to uncomfortably dry conditions – particularly in very cold climates. As such the selection of a ventilation rate determines the need for supplemental humidification.

Experience has shown that when ventilation rates of 15 cfm per person or greater are maintained, supplemental humidification in residences is required – even those with high performance building envelopes. Where ventilation rates of 10 cfm per person are maintained, supplemental humidification is typically not required and relative humidities stay above 20 percent.

Ventilation rates of 10 cfm per person should be provided in conjunction with source control of contaminants and the construction of high performance building envelopes.

At a ventilation flow rate of 40 cfm (typical for a 3 bedroom house), outside air can be directly introduced to the return side of an air handler (furnace) and not result in condensation within the heat exchanger assembly (Figure 5). At higher ventilation flow rates, stand-alone supply ventilation systems are necessary (Figure 6).

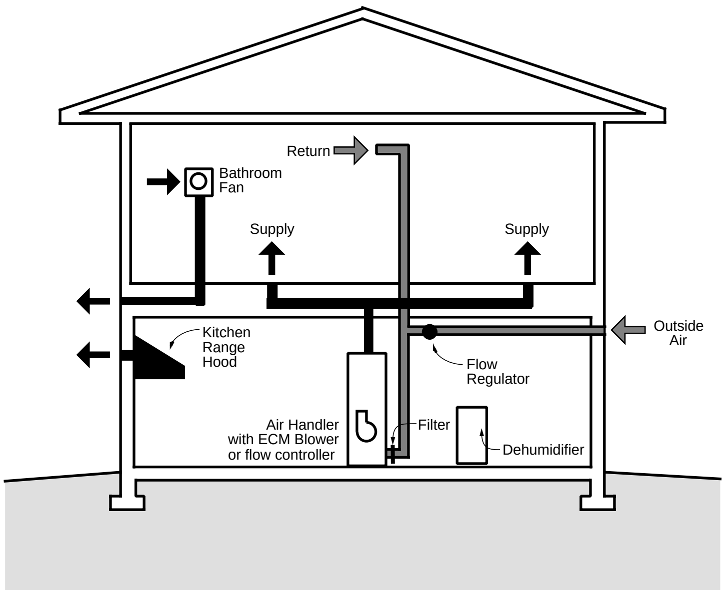


Figure 5:
Supply Ventilation System Integrated with Heating and A/C

- Air handler operated based on time of occupancy by a flow controller pulling outside air into the return system
- Flow controller should not allow air handler to run for 15 minutes after coil becomes de-energized to prevent re-evaporation of condensate from coil and drain pan
- A flow regulator provides fixed outside air supply quantities independent of air handler blower speed
- House forced air duct system provide circulation and tempering
- Point source exhaust is provided by individual bathroom fans and a kitchen range hood
- In supply ventilation systems, pre-filtration is recommended as debris can affect duct and fan performance reducing air supply
- Kitchen range hood and bathroom fans provide point source exhaust as needed
- Exhaust fans should not run continuously
- Outside air supply can be controlled by a damper. Closing the outside air damper during unoccupied periods will allow the flow controller to periodically mix the interior air without bringing in outside air helping the dehumidifier control interior RH — humid air is brought to the dehumidifier. The cooling function of the A/C can also be shutdown during this time (i.e. A/C on blower only operation).
- Outside air supply should have a closeable damper for periods whn outside air is poor, i.e. smoke from fires

Hot-Humid Climates

As window systems have improved and as roof and wall insulation levels have increased, the solar gain or heat load on buildings has been significantly reduced. This should lead to a reduction in the size of air conditioning equipment. Often, this is not the case. This “oversizing” leads to an inability of the air conditioning equipment to control interior humidity. Interior moisture is removed by air conditioning equipment only when air conditioning is activated by the thermostat. If the air conditioning system is not running, it is not dehumidifying. Oversized equipment runs for shorter periods such that the coils don’t get cold enough to remove much moisture before the thermostat is satisfied, especially under part load conditions.

In many cases, units small enough to match the loads are not commonly available. This is particularly acute in townhouse and condominium construction where the smallest commonly available units are 2-Ton and the typical loads are 1 to 1.5 Ton. These are full load values, meaning that under most cooling periods, part load conditions are the norm and even correctly sized equipment doesn’t run often enough or long enough to control interior humidity.

The problems are further exacerbated by air leakage at equipment cabinets and ductwork located external to the conditioned space. This leakage and the associated air pressure differences lead to infiltration of exterior humid air. The latent (moisture) load associated with this infiltrating air dwarfs the sensible (temperature) load. Comfort and interior humidity problems are likely.

By constructing a performance building envelope that minimizes heat gain and by providing outside air, it is not likely that even correctly sized air conditioning equipment will be able to control interior humidity levels under part load conditions. Supplemental dehumidification will be required. A dehumidifier or ventilating dehumidifier will be necessary.

The key steps in providing controlled ventilation in high performance building envelopes in hot-humid climates are as follow:

- reduce latent and sensible loads by locating ductwork and air handlers within building conditioned spaces eliminating leakage to the exterior
- reduce latent and sensible loads by balancing interior pressures by transfer grilles eliminating induced infiltration
- provide outside air only as needed and in the quantities needed
- use supply ventilation strategies that pressurize building enclosures
- properly size air conditioning equipment
- provide supplemental dehumidification

Adding controlled ventilation in hot-humid climates can seem at first to be a contradiction. Supplying outside air increases interior moisture levels and the latent load. Isn't this bad? Yes, but people also need outside air and outside air is required to dilute interior contaminants emitted from furnishings, the building structure and occupant activities. The key is only to supply the amount of outside air that is needed – and not more. And then address the resulting latent (interior humidity) load.

The contradiction gets worse when you consider the effect of duct leakage. Most ductwork and air handlers leak and are located outside of the conditioned space in vented attics, vented crawl spaces or garages. This results in excessive air change. Most houses in hot-humid climates are over-ventilated when the air handler operates. So you'd have to be crazy to add controlled ventilation? Well, no. The key is to get rid of the duct leakage induced air change which is uncontrolled and then add controlled ventilation. This approach typically results in a lower latent load. It is not unusual to have more than 150 to 200 cfm of duct leakage induced air change. This is replaced by 50 to 60 cfm of controlled ventilation after the duct leakage is eliminated.

Relying on duct leakage-induced air change to provide ventilation causes other problems. The outside air that is induced to enter often enters from the attic, crawl space or garage – locations that are not conducive to the highest quality of outside air by virtue of temperature, humidity or contaminants.

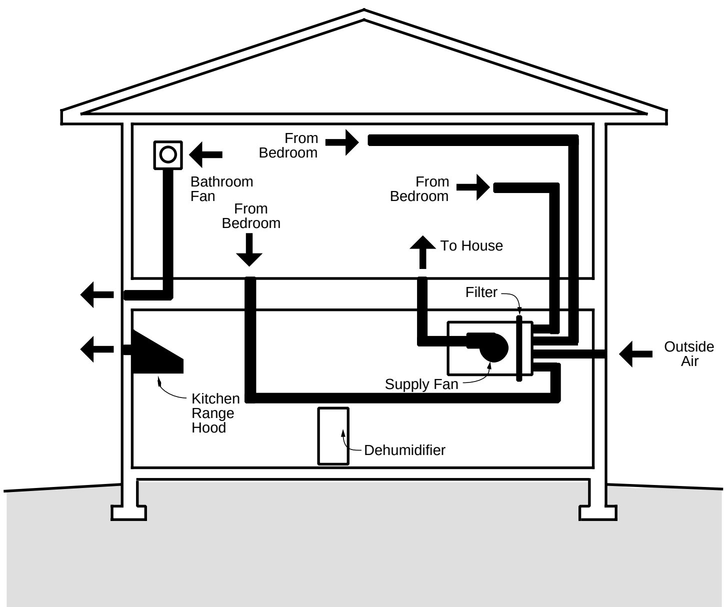


Figure 6:
Supply Ventilation System with Circulation and Point Source Exhaust

- Supply fan brings in outside air and mixes it with air pulled from bedrooms to provide ciculation and tempering prior to supplying to common area
- Run time is based on time of occupancy
- In supply ventilation systems, pre-filtration is recommended as debris can affect duct and fan performance reducing air supply
- Kitchen range hood and bathroom fans provide point source exhaust as needed
- Exhaust fans should not run continuously
- Supply ventilation system and A/C can be shutdown during unoccupied periods and only dehumidifier operated to control interior humidity
- Outside air supply should have a closeable damper for periods when outside air is poor, i.e. smoke from fires

The ideal approach to ventilation in hot-humid climates is to properly size equipment and minimize the need for outside air. The air should be obtained in a controlled manner (mechanically with a fan). The air should be conditioned where it comes into the building. It should be dehumidified by cooling it below its dewpoint (typically below 55 degrees F.) and used to maintain the building enclosure at a slight positive air pressure relative to the exterior (Figure 7). By doing so, it can be used to control the infiltration of exterior hot, humid air. Furthermore, the building envelope should be built in a manner that aids in the pressurization of the building. Tight construction with duct work and air handlers located within conditioned spaces is recommended.

