Chapter 2

The House as a System

We sometimes think of our homes as independent structures, placed on an attractive lot, and lived in without regard to the world around. Yet, most homes have problems - some minor nuisances, others life-threatening:

- Mold on walls, ceilings, and furnishings
- Mysterious odors
- Excessive heating and cooling bills
- High humidity
- Rooms that are never comfortable
- Decayed structural wood and other materials
- Termite or other pest infestations
- Fireplaces that do not draft properly
- High levels of formaldehyde, radon, or carbon monoxide

These problems occur because of the failure of the home to properly react to the outdoor or indoor environment. The house should be designed to function well amid fluctuating temperatures, moisture levels, and air pressures. Quality builders are concerned about these problems, but are not always certain what steps to take to prevent them. They must start by considering what makes buildings healthy and comfortable.

The following factors define the quality of the living environment. If kept at desirable levels, the house will provide comfort and healthy air quality.

- Moisture levels - often measured as the relative humidity (RH). High humidity causes discomfort and can promote growth of mold and organisms such as dust mites
- Temperature - both dry bulb (that measured by a regular thermometer) and wet bulb, which indicates the amount of moisture in the air. The dry bulb and wet bulb temperatures can be used to find the relative humidity of the air.
- Air quality - the level of pollutants in the air, such as formaldehyde, radon, carbon monoxide, and other detrimental chemicals, as well as organisms such as mold and dust mites. The key determinant of air quality problems is the strength of the source of pollution.
- Air movement - the velocity at which air flows in specific areas of the home. Higher velocities make occupants more comfortable in summer, but less comfortable in winter.
- Structural integrity - the ability of the materials that make up the home to create a long-term barrier between the exterior and inside.

Concepts

Heat Flows in Homes

Heat transfer - heat loss and heat gain - between a home and its exterior envelope has a major impact on health and comfort. Figures 2-1, 2-2, and 2-3 explain the three primary modes of heat transfer.

When building energy efficient homes, many builders focus on reducing conduction heat gain and loss by installing more insulation. However, air leakage and duct leakage are serious contributors to heating and cooling bills. They can also create moisture and indoor air quality problems. Unfortunately, many homes labeled as energy efficient are not sealed for air leaks or duct leaks. In summer, cooling needs are driven by the location and shading of windows. Also, the percentage of the cooling load that is for latent cooling (humidity removal) can increase substantially in homes with well insulated thermal envelopes.

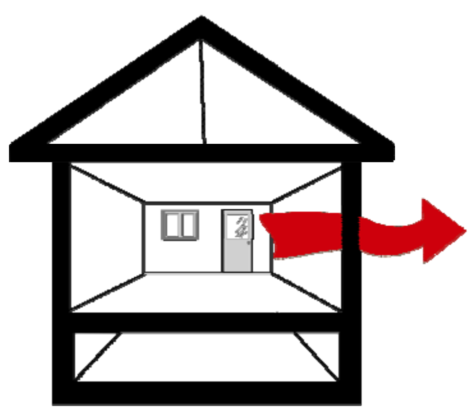
Several general areas contribute significantly to energy bills. The largest is air leaks through the envelope. We expect the walls, floors and ceiling to keep the elements outdoors. There are many penetrations in these that allow air to move into and out of the house. With that air, heat and moisture can enter the house, contributing as much as 30-40% of the energy bill alone. The next greatest loss comes from poorly sealed duct work, which can contribute 10-20% of the typical energy bill. Windows are not as good at resisting energy flow as insulated walls. They let the sun shine in winter and summer. However, in winter, heat radiates out through them as well. Typical single pane windows allow heat to flow in or out 10 times more easily than a good wall and can contribute 10% to the energy bill. Walls and ceilings can easily contribute 15% to the bill. Not all of these losses can be prevented, but they can be managed and optimized.

There are also internal heat and moisture sources from the inhabitants, lighting, cooking, bathing, etc. that are a part of living. These are influenced by lifestyle and the house has limited effect on them. Depending on the family, these items can be from 30-50% of the energy bill. Controlling them efficiently can make a house more comfortable without a great expense.

Conduction

- The transfer of heat through solid objects, such as the ceiling, walls, and floor of the home.
- Insulation and quality windows reduce conduction losses.

