ENERGY STAR® Qualified Homes

BUILDING SCIENCE INTRODUCTION

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The ENERGY STAR New Homes Program uses both current building science theory and practical experience to look at building design, construction techniques, materials, and HVAC equipment, and to investigate their effects on building occupants. The ENERGY STAR New Homes Program sees a house as a system, where changes in one part of the building may have effects on all other portions of the building.

Many aspects of building design, construction, and operation can affect the health and comfort of the people in the building. This introduction focuses on three particular areas:

- Air Flow
- Heat Flow
- Moisture Flow

For each of these issues, the introduction explores causes, control measures, and effects on both buildings and occupants. This introduction defines many of the theories behind the ENERGY STAR New Homes requirements.

AIR FLOW

In simplest terms, air needs an opening or hole to flow through and a driving force to move it. Many different factors control how air flow affects a house. This section examines the forces and conditions that allow air to flow into, out of, or within a building, including:

- Controlled versus uncontrolled airflow
- Causes of air pressure
- Holes and pathways
- Effects of air flow

In order for air to flow into, out of, or within a building, two requirements must be met: a hole or path must exist for the air to flow through, and there must be a driving force.

Air flows within buildings are either *controlled* or *uncontrolled*. In either case, the actual flow of air is determined by several factors, including hole size, resistance to flow, and pressure effects.

Controlled Versus Uncontrolled Air Flow

Controlled Air Flow

Controlled air flow is generated by a mechanical device and is designed to help ventilate a building and/or distribute conditioned air throughout a building. Ventilation systems, fans, spot ventilators, make-up air, and heating and air conditioning system flow are typical sources of controlled air flow.

Uncontrolled Air Flow

Uncontrolled air flow is any non-designed movement of air into, out of, or within a building. This can be caused either by wind, by the force of heated air rising within the building, or by out-of-control fans. Leaks in a building's air-distribution system are also uncontrolled air flow.

Limiting Factors to Air Flow

Flow Determinants

The amount of air that flows through a hole is limited by three factors:

- The effective hole size
- The magnitude of pressure across the hole
- The amount of time the pressure is present

Pressure Effects

Air always flows from a high-pressure area to a low-pressure area, much like water running downhill. Therefore, without an effective barrier, air outside a home at a higher pressure will always attempt to enter the home. Similarly, inside air at a high pressure with reference to the outside will always attempt to exit the house.

Path of Least Resistance

The nature of air flow always seeks the path of least resistance. Given several choices of openings for entering or exiting a building, the air will move through the largest hole that offers the least resistance.

One Cubic Foot In = One Cubic Foot Out

Generally speaking, for every portion of air that enters a house, an equal amount of air must also exit the building, and vice versa. One example of this rule is the clothes dryer: if a dryer exhausts 200 cubic feet per minute (CFM) of air out of a building, then 200 CFM must enter the building to replace the air exhausted. In such a situation, applied building science asks the question: "Where is this make-up air entering the building, and what are its effects?"

Measuring Pressure

One way to measure very small pressures is in units called Pascals. There is about 1 Pascal of pressure exerted on a piece of bread by a pat of butter. Since a Pascal is a very small amount of pressure, it requires a precise pressure gauge to measure it. These pressure differences are generally measured across boundaries and barriers. For example, measuring the pressure difference across a building's exterior wall determines the pressure inside the house with reference to the air pressure outside. A common reason for measuring pressure is to assure that combustion devices are operating properly.

Air Pressure Causes

Pressure differences across holes, boundaries, and barriers within a building are caused by one of three forces: *wind*, *heat*, or *fans*.

Wind

Wind blowing against a building can cause large pressure differences between one side of the building and the other, depending upon both the speed and direction of the wind. On the windward side of a building, the wind causes a positive pressure to build against the outside, causing air to enter the building. On the leeward side of a building, a negative pressure difference develops with reference to the inside of the building, and air exits the building through holes and other leak sites.