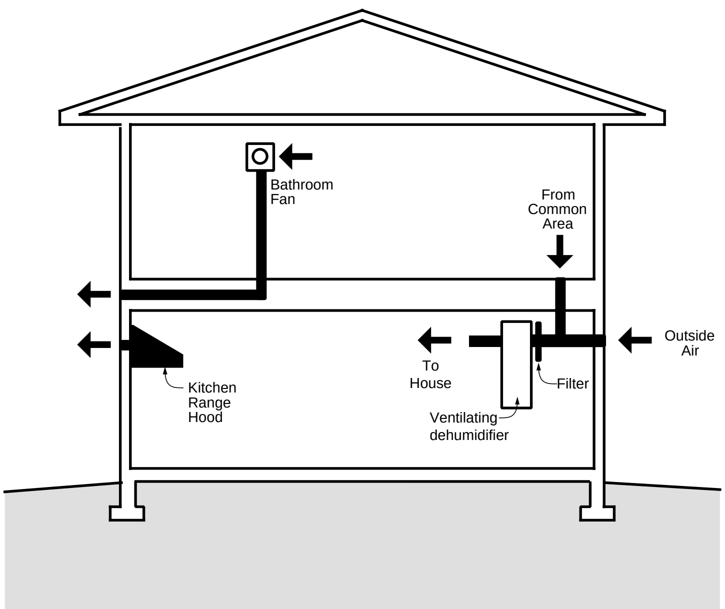


Figure 7:
Supply Ventilation System with Dehumidification and Point Source Exhaust

- Ventilating dehumidifier brings in outside air and mixes it with air pulled from a common area (living room, hallway) to provide circulation and tempering prior to supplying to common area
- Run time is based on time of occupancy
- In supply ventilation systems, pre-filtration is recommended as debris can affect duct and fan performance reducing air supply
- Kitchen range hood and bathroom fans provide point source exhaust as needed
- Exhaust fans should not run continuously
- Outside air supply can be controlled by a damper to allow dehumidifier to dehumidify without providing outside air during unoccupied periods. A/C can also be shutdown during this period allowing dehumidifier only to control interior RH
- Outside air supply should have a closeable damper for periods when outside air is poor, i.e. smoke from fires

Air Distribution

The following features characterize high performance building envelopes:

- high performance glazing
- high levels of insulation
- low building envelope leakage

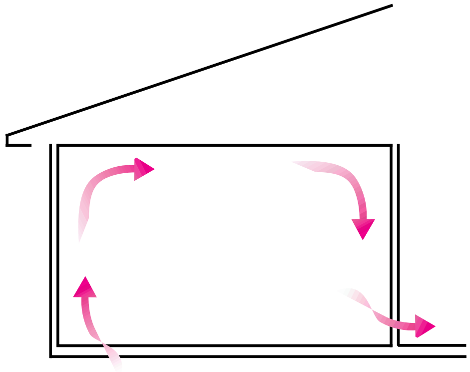
Each of these features has an impact on the design, installation and performance of air distribution systems.

High Performance Glazing

Mean radiant temperatures in houses are an important comfort factor and are typically dominated by the coldest or warmest surface in a space. Windows are often the coldest or warmest surface in a room due to their low thermal resistance. As a result, forced air heating distribution systems locate supply registers under windows in order to wash the interior surface of the glazing with warm air heating the glass thereby raising the mean radiant temperature in the space (Figure 8).

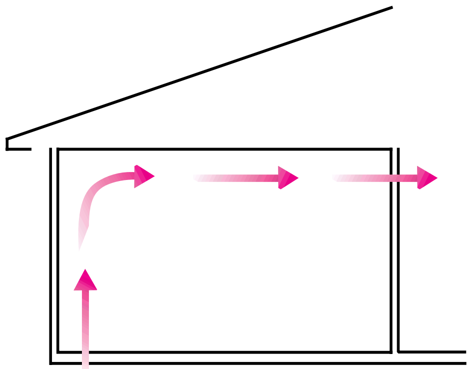
With air conditioning systems, supply registers are located over windows in order to wash the interior surface of the glazing with cold air thereby lowering the mean radiant temperature in the space (Figure 8).

With the advent of high performance glazing systems, notably low E and spectrally selective glass (low E2), the interior surface temperature of glazing systems is typically close to the interior surface temperature of the remainder of the insulated exterior wall. This has huge implications for the location of supply registers in that they no longer need to be located over or under windows to provide an air wash that moderates mean radiant temperatures.



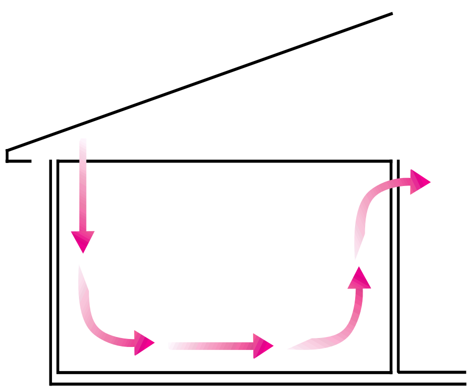
Classic Heating

- Supply at floor perimeter
- Return low in interior wall
- Poor windows
- Poor ceiling insulation



Recent Heating

- Supply at floor perimeter
- Return high in interior wall
- Poor windows
- Good ceiling insulation



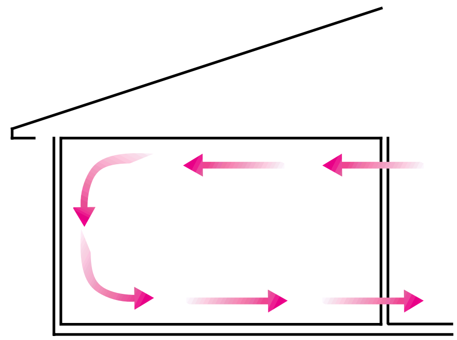
Classic Cooling

- Supply at ceiling perimeter
- Return high in interior wall
- Poor windows

Figure 8

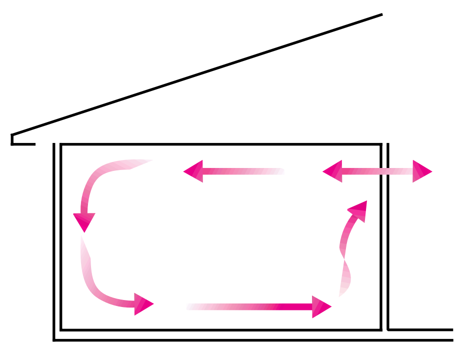
High Levels of Insulation

As levels of thermal insulation are increased in exterior wall assemblies with the use of insulating exterior sheathing and 2x6 framing the interior surfaces of exterior walls operate much more closely to room air temperature regardless of exterior temperature. As in the case of high performance glazing systems, this means that supply registers no longer need to be located at exterior walls. Combining the effects of both high performance glazing and high levels of wall insulation leads to the freedom to locate supply registers almost anywhere in a space (Figure 9).



Advanced Space Conditioning Heating and Cooling

- Supply high in interior wall
- Return low in interior wall
- Good windows
- Good insulation



Advanced Space Conditioning Heating and Cooling

- Supply and return both high in interior wall
- Good windows
- Good insulation

Figure 9

Low Building Envelope Leakage

Tight building envelope construction significantly reduces heat gain and heat loss. Additionally, it reduces stack effect driven air flows allowing the air flow created by the air distribution system to dominate the air flow created by the stack effect. When combined with high levels of thermal insulation and high performance glazing, the low building envelope leakage allows the use of a single centrally located return in a multi story residence rather than multiple returns at each floor level. The low heat loss limits thermal stratification in two story houses during heating periods.