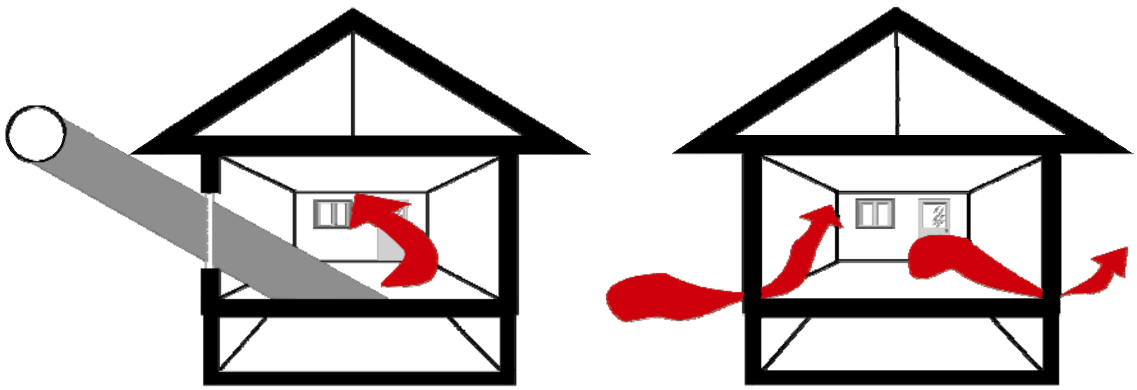
Figure 2-1
Home Losing Heat through Conduction in Winter



Convection

- The flow of heat by currents of air.
- As air becomes heated, it expands until it transfers the heat to an adjacent object which cools it; at which point it contracts and sinks. Inside of a space this forms a cycle of air movement until the walls of the space reach equilibrium with the air temperature.
- The flow of air into a home is known as infiltration; the outward flow is called exfiltration. In this publication, infiltration and exfiltration are known together as air leakage.

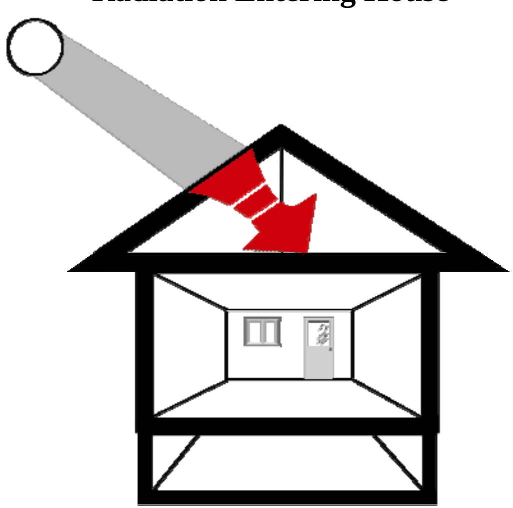
Figure 2-2
Convection in the Home



Radiation

- The movement of energy from warm to cooler objects across empty spaces.
- Examples include radiant heat traveling from inner panes of glass to outer panes in double glazed windows in winter, roof deck to attic insulation during hot, sunny days.
- Can be reduced by installing reflective barriers; examples include radiant heat barriers in attics and low-emissivity coatings for windows.