The effect that wind has on a building depends on four factors:

- The number and size of holes in the building
- Where the holes are located
- The amount of time the wind blows on average (e.g., buildings located in open plains, atop mountains, or near large bodies of water are subjected to wind blowing for longer periods of time than other buildings)
- The amount of shielding present, such as from trees, hills, and other buildings

Heat

Pressure is also caused by the buoyancy of hot air, which naturally attempts to rise to the top of a building. This is called stack pressure.

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The magnitude of this pressure depends on the temperature difference between the inside and outside of the building, as well as the height of the building. If the building height or temperature difference doubles, then the stack pressure doubles as well. Generally speaking, the upper regions of a building are at a positive pressure with reference to the outside, and the lower regions are at a negative pressure with reference to the outside.

Neutral Pressure Plane

Both positive and negative pressure zones can exist in the same building at the same time, with a zone of neutral pressure between them. This area between the two pressure zones is known as the neutral pressure plane. Air neither moves in nor out of the house at the neutral plane; on the lower side of the plane, air is being drawn into the home and on the upper side, air is being forced out. Since no air moves at the neutral pressure plane, the greatest amounts of air infiltration or exfiltration occur at those points in the house farthest away from the plane.

Fans

Fans (particularly exhaust fans and HVAC air handlers) can contribute to pressures changes in several different ways. Under ideal design conditions, neither should have a negative effect on building leakage. Unfortunately, leakage in the building envelope or the ducting, or an imbalance in the supply and return ducts can cause these fans to have a drastic effect. While natural forces (wind and stack) produce between one and ten Pascals of pressure on residential buildings, fans can produce as high as 60 Pascals of pressure.

Exhaust Fans

Exhaust fans (bathroom, kitchen, and laundry exhaust fans, cooktop fans, dryers, and central vacuum systems) draw air from the living area of the house. This air must be replaced by air drawn in from the outside. Without proper design, these fans frequently compete with fireplaces, gas-fired water heaters, furnaces, boilers, and other combustion devices for the air inside a building.

HVAC Fans

Heating, ventilation, and air conditioning (HVAC) systems that allow air leakage can produce pressure differences across the shell of buildings. If duct leakage exists, it will be exacerbated by HVAC fans. There are two types of duct system leakage: duct leakage to the outdoors and duct leakage to the inside of the building. Duct system leakage to the inside or outside of the home, through either the supply or return ducts, can have serious consequences.

Duct Leakage to the Outside

Duct systems that leak to the outside of the building on both the supply and return sides of the system can cause infiltration rates to increase by as much as 300%. As noted earlier, every cubic foot of air lost to the outside through duct leakage must be replaced. Caught in a vicious cycle, air lost from the ducts must be replaced by outside air drawn in through leaks in the building shell. Unfortunately, most duct leakage occurs when the weather is at its worst – during the peak of summer and winter, when energy efficiency and comfort are in greatest demand.

Supply-side leakage to the outside can cause a negative pressure difference in the building with reference to outside. Return-side leakage, on the other hand, can cause a positive pressure difference in the building with reference to the outside. On average, such leakage can cause a 10% to 20% increase in heating and cooling energy use, along with a 20% to 50% decrease in heating and cooling equipment efficiency.

Duct system leakage to the interior of a building doesn't cause large increases in energy use or decreases in equipment efficiency. Supply leakage to an interior portion of a building, such as ducts located between floors, walls, closets, and basements, can pressurize a small, localized area, causing the rest of the building to depressurize in response. Similarly, return leakage can depressurize the area where it is located, causing the rest of the building to pressurize. Duct leakage to the inside of a building is more a source of comfort and health and safety problems than a cause for infiltration.

Return leakage where combustion appliances are located (basements, equipment rooms, and closets) has been found to cause spillage, backdrafting, carbon monoxide production, and flame roll-out resulting in fire. The importance of this fact cannot be overstated.

Air Flow Imbalance

An imbalance of air flow across interior or exterior walls, ceilings, and floors can also cause pressure differences. Imbalanced air flow can occur if the supply and return to an area are not equal or if closed interior doors block the supply and return paths.