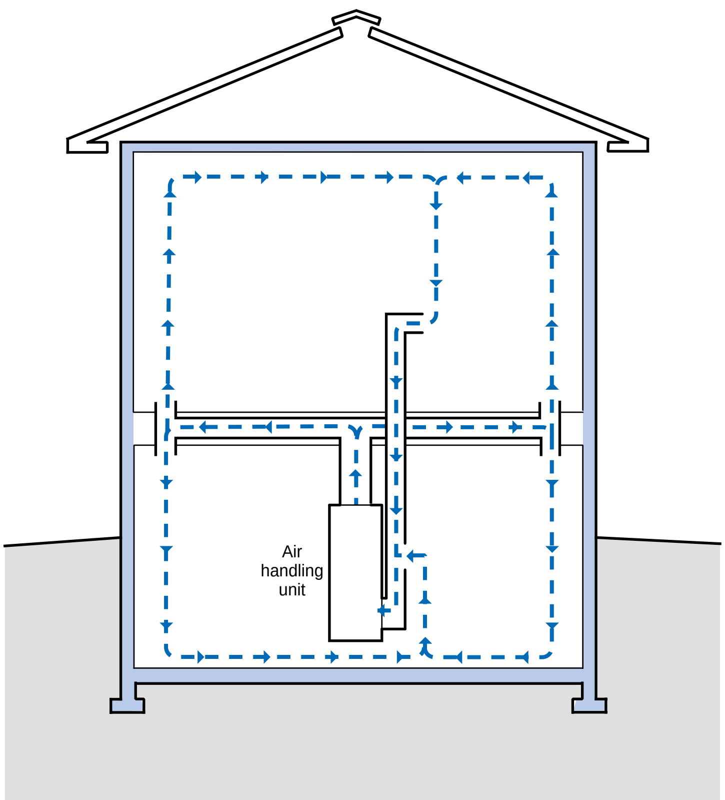


Figure 10
Ductwork and Air Handlers in Basements

- No air pressure differences result in a house with an air handler and ductwork located in a basement if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

Distribution System and Building Envelope Integration

Performance problems are common in typical residential construction where ductwork and air handlers are located outside of conditioned spaces. The problems arise due to leakage of distribution air and due to loses and gains due to conduction. Ductwork should not be installed in exterior walls, garages, vented attics and vented crawlspaces. Air handlers should not be installed invented attics, vented crawlspaces and garages.

A typical ducted, forced air heating or cooling system can be viewed as two systems, a supply duct system and a return duct system connected together through a fan located within an air handling unit. In buildings in heating climates most supply duct systems and air handling units (furnaces) are normally located in basement spaces (Figure 10) whereas in cooling climates most supply duct systems and air handling units (air conditioners) are located either in vented attics or in vented crawl spaces (Figure 11).

Air handlers create air pressure differences in buildings in two ways:

- duct leakage; and
- unbalanced flows

Most forced air duct systems leak substantial quantities of air. Field investigations have shown that 10 to 15 percent leakage of duct flow is typical. Leakage of 25 to 35 percent of duct flow is not uncommon. The effect of duct leakage on building enclosure pressures and air quality can be significant.

For example, if leaky supply ductwork is installed in the attic or crawl space of a building (or on the roof top), air is extracted out of the building, depressurizing the conditioned space. This leads to the infiltration of hot, humid air and likely mold and other biological growth related

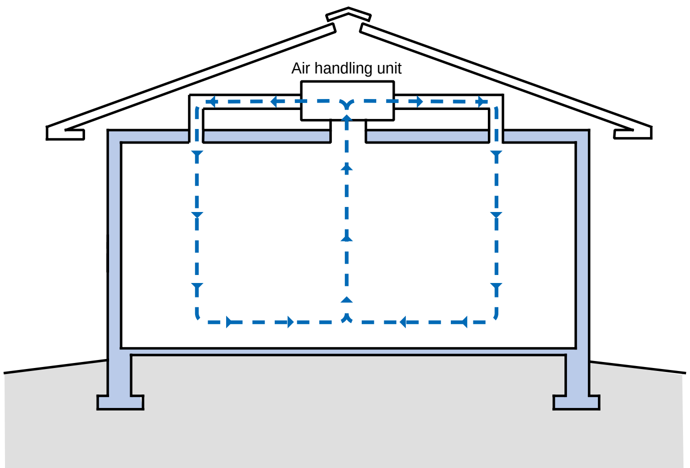


Figure 11
Ductwork and Air Handlers in Vented Attics

- No air pressure differences result ina house with an air handler and ductwork located in a vented attic if there are no leaks in the supply ducts, the return ducts or the air handler and if the amount of air delivered to each room equals the amount removed

problems in the south, and the infiltration of radon and soil gas in all climates. Furthermore, negative air pressures can lead to the spillage and backdrafting of combustion appliances.

If leaky return ductwork is installed in an attic, air is supplied to the building from the attic, pressurizing the conditioned space. Infiltration of hot, humid air (in cooling climates) or

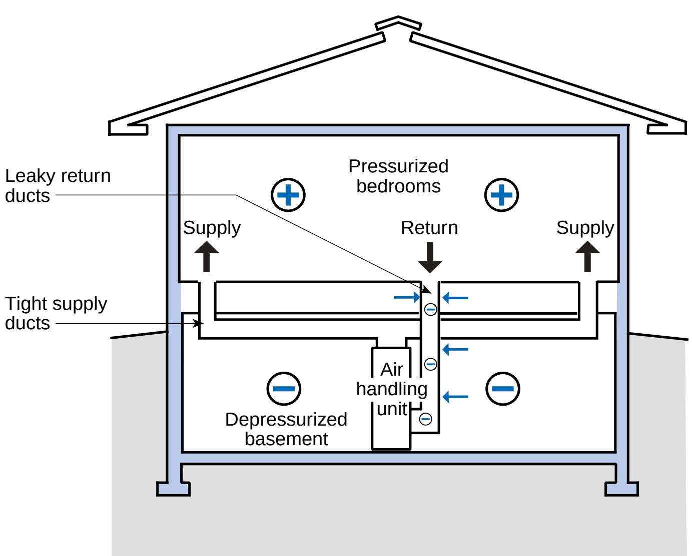


Figure 12
Leaky Ductwork and Air Handlers in Basements

- Air pressurization patterns in a house with leaky ductwork in the basement

infiltration of radon and soil gas (all climates) does not occur, but the pressurization is accomplished with hot, humid air (in cooling climates) significantly increasing interior moisture levels. If the moisture removal capability of the cooling system is unable to remove this moisture, mold and other biological growth also occurs.

Leakage of ductwork enclosed within building cavities can lead to the depressurization or pressurization of the cavities themselves. This is very common in facilities where individual room air handlers with leaky housings are built into exterior corners or built into dropped ceiling locations where demising wall cavities are connected directly to exterior walls. It is not unusual to have a room at positive air pressure relative to the exterior, while the wall cavities are at a negative air pressure relative to the exterior.

Negative air pressure fields in interstitial spaces can extend great distances away from air handling equipment due to the perforated nature of most framing systems coupled with electrical, plumbing, and mechanical servicing.

In buildings with basements, the supply system is usually a relatively "tight" system with supply ducts usually running to every room in the building. The return system is usually a relatively "leaky" system which often utilizes partition wall stud spaces, floor joist space cavities with sheet metal nailed to their lower surfaces and holes cut in floor sheathing with wood blocking as part of the "ducting". Furthermore, there is often only one or two common returns for the whole building. It is rare to find a return register in every room in which a supply register is also located. Even if return registers are matched to supply grills on a room-by-room basis, the return system is often so leaky that it draws only limited return air from the return registers.

A leaky return duct system can draw a significant amount of air from the surrounding air space. Figure 12 illustrates the

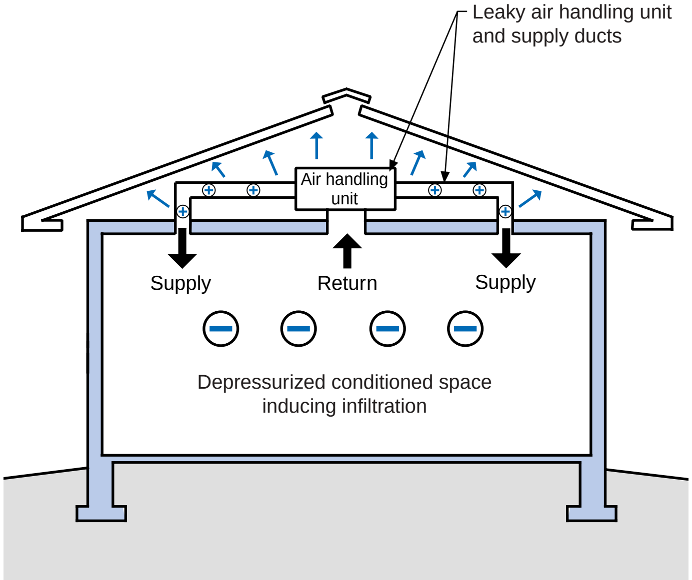


Figure 13
Leaky Ductwork and Air Handlers in Vented Attics

- Supply ductwork and air handler leakage is typically 20% or more of the flow through the system

example where much of the return air is drawn from the basement through the leaks in the return system leading to the depressurization of the basement area relative to the exterior and the main level.