Figure 2-3
Radiation Entering House



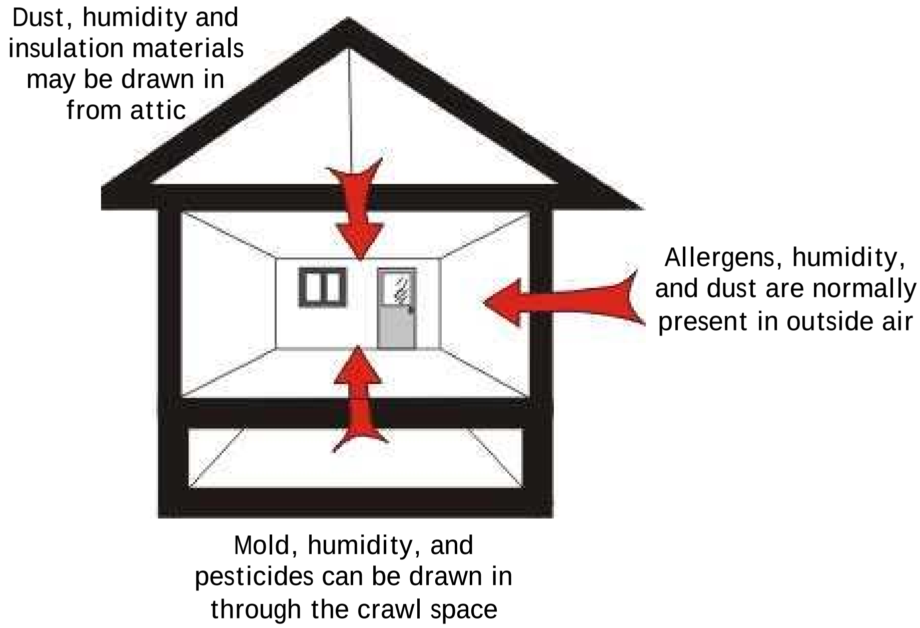
Air Leaks and Indoor Air Quality

Both building professionals and homeowners have concerns about indoor air quality. It is important to understand that few studies on the subject have shown a strong relationship between indoor air quality and the air tightness of a home. In order for a home or any other occupied space to be livable, a certain amount of fresh air exchange must occur continually since the normal process of breathing exchanges oxygen with carbon dioxide which will accumulate unless it is replaced with fresh air. The amount necessary for any inhabited space has been determined to be 0.35 fresh air changes per hour. Building a leaky home may help lessen the intensity of the problem, but will neither eliminate it, nor necessarily create a healthy living situation. Air leaks often bring in air quality problems from outside, such as:

- Mold spores from crawlspaces and outdoors
- Radon, while rare in Louisiana, entering from crawlspaces and under-slab areas
- Water vapor from crawlspaces and outdoor air
- Pollen and other allergens from outdoor air
- Dust and other particles from crawlspaces and attics

The best solution to air quality problems is to build a home as tightly as possible and install an effective ventilation system that can bring in fresh, filtered outside air (not crawlspace or attic air) under the control of the homeowner.

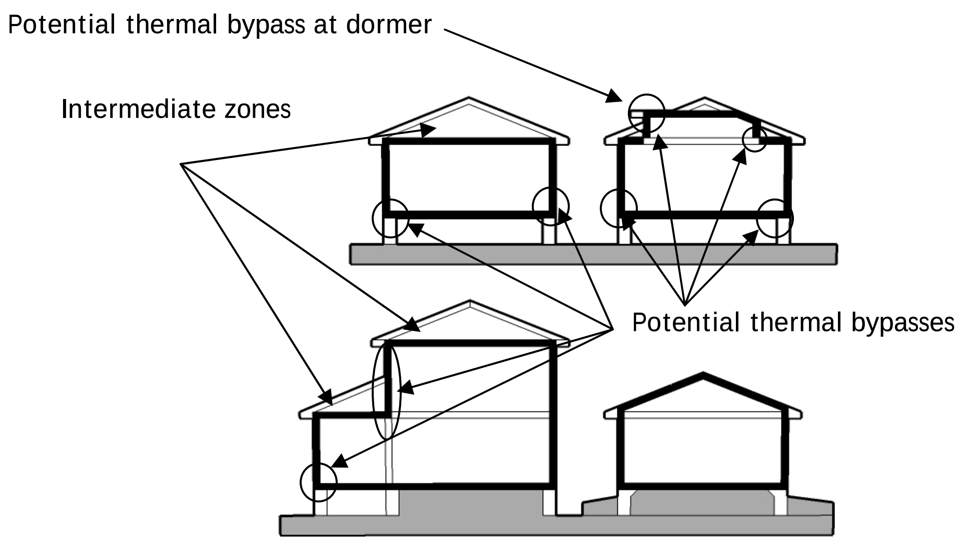
Figure 2-4
Air Quality Problems from "Fresh" Air



Creating Boundaries

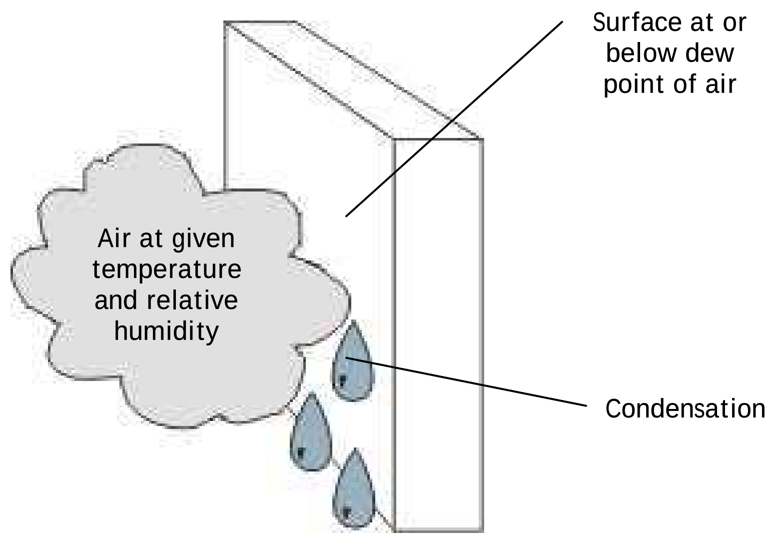
In the field of building science, the term boundary has been applied to an external barrier created to control moisture, air leakage, and thermal conduction losses and gains. Every successful energy efficient home should have a moisture boundary, air leakage (pressure) boundary, and thermal boundary that separate unconditioned areas of the home from areas with heating or cooling.