Imbalanced Supply and Return

Imbalanced flow often occurs when a room has more supply air delivered than is removed by the return, allowing the room to pressurize. This can lead to air leaking out through the walls of the room or traveling into the attic or crawlspace. Similarly, if the return flow from a room is larger than the supply flow, the room can depressurize, drawing air in from outside.

Interior door closure

Buildings that have central return systems can experience large pressure differences when certain interior doors are closed. This HVAC design delivers air to each room, but does not have a return in each room. When a door is closed it becomes a barrier between the return – located in the main body of the house – and the supply air delivered to the closed room. The return attempts to draw this missing air from the rest of the house, depressurizing the main body of the home and possibly causing backdrafting problems with any fireplaces, wood stoves, or other combustion appliances.

Likewise, without any local returns, the closed rooms become pressurized, driving warm, moist, interior air into the walls and ceilings, possibly leading to mold growth and even rot in the structural assemblies.

In both cases, the magnitude of these pressure differences depends on the tightness of the rooms with reference to the main body of the house and to the outside, as well as the amount of air supplied to each room.

Holes and Pathways

As explained earlier, in order to have uncontrolled air flow (infiltration) into a building, holes must exist in the building's shell. Reduce the number of holes in the building, and you reduce the amount of uncontrolled air flow.

There are only two kinds of holes in buildings: undesigned holes and designed holes. Designed holes, as the name implies, are those necessary to allow the proper flow of air, such as vents and chimneys. Undesigned holes, though, allow uncontrolled air leakage and rob a home of its efficiency and healthy environment.

Undesigned Holes

Undesigned holes in the home are found in the attic, walls, and floors. Any of these holes that connect to the outdoors should be adequately blocked, caulked, gasketed, or otherwise adequately sealed.

Sometimes these holes are connected to floor, wall or ceiling cavities, or to spaces under bathtubs and stairs, around chimneys, above cabinets, etc. These spaces become pathways for air to move between the inside and outside of the building.

For example, air can leak into the space between the first-floor ceiling and the second-floor floor if the band joist isn't sealed. That air, and any moisture it's carrying, can then flow freely through recessed light fixtures, dropped ceilings over cabinets, etc., and cause serious moisture and comfort problems.

Undesigned holes should be air-sealed and blocked to control the potential spread of draft, smoke, and fire.

Designed Holes

Designed holes include any hole or system that is designed to have air passing through it in a specific direction. Designed holes should not be blocked, sealed, restricted, or have their direction of flow reversed. Examples of such holes include flues and combustion vents, chimneys, make-up fans, exhaust fans, dryer vents, cooktop fans, ventilation systems, central vacuums, windows and doors, and fresh air inlets/outlets.

When examining air flow into and out of a building, applied building science addresses three areas of concern: effects on the occupants, effects on the durability and structural integrity of the building, and effects on the energy efficiency of the building.

Effects of Air Flow

Effects of Air Flow on Occupants

Improper air flow can have severe effects on the health and safety of the people in the building by promoting mold growth, spreading pollutants, and possibly creating backdrafting of combustion appliances.

Combustion

Negative pressure can cause backdrafting and prolonged spillage from fireplaces, gas-fired water heaters, furnaces, boilers, or any other device that uses house air for combustion. It can also cause flame roll-out from the bottom of residential water heaters and increased carbon monoxide production in both water heaters and furnaces.

Moisture/Mold

During the summer months, negative pressures inside the home can draw in warm moist air from outside. When this moist air comes in contact with surfaces that are below the dew-point temperature, condensation often forms, providing an excellent breeding ground for mildew and other molds, which are known respiratory irritants. The same is true during the winter if the house is pressurized, driving moisture-laden air out of the building.

Pollutants

The air in a home often contains many pollutants, such as smoke, pollen, dust mites, animal dander, radon, and fumes from cleaning supplies. Particulate pollutants and volatile organic compounds (VOCs) are drawn from one area of the home to another by undesigned air flow. Soil gases (such as radon) can be drawn up from the crawlspace or basement in to the building by negative pressures. Combustion devices and fireplaces can backdraft, causing carbon monoxide gases to enter the home.