In cooling climates where ductwork and air handlers are often located outside of conditioned spaces in attic spaces and vented, unconditioned,

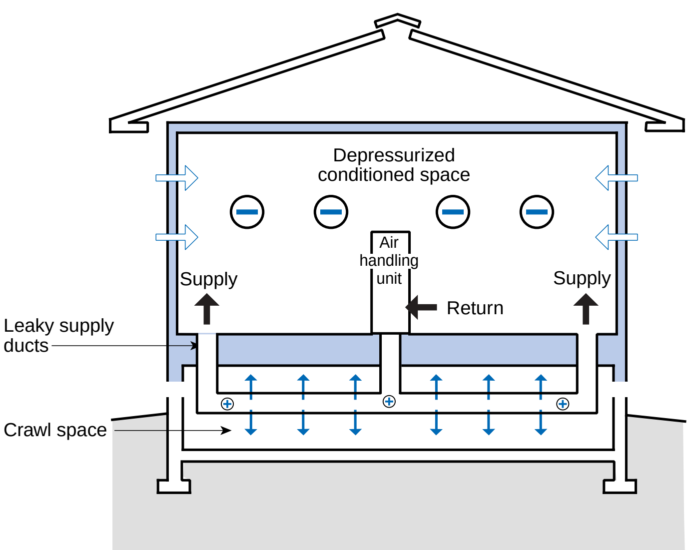


Figure 14
Leaky Supply Ductwork in Vented Crawl Space

- Air pressurization pattern with mechanical system ducts in the crawl space

crawl spaces, leaky supply ducts tend to depressurize the conditioned space inducing the infiltration of exterior hot, humid air (Figure 13) often creating moisture problems and increasing cooling loads.

Leaky supply ducts located in crawl spaces also tend to do the same (Figure 14). Leaky return ducts located in attic spaces can also draw hot, humid air into the enclosure as well as leaky return ducts located in crawl spaces which can draw hot humid air, radon and pesticides into the enclosure. Where both leaky supply ducts are located in attics and leaky return ducts are located in crawl spaces, air pressures in the conditioned space may not be significantly effected (Figure 15). However, hot, humid air, radon and pesticides can be drawn into the enclosure from the crawl space increasing cooling loads, the probability of moisture related problems and risking occupant health, while cool conditioned air is dumped into the attic space reducing the efficiency of the cooling system.

In addition, in rooms where there is a supply register and no return register, such as bedrooms, pressurization occurs when doors are closed (Figure 16). This room pressurization can lead to common area (hallways, living room, etc.) and basement depressurization.

In heating climates where depressurization of the basement space occurs, this can lead to the infiltration of "soil gas" and associated airborne moisture from the humidification of the infiltrating air by the humid ground. Furthermore, radon gas is also likely to be carried along with the moisture in the infiltrating air. Depressurization of the basement space can also lead to the spillage of products of combustion from water heaters and furnaces with standard chimneys.

In heating climates where pressurization of the above grade space (bedrooms) occurs, this can lead to the exfiltration of interior, possibly moisture laden, air. If this airborne moisture condenses within building assemblies it can lead to moisture related problems.

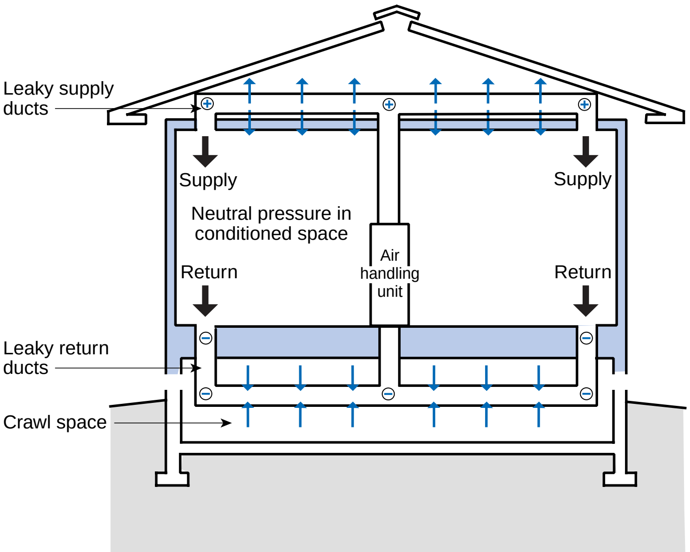


Figure 15
Leaky Supply and Return Ducts

- Air pressurization pattern with mechanical system ducts in the attic and crawl space

The process of inducing infiltration below grade and exfiltration above grade as a result of the pressure differences created by the forced air system in essence turns the forced air system into a ventilation system providing air change. Unfortunately this air change can lead to infiltration of moisture and radon below grade and the exfiltration of moisture above grade.

These elevated levels of air change as a result of the pressure effects of forced air systems can have significant impacts on energy consumption. Two buildings with identical levels of insulation and leakage openings in the same climate, but with one building with a forced air ducted system and the other building with a radiant system, will have significantly different levels of energy use. The building with the forced air system has much higher energy consumption levels due to the pressure effects of leaky ductwork.

A common example of an air pressure related moisture problem in a cooling climate is where a forced air cooling system air handler is located in a closet/utility room and a large unsealed opening exists between the supply ductwork which is located in the attic space and the ceiling of the closet/utility room where the supply ductwork penetrates the ceiling (Figure 17). Return air for the system is drawn from the hot, humid attic space into the utility room through the opening around the ductwork and into the return grill of the air handler. There are cases where the temperature of the building enclosure has actually gone up when the air conditioner/air handler was turned on in similar installations. The cooling load increase from the hot, humid air drawn from the attic into the system was actually greater than the capacity of the cooling system. Another serious consequence of leaky air handlers and leaky ductwork is the backdrafting of combustion appliances and possible flame roll-out (Figure 18).

One of the most common symptoms of the HVAC system induced air pressure differentials described is the soiling of carpeting. As air moves between rooms, into and out of interstitial cavities, across exterior wall

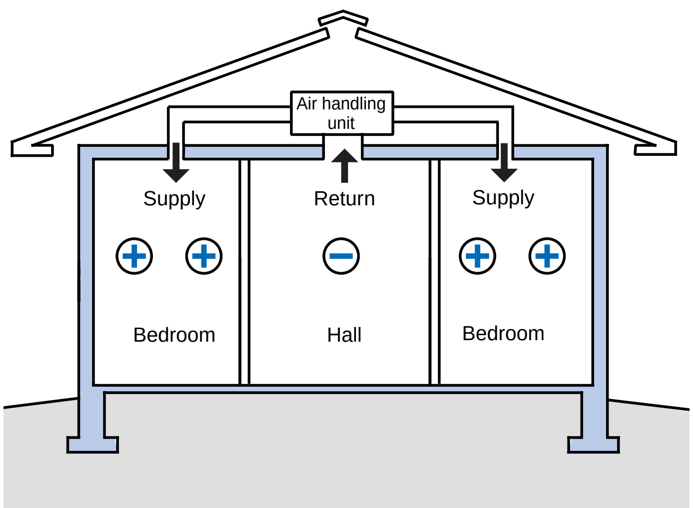


Figure 16
Insufficient Return Air Paths

- Pressurization of bedrooms often occurs if insufficient return pathways are provided; undercutting bedroom doors is usually insufficient; transfer grilles, jump ducts or fully ducted returns may be necessary to prevent pressurization of bedrooms
- Master bedroom suites are often the most pressurized as they typically receive the most supply air
- When bedrooms are pressurized, common areas depressurize; this can have serious consequences when fireplaces are located in common areas and subsequently backdraft

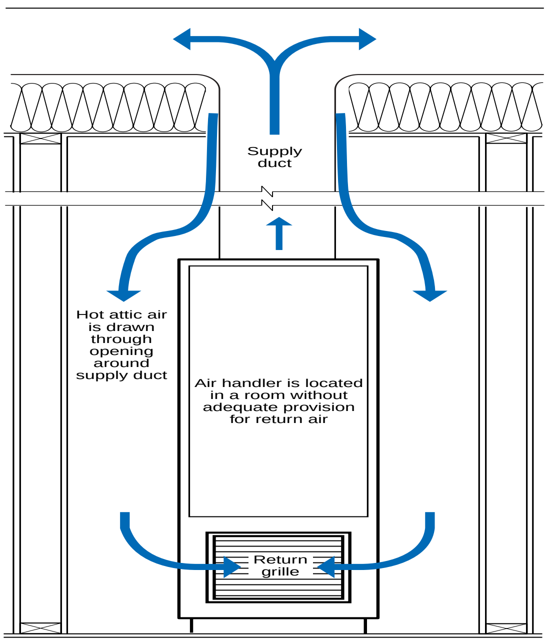


Figure 17
Air Handler Closet Depressurization

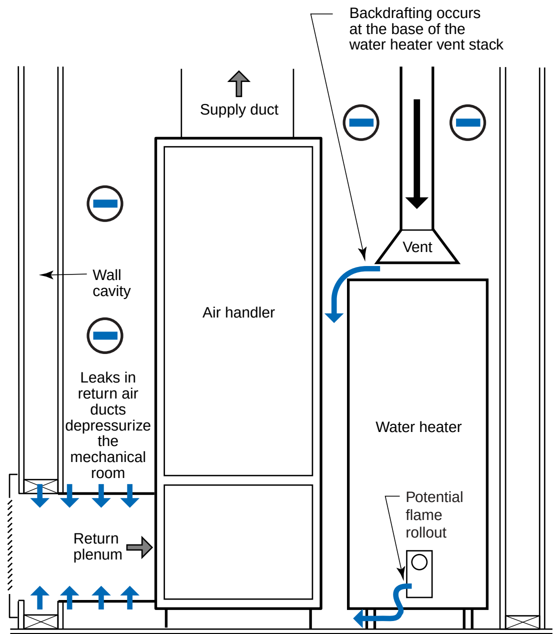


Figure 18
Backdrafting in Mechanical Room
- Mechanical room depressurized by return system leakage

assemblies and between above grade and below grade spaces it migrates under baseboards and under doors. Where carpeting is also present, this moving air is “filtered” by the porous carpet fibers at leaving telltale dark marks at baseboards, under doors and at stair treads. The effect is significantly enhanced where airborne particulates are found in high concentrations such as in smoking occupancies or where aromatic/scented candles are burned. Candles that burn with these types of additives release significant quantities of soot that get filtered at carpet/baseboard intersections, get deposited under doors due to impaction as well as plate out at cold surfaces due to Brownian motion and plastic surfaces due to electrostatic attraction.