Comfort

The actual movement of air within a building can often affect the occupants' comfort. During the winter, movement of cooler air currents is often perceived as unwelcome "drafts." During the summer, however, air movement over exposed skin enhances evaporation, making occupants feel both cooler and dryer. This air movement can be caused by either convection currents or by mechanical means.

Convection Currents

Air naturally rises when heated and falls when cooled; such movements are known as convection currents. These currents can occur whenever air in a building is heated or cooled in an uncontrolled fashion by improperly-insulated surfaces (i.e., poorly insulated walls, single-pane windows). The result is often that the occupants feel "drafts" and are uncomfortable.

Convection currents can also occur within building cavities found in the building. Examples of this situation are:

- A cavity is tight to the inside of the building but leaky to the exterior. This allows the air inside the cavity to be heated or cooled through its contact to the outside, leading to convection currents.
- A cavity is tight to the interior of the building and to the outdoors, but gaps exist between the insulation and the exterior surfaces of the cavity, allowing convection currents to circulate.
- A cavity is leaky to both the inside and the outside of the building and the air is heated in the cavity. This allows air to leak in to the cavity in either direction where it is heated; it then develops convection currents. This worst-case scenario allows direct leakage of outside air to the inside, and vice versa.

Mechanical Forces

Forced-air heating and cooling equipment is designed to move specific quantities of conditioned air throughout a building. If the air moves too quickly, it can have a noticeable cooling effect on the occupants. This is a cause for discomfort during the winter months, bringing complaints of "drafts," but can actually increase occupant comfort during the summer. Proper design of HVAC equipment and ducts and proper orientation of the duct registers can help to reduce this effect.

Effects of Air Flow on Building Durability

Improper air flow can draw in moist air from outside, or force moist interior air out into the walls, ceilings, and other structural assemblies. In either case, this air-transported moisture can have serious effects on the durability of a building.

Condensation forms when air with a high relative humidity (RH) (either indoors or outdoors) comes in contact with surfaces that are below the dew-point temperature. Whether it be interior window sills or hidden structural assemblies, once wood absorbs 30% of its weight in water it can begin to rot. The most effective approach to reducing air-transported moisture is to seal the building tightly against air infiltration or exfiltration. This keeps damp outside air outside and allows the building's ventilation and air-conditioning system to remove excess moisture from the air inside the building.

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Effects of Air Flow on Energy Efficiency

Unwanted air flow can reduce the energy efficiency of a building, even if the building is tightly sealed to the outside. The following examples demonstrate this effect for both air flow that increases a building's air-change rate, and air flow that does not.

Air Flow that Increases Building Air-Change Rates

When heating and cooling equipment is initially sized for a building, the heat load calculations assume some natural infiltration rate (uncontrolled air flow). A higher infiltration rate means a lower overall efficiency for the building. Infiltration rates and subsequent efficiency loss can be affected by both natural and mechanical air movements.

Natural Air Flow that Increases Building Air-Change Rates

The forces of wind and stack cause a certain amount of air infiltration in most buildings. In older buildings an amount equal to the entire volume of the house may enter and exit every hour. This is called one air change per hour (ACH). Some newly built homes may suffer only 0.25 ACH or less. The effect of both wind and stack can be reduced by tightly sealing all undesigned holes in the shell of the building.

Mechanical Air Flow that Increases Building Air-Change Rates

HVAC fans and other mechanically-driven forces can have a much greater effect on a building's air-change rate than natural forces. Research has found duct leakage and imbalance can increase infiltration rates by as much as 300%. Mechanical infiltration can also cause air to pass through the thermal boundary of the building. Uncontrolled air infiltration caused by mechanical systems can be controlled by air-sealing any holes in the air-distribution systems, and properly balancing the air flow and pressure throughout the building.

Air Flow that Does Not Increase Building Air Change Rates

Convection currents inside some cavities are an example of air flow that can reduce the overall energy efficiency of a building system, even though it does not increase infiltration or air-change rates.

Air Flow in Building Cavities

Even cavities that are airtight with respect to the outside can affect the energy efficiency of a building. These normally conditioned spaces (such as hall closets), if open to the interior of the house but not receiving air from the HVAC system, become a potential heat (or cooling) sink. For example, if the interior walls or a dropped ceiling are open to the attic space, then as the air inside these spaces becomes heated, it will rise to fill the attic as well. This expands the volume of the building's conditioned space to include the area in the attic, increasing the building's energy demands and possibly reducing comfort levels as well. The HVAC equipment must then work overtime to heat or cool space that no one occupies. In such a situation, the building may be very tight according to a blower door test but still have unusually high energy use. The obvious solution to such problems is to ensure that all potential air pathways are sealed tightly against the building's interior as well as exterior.

Thermal Bypass

Any conditioned air that is able to pass through or around insulation into an unconditioned area lowers the energy efficiency of a building. Such efficiency loss is referred to as thermal bypass. To prevent this type of loss, buildings should be tightly air-sealed and all insulation installed directly against the adjacent air barrier, allowing no unintentional air spaces.

HEAT FLOW

In a typical home, a large portion of all energy consumed is spent on heating and cooling. Air leakage and too little or improperly-installed insulation accounts for a large portion of this. A good thermal boundary, which includes insulation, windows, and doors, not only reduces energy waste but greatly increases an occupant's comfort.

This section examines the basics of heat flow and heat loss, including:

- Basics of heat flow
- Heat loss calculations
- Common insulation mistakes
- Effects of heat flow

Basics Of Heat Flow

Heat flow can occur through three mechanisms: conduction, convection, and radiation. The principles of applied building science consider how each type of heat flow can affect buildings, equipment, and occupants.

Conduction

When two surfaces at different temperatures are in direct contact, heat will naturally flow from the warmer material to the cooler, until a balance is reached. The rate at which this heat transfer occurs depends on the temperature difference between the two surfaces and on the thermal resistance (R-value) of the material.

Convection

Warm air naturally rises within a space, and colder air falls. These movements of warm and cold air are known as convection currents, which sometimes move in circles called convective loops.

Radiation

Warm objects give off waves of heat, which can travel across an open space and be absorbed by cooler objects. The most common example of this is the sun, which radiates heat across space to warm the Earth. Even our own bodies radiate a certain amount of heat.

Typical insulation materials do not reduce radiation heat loss unless they contain a radiant barrier (such as reflective foil).

BTU

Heat is frequently measured in British Thermal Units (BTU). One BTU is equal to the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. A single burning match gives off approximately one BTU of heat.

U Factor

How quickly heat flows through a material is called the material's U-Factor. Technically, the U-Factor is the number of BTUs of heat that will flow through one square foot of the material in one hour for each one degree of temperature difference from one side of the material to the other.

A single pane of glass, for example, has a U-Factor of 1.13. A double pane has a U-Factor of .45. The rate of heat flow through the single pane of glass is more than double that through the double pane.

The higher the U-Factor, the quicker the heat flows.

R-Value

The ability of a material to resist heat flow is measured in R-Value. R-Value is the inverse of U-Factor (R=1/U). The higher the R-Value, the slower the heat flow through the material.

Heat Loss Calculations

Given the R-Value and area of a section of a building envelope, it is possible to calculate the rate of heat loss by conduction (in BTUs per hour) through that section at any given temperature difference. The equation for calculating heat loss is:

Heat Loss = [(Area) x (ΔT)] / R-Value

- Area = the number of square feet
- ΔT = the temperature difference in Fahrenheit between the inside and the outside
- R-Value = the combined R-Values of the entire assembly

Total R-Value Calculations

Heat loss calculations generally assume that the performance of each material is equal to its rated R-Value. If R-13 insulation is used, for example, calculations are made using R-13 for the insulation value. In the field, however, there are often voids, gaps, and compression which change the actual R-Value of the insulation.