Return Paths

All spaces with supply registers should have a clear path to a return grille in order to prevent the pressurization of bedrooms and the depressurization of common areas. Bedrooms should either have a direct-ducted return or a transfer duct or grille. Undercutting of bedroom doors rarely works and should not be relied upon to relieve bedroom pressurization. A central “hard” ducted return that is airtight and coupled with transfer grilles to relieve bedroom pressurization significantly outperforms a return system with leaky ducted returns in every room, stud bays used as return ducts and panned floor joists. See Figures 19 through 23 for effective transfer grille and “jump duct” details.

Heating and Cooling Equipment

Equipment should be sized correctly and only sealed combustion furnaces installed within conditioned spaces. Equipment should be located so it is accessible. If equipment is not accessible, dirty coils and dirty filters will occur from a lack of servicing and result in a reduction of air flow. Too little air flow across the indoor coil can potentially lower the coil temperature to the point of ice formation and serious damage.

Improperly charged systems can significantly affect efficiency. Overcharging or undercharging refrigerants by 10 or 15 percent can reduce some equipment efficiency by 10 or 15

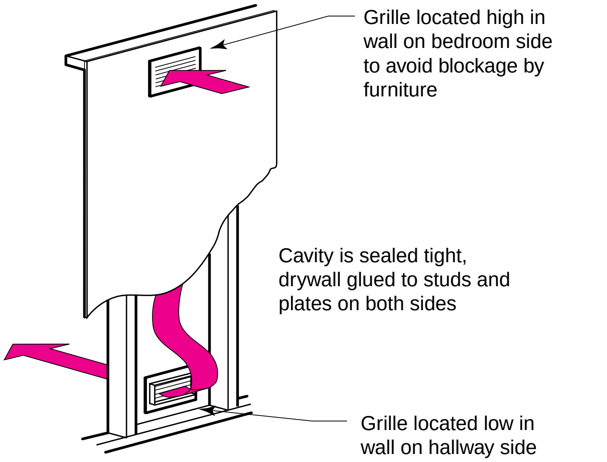


Figure 19
Transfer Grille — Offset

- Relieves pressure differences between spaces
- Typically 8"x16" or 10"x16"
- Door undercut of 1" minimum still required

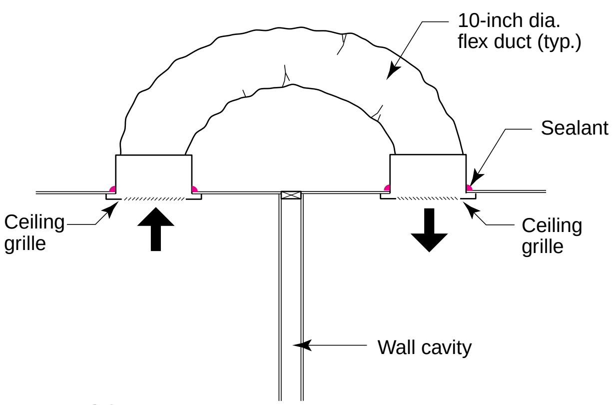


Figure 20
Jump Duct

- Relieves pressure differences between spaces
- Door undercut of 1" minimum still required

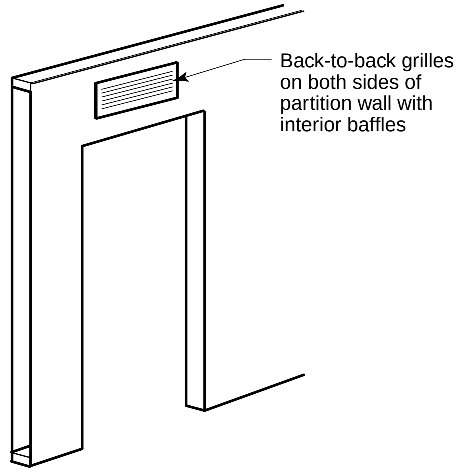


Figure 21
Transfer Grille — Over Door Opening

- Relieves pressure differences between spaces
- Interior baffles control sound and light transfer
- Door undercut of 1" minimum still required

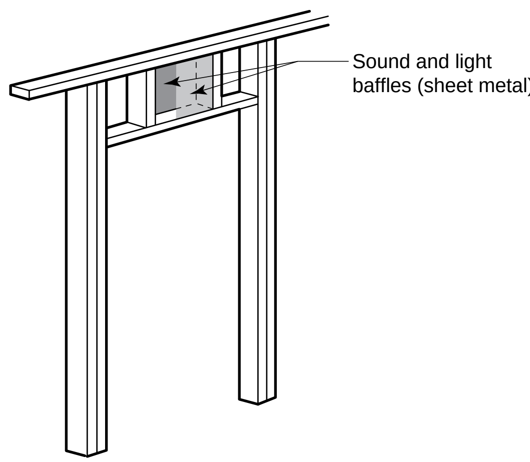


Figure 22
Transfer Grille — Construction

percent. Equipment should be selected where over or undercharging does not lead to significant effects. Accordingly, cooling equipment should be specified with thermal expansion valves (TXV's) rather than capillary tubes and equipment start up should require refrigerant charge to be based on actual measured line lengths.

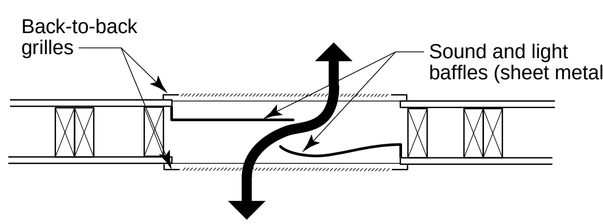
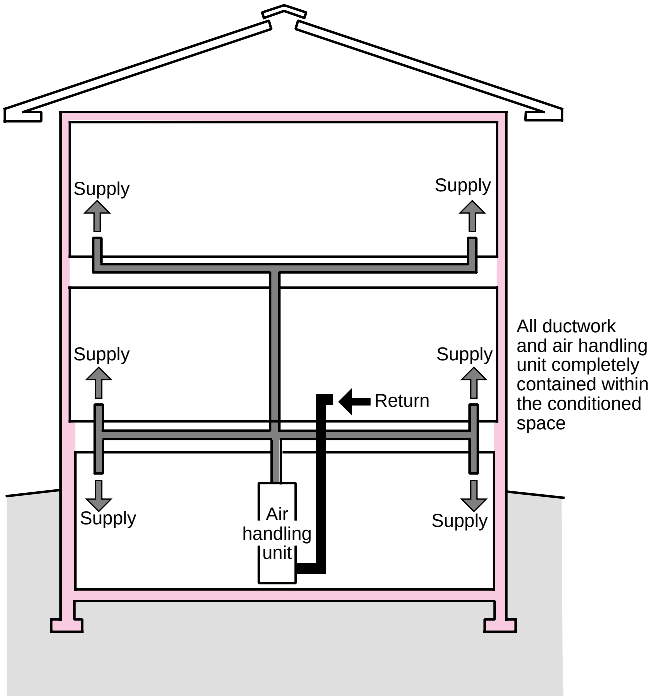


Figure 23
Transfer Grille — Section

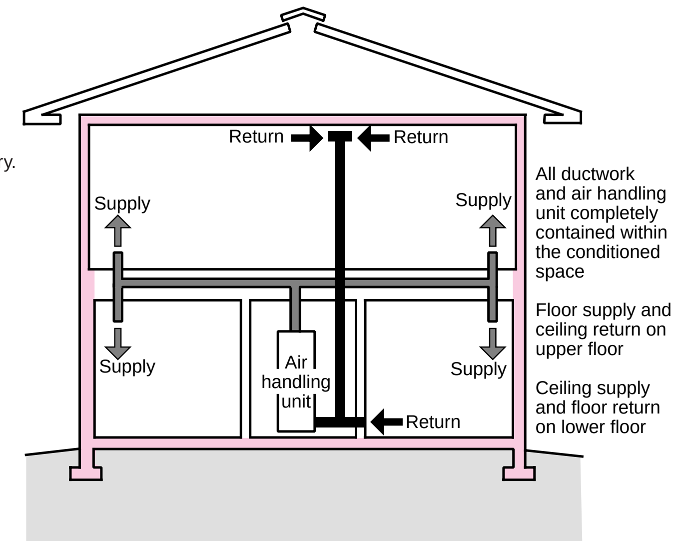
- Typically 6"x20"



Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 24
Basement Foundation — Vented Attic

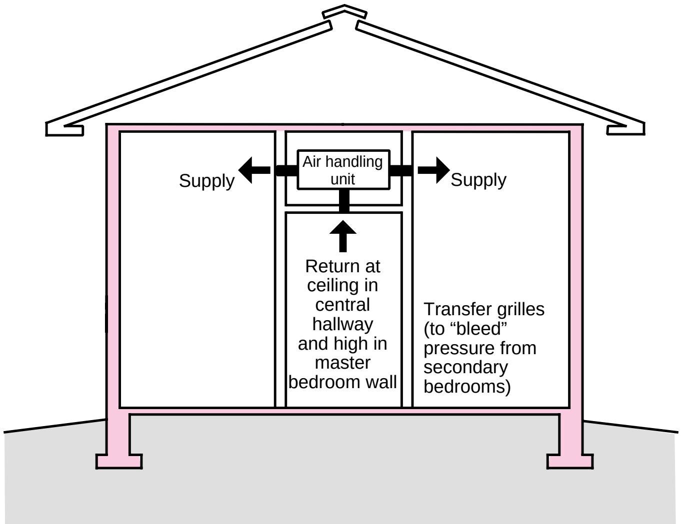
- The air handling unit is located in a conditioned basement
- Transfer grilles "bleed" pressure from secondary bedrooms
- Typical, low efficiency gas appliances that are prone to spillage or backdrafting are not recommended in this type of application; heat pumps, heat pump water heaters or sealed combustion furnaces and water heaters should be used
- A hot water-to-air coil in an air handling unit can be used to replace the gas furnace/heat exchanger; the coil can be connected to a standard gas water heater with a draft hood located in the garage. Alternatively, the gas water heater can be sealed combustion or power vented and located within the conditioned space.



Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 25
Slab-on-Grade with Dropped Ceiling
Vented Attic

- The air handling unit is located in an unvented, conditioned crawl space. The crawl space has a supply duct and either a return or transfer grille; a transfer grille can be provided through the main floor to return air to the common area of the house and subsequently to the return grille on the main floor.
- Typical, low efficiency gas appliances that are prone to spillage or backdrafting are not recommended in this type of application; heat pumps, heat pump water heaters or sealed combustion furnaces and water heaters should be used
- A hot water-to-air coil in an air handling unit can be used to replace the gas furnace/heat exchanger. The coil can be connected to a standard gas water heater with a draft hood located in the garage. Alternatively, the gas water heater can be sealed combustion or power vented and located within the conditioned space.
- Although the air handling unit can be located in a conditioned crawl space it is strongly recommended it be located within the occupied space for easy access
- This roof can also be constructed to be unvented by not installing vents thereby controlling humidity inflow into attic spaces



Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 26
Slab-on-Grade with Dropped Ceiling Vented Attic

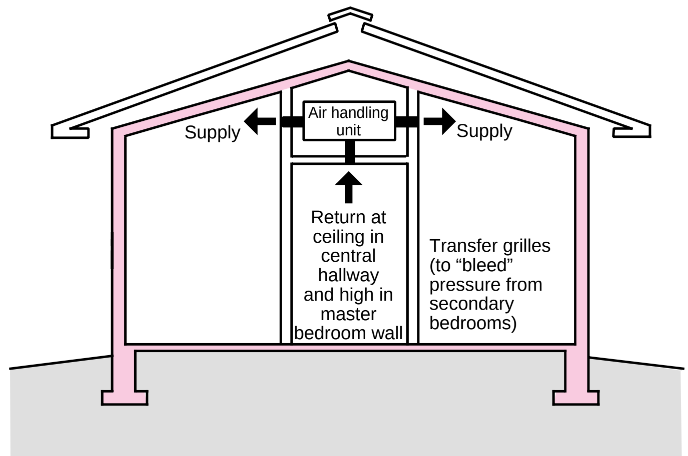
- In this approach, exterior wall heights are typically increased to 9-feet or more leaving hallway ceiling heights at 8-feet
- The air handling unit is located in an interior closet and the supply and return ductwork are located in a dropped hallway
- Transfer grilles bleed pressure from secondary bedrooms
- Ductwork does not have to extend to building perimeter when thermally efficient windows (low-E, spectrally selective) and thermally efficient building envelope (well-insulated 2x6 frame walls with 1" fo insulating sheathing) construction is used; throw-type registers should be selected
- Typical, low efficiency gas appliances that are prone to spillage or backdrafting are not recommended in this type of application; heat pumps, heat pump water heaters or sealed combustion furnaces and water heaters should be used
- A hot water-to-air coil in an air handling unit can be used to replace the gas furnace/heat exchanger. The coil can be connected to a standard gas water heater with a draft hood located in the garage. Alternatively, the gas water heater can be sealed combustion or power vented and located within the conditioned space.
- This roof can also be constructed to be unvented by not installing vents thereby controlling humidty inflow into attic spaces

Water Heaters

Standard atmospherically vented water heaters should never be installed within conditioned spaces. Their installation should be limited to garages. Only sealed combustion or power vented gas water heaters should be installed within conditioned spaces.

Examples of Advanced Space Conditioning

Mechanical equipment and ductwork should not be located outside of a home's thermal barrier and air pressure boundary. The building's thermal barrier and air pressure boundary enclose the conditioned space. The pressure boundary is typically defined by the air flow retarder. Therefore, mechanical equipment and ductwork should not be located in exterior walls, vented attics, vented crawl spaces, garages or at any location exterior to a building's air flow retarder and



Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

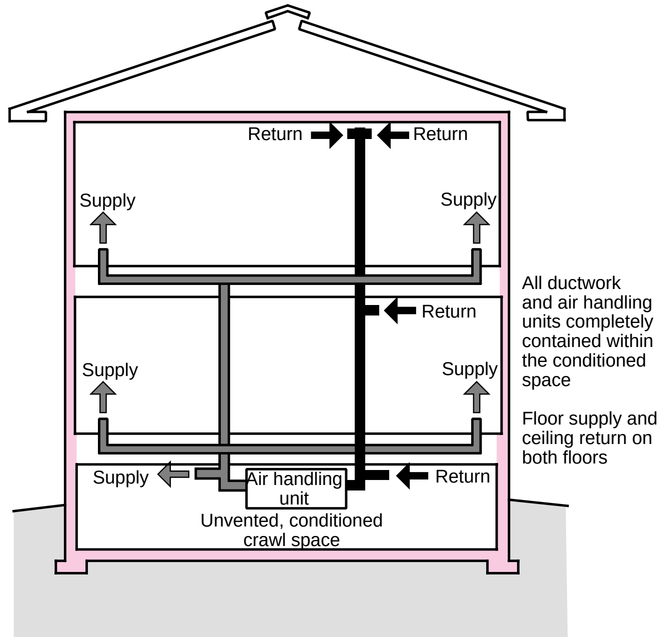
Figure 27
Slab-on-Grade with Dropped Ceiling Vented Attic

- The air handling unit is located in an interior closet and the supply and return ductwork are located in a dropped hallway
- Transfer grilles bleed pressure from secondary bedrooms
- Ductwork does not have to extend to building perimeter when thermally efficient windows (low-E, spectrally selective) and thermally efficient building envelope (well-insulated 2x6 frame walls with 1" fo insulating sheathing) construction is used; throw-type registers should be selected
- Typical, low efficiency gas appliances that are prone to spillage or backdrafting are not recommended in this type of application; heat pumps, heat pump water heaters or sealed combustion furnaces and water heaters should be used
- A hot water-to-air coil in an air handling unit can be used to replace the gas furnace/heat exchanger. The coil can be connected to a standard gas water heater with a draft hood located in the garage. Alternatively, the gas water heater can be sealed combustion or power vented and located within the conditioned space.
- This roof can also be constructed to be unvented by not installing vents thereby controlling humidty inflow into attic spaces

thermal insulation. All air distribution systems should be located within the conditioned space. Additionally, ductwork should never be installed in or under floor slabs due to soil gas, radon, moisture condensation issues, and flooding of ductwork.

Figures 24 though 29 illustrate six approaches that locate air handlers and ductwork completely within conditioned spaces, inside of the building thermal barrier and pressure boundary.