Insulation

Insulation prevents heat transfer by trapping pockets of air. Modern insulation products can do an excellent job of preventing heat from passing through a building's walls, ceilings, and floors. Unfortunately, improper installation of these insulating materials can greatly reduce their effectiveness. The four most common mistakes made during insulation installation are gaps, voids, compression of insulation, and misalignment between the insulation and the adjacent air barrier.

Gaps

Gaps are a result of cavities not being adequately filled with insulation. These spaces can allow both conductive and convective heat loss. Wiring, plumbing, and vents can all create gaps unless the insulation installers are careful to ensure complete and full coverage. Inset stapling of insulation batts can allow small gaps on both sides of a wall cavity, where convective air currents can develop.

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Energy Design Update reported that research conducted by the National Research Council of Canada (NRCC) found that small gaps in fiberglass batts installed in a wall can cause as much as 32% loss in R-value at -30º F. They measured an R-value loss of 4.6 (an installed R-value of 14.4) at 23º F.

Voids

Voids are simply areas that have no insulation. Older homes and some warm-weather vacation homes may have little or no insulation installed simply because of a lack of funds or availability of materials.

Compression

Insulation that is compressed has reduced R-value. Insulation should be installed and maintained at the manufacturer's suggested density and thickness to ensure proper heat flow resistance.

Insulation/Air Barrier Misalignment

The insulation and air barrier should be installed at the same location and in contact with each other whenever possible. When they are misaligned due to a faulty air barrier, heated air is able to bypass the insulation. This situation often occurs at dropped ceilings, soffits, shafts, chimney framing, or floor systems.

Many insulation installers mistakenly install insulation over such large, undesigned holes, rather than fastening the insulation directly against the air barrier (gypsum board, flooring, etc.). This creates an air space where convection currents may form and then rise through the insulation into the unconditioned space above.

Pressure Imbalances

Pressure imbalances, both negative and positive, cause air to cross the insulation. This type of thermal bypass reduces the installed R-value. Imbalances are caused by exhaust devices, duct leakage, and interior door closures in houses using central air return. Air-sealing the building and ducts plus pressure-balancing the house helps reduce the imbalance.

Effects Of Heat Flow

Effects of Heat Flow on Occupants

Health and Safety

As noted previously, mold and mildew growth can occur when moisture-laden air comes into contact with cold surfaces. Proper heat flow within a building helps to prevent such localized cold spots. However, during the summer months, improperly-directed cooling vents, leaky ductwork, or an oversized system can allow condensation to form.

Comfort

Comfort is defined in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook of Fundamentals as, "that condition of mind in which satisfaction is expressed with the thermal environment." Basically what that means is that comfort is in the mind of the occupant! No one can tell occupants that they are comfortable; they have to decide it on their own.

Most people would like to have the highest level of comfort possible at the lowest cost. Even the caveman wanted his cave to be warm and toasty without having to go outside too often to find more firewood. It's certainly not an unreasonable desire. And applying the principles of building science will help these occupants find their own levels of comfort at an affordable price.

Most buildings "leak" comfort. Two simple illustrations are a bucket and a boat: you don't want leakage out of your bucket or into your boat. The same is true with both buildings and bodies. In buildings, you don't want leakage of heat to the outdoors when it is cold or heat leakage in during the summer months. Similarly with bodies, allowing too much body heat to escape in winter can leave you chilly (or even frostbitten) and gaining too much heat during the summer can make you miserable.

Effects of Heat Flow on Building Durability

Moisture vapor attempts to move from a warm area to a colder one, where it can more readily condense. When such condensation occurs inside walls and other structural assemblies, actual rotting of the wood can occur (along with degradation of other building materials like plaster board and insulation), as well as mold growth. Undesigned heat flow in buildings, even when caused by solar radiation or otherwise normal heating/cooling scenarios, can draw moisture-rich air into the structural assemblies from either inside or outside the building.

Effects of Heat Flow on Energy Efficiency

When thermal barriers are not properly installed, or air is allowed to pass through insulation, the resulting heat loss or gain can greatly reduce energy efficiency. This heat loss or gain generally occurs under five different situations:

- Compression of insulation
- Voids within the insulation
- Gaps between the insulation and the intended area of coverage
- Convective airflow within insulation
- Air leakage bypassing the thermal boundary

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MOISTURE FLOW

Controlling moisture flow in a building has significant impacts on occupant health and safety, comfort, building durability and energy efficiency. This section will cover the basics of moisture and its effects on the house system. It will also discuss how geographic location and house type can affect choices of moisture control strategies.

Applied building science is concerned with four different moisture transport mechanisms and the effects of that moisture flow:

- Bulk water movement (rain, snow, or groundwater)
- Capillary action (capillarity)
- Air transported moisture
- Vapor diffusion

Bulk Moisture

Bulk moisture movement (or liquid flow) has the potential to be the most damaging moisture transport mechanism confronted by a building. Typically thought of as rain or snow, bulk moisture movement also includes flowing groundwater. Three conditions are required to allow bulk moisture flow into a building:

- A source of water
- A hole in the building envelope
- A driving force such as gravity or air pressure

In most locations, there will be water present during at least part of the year. The keys to controlling that water are to direct it away from the home and to seal any holes that water might come through.

Directing water away from the home is accomplished by proper grading, drainage, gutters, and downspouts. Proper sealing is done by meticulous attention to flashing and caulking details, and door and window installation.

Capillary Action

Capillary action refers to the ability of water to travel up against the pull of gravity through a porous material. One common example of this action is water "wicking" up through a paper towel, following the direction of the paper fibers. Although not as serious as bulk water movement, capillary forces are both powerful and rather secretive, since they often work in the dark of a crawlspace, causing significant damage to a building without the occupant's knowledge.

Opposite to what one might expect, capillary action prefers small holes or pores, rather than larger ones. Large pore sizes, such as those found in some forms of pea gravel and coarse sand, can actually serve to "break" the flow of capillary water. Smaller pores though, such as those found in concrete and brick, provide excellent paths for such wicking action to occur.

Since concrete is commonly used in building foundations, we often see evidence of capillarity in basements and crawlspaces. The concrete footings wick the water up from the ground, where it then travels up the foundation wall. Evidence of capillary action is often seen on many older brick foundations as a white line visible a foot or so above the ground. This white line is caused by a process known as efflorescence, which occurs when water that is drawn up by capillary action evaporates, leaving behind a residue of salts, minerals, and other materials. Plastic sheeting placed in footing holes prior to pouring of concrete can help to prevent groundwater wicking.

Capillary action is also an important issue above-grade. Even two non-porous materials, if placed closely enough together, will provide a channel for capillary action to occur. One common example of this occurs with lapped wood siding. Rain water striking the side of the house will run down the siding to the edge. Capillary forces can then draw the bead of water up and behind the siding, thus wetting the back side of the siding. Obviously, such forms of capillarity can be hard to observe until serious damage has already occurred.

Capillary action can best be controlled by providing a capillary "break" such as plastic, metal, damp-proofing compound or another impermeable material, or by leaving air spaces that are too large for capillarity to occur.

Air-Transported Moisture

Air-transported moisture (in the form of water vapor hitchhiking on air) can leak into, or out of, buildings. As noted earlier, both uncontrolled pressure sources (such as wind or stack effect) and controlled sources (fans and air handlers) can move significant amounts of moist air past a building's envelope through holes. Leaky ductwork can cause moisture problems by not only increasing the amount of infiltration, but by drawing air in from the humid crawlspace or basement areas. As this humid air travels through a building, the moisture in it will condense on any surface whose temperature is below the dew point.

The amount of condensation that forms is dependent upon several factors: inside versus outside temperatures, the relative humidity, and the speed of the air moving across the condensing surface. Colder surfaces (like windows and poorly-insulated walls) condense moisture more easily; slower-moving air allows more time for condensate to form. And obviously, the higher the relative humidity, the more moisture available in the air in the first place.