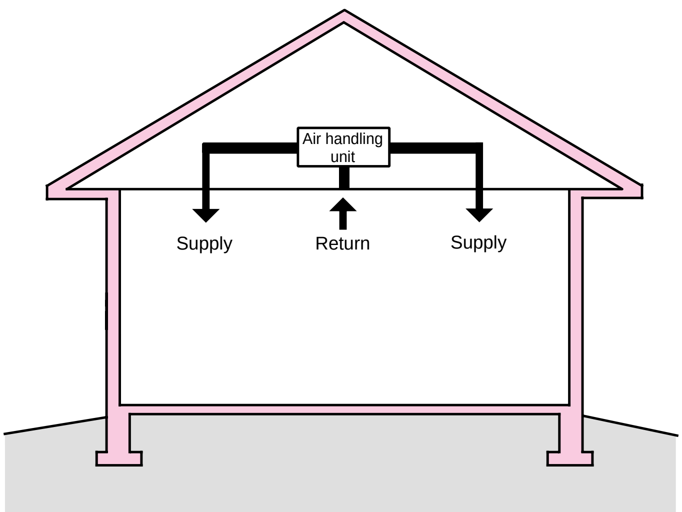
Detailed working drawings and building descriptions follow in Appendix B.



Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 28
Crawl Space — Vented Attic

- The air handling unit is located in a conditioned basement
- Transfer grilles "bleed" pressure from secondary bedrooms
- Typical, low efficiency gas appliances that are prone to spillage or backdrafting are not recommended in this type of application; heat pumps, heat pump water heaters or sealed combustion furnaces and water heaters should be used
- A hot water-to-air coil in an air handling unit can be used to replace the gas furnace/heat exchanger; the coil can be connected to a standard gas water heater with a draft hood located in the garage. Alternatively, the gas water heater can be sealed combustion or power vented and located within the conditioned space



Note: Colored shading depicts the building's thermal barrier and pressure boundary. The thermal barrier and pressure boundary enclose the conditioned space.

Figure 29
Slab-on-Grade
Unvented, Conditioned Attic

- The air handling unit is located in an unvented, conditioned attic; the attic insulation is located at the roof deck
- Typical, low efficiency gas appliances that are prone to spillage or backdrafting are not recommended in this type of application; heat pumps, heat pump water heaters or sealed combustion furnaces and water heaters should be used
- A hot water-to-air coil in an air handling unit can be used to replace the gas furnace/heat exchanger. The coil can be connected to a standard gas water heater with a draft hood located in the garage. Alternatively, the gas water heater can be sealed combustion or power vented and located within the conditioned space.

Appendix A

Building America Metrics

Overall thermal transmission coefficients for buildings and equipment efficiencies should meet Energy Star requirements (30 percent less than a reference house as defined by the 1993 Model Energy Code).

Air leakage of buildings (determined by pressurization testing) should be less than 2.5 square inches per 100 square feet of building envelope area (CGSB, calculated at a 10 Pa pressure differential); or, less than 1.25 square inches per 100 square feet of building envelope area (ASTM, calculated at a 4 Pa pressure differential); or, less than 0.25 cfm per square foot of building envelope area at a 50 Pa pressure differential.

Controlled mechanical ventilation at a minimum base rate of 20 cfm per master bedroom and 10 cfm for each additional bedroom should be provided when the building is occupied. A capability for intermittent base rate ventilation of 0.05 cfm per square foot of conditioned areas should also be provided. Intermittent spot ventilation of 100 cfm should be provided for each kitchen. Intermittent spot ventilation of 50 cfm or continuous ventilation of 20 cfm when the building is occupied should be provided for each washroom/bathroom. Positive indication of shut-down or improper system operation for the base rate ventilation should be provided to occupants.

Mechanical ventilation should use less than 0.5 watt/cfm.

Mechanical ventilation system airflow should be tested during commissioning of the building.

Total ductwork leakage for ducts distributing conditioned air should be limited to 10.0 percent of the total air handling system rated air flow at high speed determined by pressurization testing at 25 Pa.

Ductwork leakage to the exterior for ducts distributing conditioned air should be limited to 5.0 percent of the total air handling system rated air flow at high speed determined by pressurization testing at 25 Pa.

Only sealed combustion or power vented combustion appliances should be installed in occupied spaces.

Major appliances should meet high energy efficiency standards using current appliance ratings. Only those appliances in the top one-third of the DOE Energy Guide rating scale should be selected.

Lighting power density should not exceed 1.0 Watts per square foot.

Information relating to the safe, healthy, comfortable operation and maintenance of the building and systems that provide control over space conditioning, hot water or lighting energy use should be provided to occupants.

Comfortable indoor conditions as defined by ASHRAE Standard 55-1989 should be provided.

The building and site should provide effective drainage measures to control rainfall runoff and to prevent entry into the building.

The building foundation should be designed and constructed to prevent the entry of moisture and other soil gases.

Building assemblies should be designed and constructed to permit drainage (when needed) and drying of interstitial spaces.

Building assemblies should be designed and constructed to prevent reduction of thermal insulation performance due to air flow and moisture from either the interior or exterior.

Radon resistant construction practices as referenced in the ASTM Standard "Radon Resistant Design and Construction of New Low Rise Residential Buildings" should be utilized.

Forced air systems that distribute air for heating and cooling should be designed to provide balanced airflow to all conditioned spaces and zones (bedrooms, hallways, basements). Interzonal air pressure differences, when doors are closed, will be limited to 3 Pa.

Filtration systems should be provided for forced air systems which provide a minimum atmospheric dust spot efficiency of 30 percent (established when using ASHRAE Standard 52-1994).

Indoor humidity should be maintained in the range of 30 to 60 percent by controlled mechanical ventilation, mechanical cooling or dehumidification.

Buildings should be designed, constructed and operated to reduce overall life-cycle impact on the environment considering energy consumption, resource use and labor inputs in the fabrication, construction, operation and renovation of the building, components and systems.

The design and construction of buildings should use recycled materials, or new materials with a high recycled content where it is both cost effective and practical.

Minimization of scrap on site should be provided.

Air Leakage – Determining Leakage Ratios and Leakage Coefficients

Using a blower door, measure the flow rate necessary to depressurize the building 50 Pascal's. This flow rate is defined as CFM50. Alternatively, determine the Equivalent Leakage Area (ELA) in square inches at 10 Pascal's using the procedure outlined by CGSB. When determining these values, intentional openings (design openings) should be closed or blocked. These openings include fireplace dampers and fireplace glass doors, dryer vents, bathroom fans, exhaust fans, HRV's, wood stove flues, water heat flues, furnace flues and combustion air openings.

Calculate the leakage ratio or the leakage coefficient using the entire surface area of the building envelope. When determining the surface area of the building envelope, below grade surface areas such a basement perimeter walls and basement floor slabs are included.

For example, a 2,550 square foot house constructed in Grayslake, IL has a building envelope surface area of 6,732 ft2 and a conditioned space volume of 33,750 cubic feet (including the basement). The measured Equivalent Leakage Area (ELA) using a blower door is 128 square inches. This also corresponds to a blower door measured CFM50 value of 1,320 cfm and a blower door measured 2.3 airchanges per hour at 50 Pascal's.

Surface Area	ELA	CFM50	ach @ 50 Pa	Volume
6,732 ft^2	128 in^2	1,320 cfm	2.3	33,750 ft^3

To determine the Leakage Ratio, divide the surface area of the building envelope by 100 square feet and take this interim value and divide it into the ELA.

6,732 ft^2 divided by **100** ft^2 equals **67.32**

128 in^2 divided by **67.32** equals **1.9** $in^2/100\ ft^2$ (Leakage Ratio)

To determine the Leakage Coefficient, divide the CFM50 value by the surface area of the building envelope.

1,320 CFM50 divided by **6,732** ft^2 equals **0.20** cfm/ft^2 (Leakage Coefficient)

Many airtightness measurements are recorded as air changes per hour at a pressure differential of 50 Pascal's (ach @ 50 Pa). To convert ach @ 50 Pa to CFM50 multiply the volume of the building envelope (including the basement) by the ach @ 50 Pa and divide by 60 min/hour.

For example, 2.3 ach @ 50 Pa across a building envelope of volume 33,750 ft^3 is equivalent to a CFM50 value of 1,320 cfm.