Decreasing the effects of air-transported moisture also depends on several factors. The best defense is to keep moist, outside air out of the building through effective sealing against infiltration, sealing the ductwork, and pressure-balancing the HVAC system. Proper use of exhaust fans in all bathrooms and kitchens helps to remove moisture-rich indoor air at its source. Preventing cold spots through adequate heating and air movement removes potential sites for condensation.

Vapor Diffusion

Even without leaks, small amounts of moisture in the form of water vapor can pass directly through a building's envelope, through a process called diffusion. Vapor diffusion from a damp or wet basement into the living space can significantly increase the moisture levels inside a home.

The amount of vapor diffusion that occurs in a building is determined by two things: the driving force that pushes it (known as the "vapor pressure differential"), and the permeability of the material the vapor is passing through. Most materials (even glass) are unable to completely stop vapor diffusion; thus, calling something a "vapor barrier" is a bit of a wrong label. The current trend in building science is to refer to materials as "vapor retarders," meaning that while they slow down the movement of water vapor, they do not completely halt the process. Materials that significantly slow down the vapor diffusion process are said to have low permeability, or simply "low-perm." Typical building codes consider a material to be a vapor retarder if it has a perm rating of 1.0 or less.

Vapor retarders are often applied in the crawlspace of a building to prevent ground moisture from evaporating and traveling up into the home. Many building codes require applying such vapor-retarding materials under wall board to prevent vapor diffusion from bringing water into the structural assemblies. In cold climates during the heating season, pressure differential drives the vapor from the inside of the building to the outside. In Minnesota, the vapor barrier is generally installed on the interior face of the wall studs. In warm climates during the cooling season, this vapor drive is from the outside of the building towards the inside – thus, in Miami, vapor retarders are often applied on the outside of buildings. Besides the perm rating of the material, the effectiveness of a vapor retarder is also a function of its surface area. A vapor diffusion retarder that covers 80% of a building is said to be "80% effective."

Effects of Moisture Flow

Effects of Moisture Flow on Occupants

<u>Health and Safety</u>

Moisture is not often thought of in terms of occupant health and safety. Yet indoor air quality professionals consider moisture to be a "pollutant" that can have a significant impact on the occupants' health. Moisture is the key ingredient for mold and bacteria growth. Not only are these fungi odorous, unsightly, and a cause of wood rot, but they can also cause asthma and allergic reactions in many individuals. There are even well-documented cases linking certain airborne fungi to more serious health problems, including cancer, birth defects, immune system suppression and tissue poisoning. Instances of "sick building syndrome" are often related to mold growth in buildings.

Excess moisture (particularly in the air) also provides a favorable environment for dust mites and cockroaches, serious sources for asthma and allergy problems. Though people don't usually react to the creatures themselves (except to maybe scream and reach for a rolled-up magazine), roach and dust mite droppings can cause asthma and allergic reactions in many people. Another unfortunate side-effect of these creatures' presence is that they often bring about increased use of insecticides. Young children in particular can be extremely susceptible to such poisons and can suffer effects such as allergic reactions.

<u>Comfort</u>

Since moisture, in the form of relative humidity, plays such a key role in how we perceive comfort, it is a primary driving force in determining how to operate building systems. According to ASHRAE, the comfort zone for buildings in the winter is between 68° and 75°F at a relative humidity of 30% to 60%. During summer conditions, the comfort range is found between 72º and 78º F at 25% to 60% relative humidity.

Effects of Moisture Flow on Durability

Moisture is a common cause of building degradation. In fact, much of what we know about applied building science today originates from early work investigating moisture impact on buildings. While the severity of moisture problems varies greatly depending on climate, few regions in North America are free from concerns about moisture in buildings.

Moisture can attack a building's durability on many fronts, from wet crawlspaces to leaking roofs. Moisture-rich air can even become trapped in building structural assemblies, possibly leading to mold growth, rot, or insect infestation. Entire industries have developed that specialize in combating these various moisture problems.