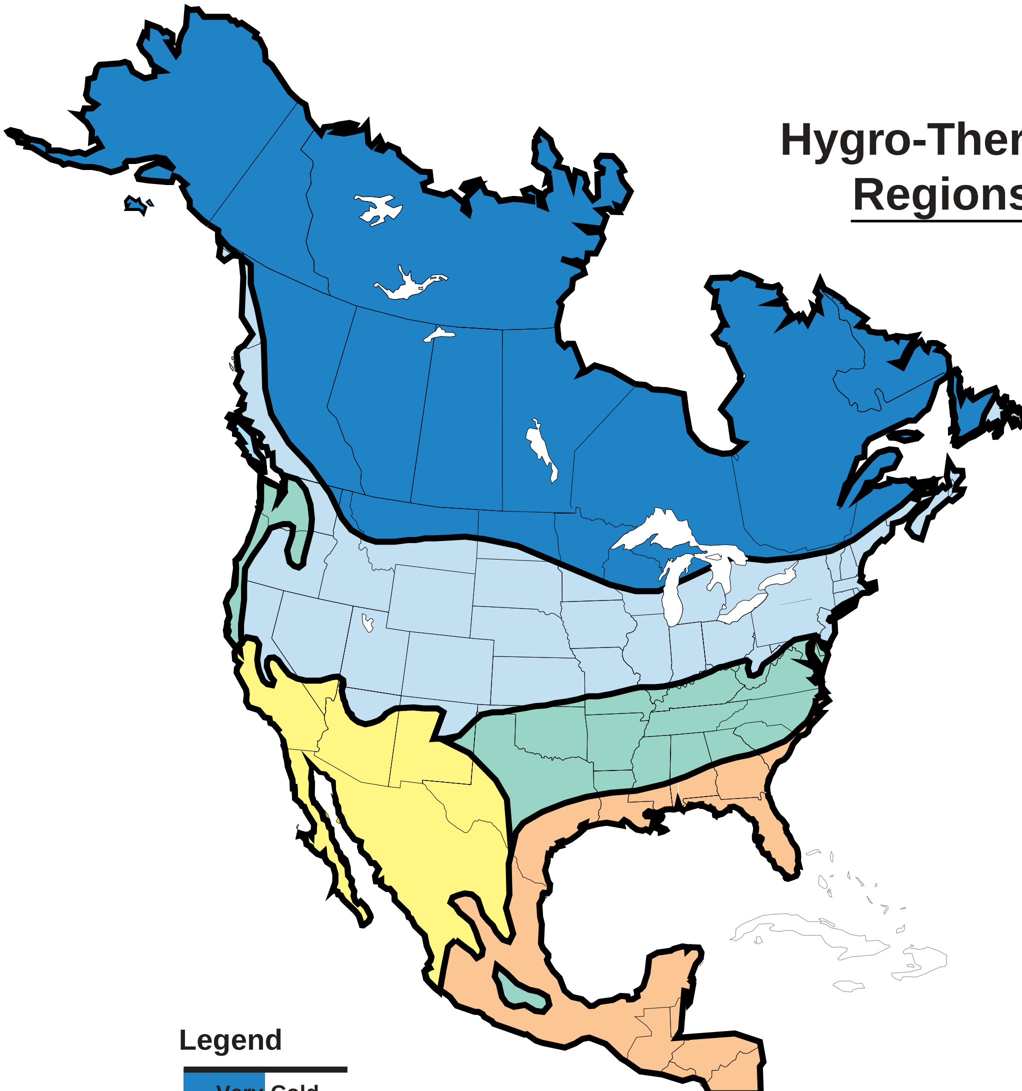
33,750 ft^3 multiplied by **2.3** ach @ 50 Pa divided by **60** min/hr equals **1,320** CFM50

Ductwork Leakage

To determine the allowable limit for ductwork leakage, determine the rated air flow rate of the air handler, furnace, air conditioner, etc. at high speed from the manufacturer's literature. For example, a Carrier or Lennox or York heat pump system may have a high speed flow rate of 1,200 cfm across the blower according to literature supplied with the unit. Ten percent of this value is 120 cfm. This 10 percent value becomes the ductwork leakage limit when the total air handling system is pressurized to 25 Pascal's with a duct blaster.

Appendix B

Hygro-Thermal Regions



Legend

Very-Cold
A very cold climate is defined as a region with approximately 8,000 heating degree days or greater

Cold
A cold climate is defined as a region with approximately 4,500 heating degree days or greater and less than approximately 8,000 heating degree days

Mixed-Humid
A mixed-humid climate is defined as a region that receives more than 20 inches of annual precipitation, has approximately 4,500 heating degree days or less and where the monthly average outdoor temperature drops below 45°F during the winter months

Hot-Humid
A hot-humid climate is defined as a region that receives more than 20 inches of annual precipitation and where the monthly average outdoor temperature remains above 45°F throughout the year*

Hot-Dry/Mixed-Dry
A hot-dry climate is defined as a region that receives less than 20 inches of annual precipitation and where the monthly average outdoor temperature remains above 45°F throughout the year;

A mixed-dry climate is defined as a region that receives less than 20 inches of annual precipitation, has approximately 4,500 heating degree days or less and where the monthly average outdoor temperature drops below 45° during the winter months

* The definition characterizes a region that is almost identical to the ASHRAE definition of hot-humid climates where one or both of the following occur:

- a 67°F of higher wet bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year; or
- a 73°F or higher wet bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year

Based on Herbertson's Thermal Regions, a modified Koppen classification, the ASHRAE definition of hot-humid climates and average annual precipitation from the U.S. Department of Agriculture and Environment Canada

Building Science Corporation

Building America Program homes in Tucson use state-of-the-art building materials and building systems including spectrally selective glass (lets the visible light through, but keeps the solar gain out) and an innovative unvented roofing system that encloses the home's air conditioning ductwork within the home's thermal barrier. Ductwork and air conditioners are now located "inside" surrounded by room temperature air at 75 degrees rather than 130 degree air found in a typical vented attic.

For example, there are six house models at the Pulte Home Corporation's Retreat at the Bluffs in Tucson. All six houses exceed EnergyStar requirements. In fact, they are predicted to use between 46% and 50% less energy (in BTU's) for heating, cooling and hot water, than a like house built to meet the 1995 Model Energy Code in this area. In addition, all six houses have controlled mechanical ventilation to insure air change required for good indoor air quality.

The houses range in size from 1,332 square feet to 1,618 square feet and sell for $73 to $78 per square foot. Utility bills for heating and cooling are guaranteed through the "Engineered for Life" program to cost between $20 and $30 per month. EFL is a BSC consortium member and spin-off of the Building America program, in partnership with GreenStone Industries and Louisiana Pacific.

Each home has a controlled ventilation system that enhances indoor air quality and comfort/freshness by bringing in outside air at preset intervals. Typical homes have no way of providing outdoor air in a controlled manner aside from relying on the construction of leaky homes and the whims of the weather (wind and temperature differences). Of course leaky homes use and lose more energy and tend to be uncomfortable from drafts. Tight homes without controlled ventilation can also have problems due to a build up of odors and other pollutants. The optimum approach for healthy, safe, comfortable, energy efficient homes is to construct a tight building envelope and provide controlled mechanical ventilation.

The homes are constructed from 2x6 framing with cavities insulated with batt insulation and a layer of foam insulation on the exterior under the stucco, providing a "super-insulated" wall assembly. The unvented roof construction provides for a much tighter building enclosure, 50 percent tighter than standard construction, eliminating drafts and improving comfort and energy efficiency.

In the cooling mode, the energy efficiency provided by the spectrally selective glazing system and the elimination of duct leakage and conductive gains from the application of unvented roof construction allows the use of air conditioning units that are smaller by 30 percent over those of typical construction.

The homes built under the Building America Program in Tucson are superior in performance and provide lower operating costs (i.e. utility bills and maintenance) than typical homes. The homes provide significant savings to the home owner with respect to reductions in electrical costs associated with air conditioning and gas costs associated with heating. The homes also significantly benefit electrical utilities because of reduced peaking and reduced installed cooling capacity.

Most importantly, Building America homes are safer than typical homes due to the provision of controlled mechanical ventilation and the elimination of negative pressures within homes that can result in soil gas, radon and pesticide ingress as well as spillage and back drafting of combustion appliances and the nuisance of dust marking on carpeting.

The key problem addressed by the Building America approach is the effect of air leakage of ductwork and air handlers located in vented attics. By moving the thermal and airtightness plane to the roof deck, all of the ductwork and air handlers are now located within the conditioned envelope. Leakage is no longer critical to the safe and efficient operation of HVAC equipment. Although a small penalty (less than 5 percent) is associated with thermal gains due to unvented roof construction, a huge thermal benefit (25 to 35 percent) is associated with the elimination of duct leakage and air handler leakage to the exterior coupled with the elimination of pressure differentials that are drivers for uncontrolled air change. Therefore the net positive effect is a 20 to 30 percent energy reduction in a significantly safer building enclosure.

In previous test houses built under the Building America Program in Las Vegas, a twenty percent reduction in measured total cooling energy consumption was achieved in the houses with unvented roofs and a fifty percent reduction in heat losses was measured in the heating mode. The houses with unvented roofs performed better than houses with a vented roofs under both cooling and heating conditions. In typical construction, venting a roof during cooling periods was found to increase heat gain due to the effect of duct leakage of an HVAC system located in a vented attic. Venting a roof during heating periods increased heat loss due to increased air leakage across the ceiling assembly and the inability to capture much of the solar gain incident on the roof assembly.

In the test houses, duct leakage of HVAC systems had no effect on energy consumption, air change or air pressure relationships in the houses with unvented roofs. However, duct leakage had a significant negative effect in the houses with vented roofs.

In the test houses, no measurable difference in roof tile temperatures occurred between vented and unvented roofs. These results were consistent with the mathematical modeling and simulations by the research team as well as being consistent with previous work done by the Small Homes Council at the University of Illinois and at the Florida Solar Energy Center (FSEC).