Figure 2-5
Thermal Boundaries



The designer and builder must direct the subcontractors about how to install continuous air and ductwork sealing materials, insulation, moisture retarders, drainage systems, and other building materials. The air quality and durability of a home depend vitally on how well these boundaries are installed and maintained.

Figure 2-6
Conditions for Condensation



How Condensation Occurs

Air is made up of gases such as oxygen, nitrogen, and water vapor. The amount of water vapor that air can hold is determined by its temperature. Warm air can hold more vapor than cold air. The amount of water vapor in the air is measured by its relative humidity (RH). At 100% RH, water vapor condenses into a liquid. The temperature at which water vapor condenses is its dew point.

$$RH = \frac{\text{The amount of water vapor in the air at a given temperature}}{\text{The maximum amount of water vapor that air can hold at that temperature}}$$

A convenient tool for examining how air, temperature, and moisture interact is the Psychometric Chart. Preventing condensation involves reducing the RH of the air, increasing the temperatures of surfaces exposed to moist air, and blocking the flow of moisture using air barriers and vapor barriers. Builders should always give spaces the ability to shed or reject moisture.

Moisture and Relative Humidity

A psychometric chart aids in understanding the dynamics of moisture control. A simplified chart shown in Figure 2-7 relates temperature and moisture. Note that, at a single temperature, as the amount of moisture increases (moves up the vertical axis) the relative humidity of the air also increases. At the top curve of the chart, the relative humidity reaches 100% - air can hold no additional water vapor at that temperature, called the dew point, so condensation will occur.

Winter Condensation in Walls

In a well built wall, the temperature of the inside surface of the sheathing will depend on the insulating value of the sheathing and the indoor and outdoor temperatures.

Example: When it is 35°F outside and 70°F at 40% relative humidity inside:

- The interior surface of plywood sheathing will be around 39°F.
- The interior surface of insulated sheathing would be 47°F.

The psychometric chart can help predict whether condensation will occur:

1. In Figure 2-8, find the point representing the indoor air conditions.
2. Draw a horizontal line to the 100% RH line.
3. Next, draw a vertical line down from where the horizontal line intersects the 100% RH line.

In the example, condensation would occur if the temperature of the inside surface of the sheathing were at 44°F. Thus, under the temperature conditions in this example, water droplets may form on the plywood sheathing, but not on the insulated sheathing.

Figure 2-7
Psychometric Chart

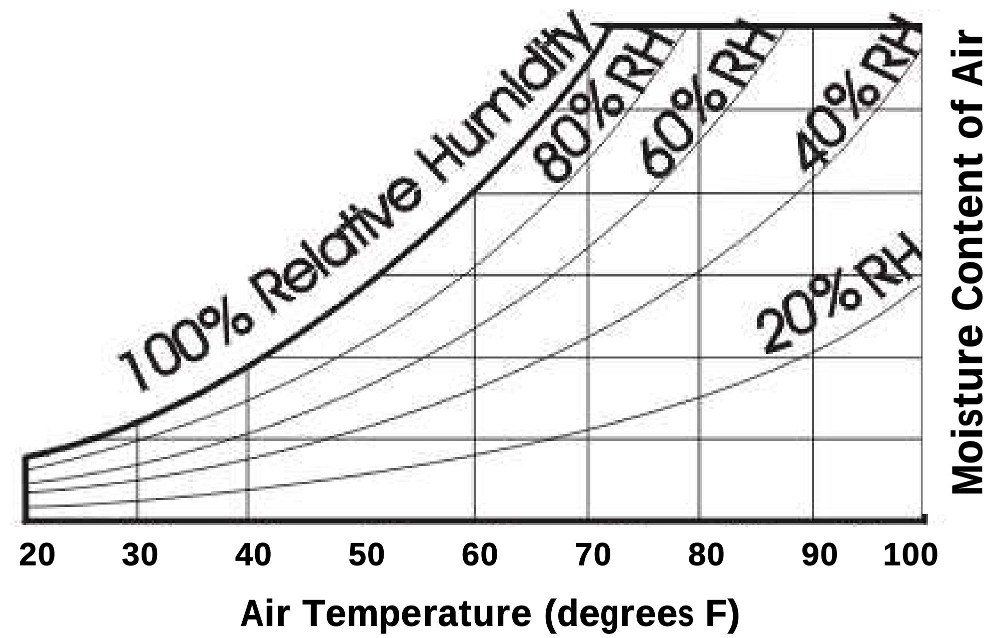


Figure 2-8
Winter Dew Point Temperature Inside Walls

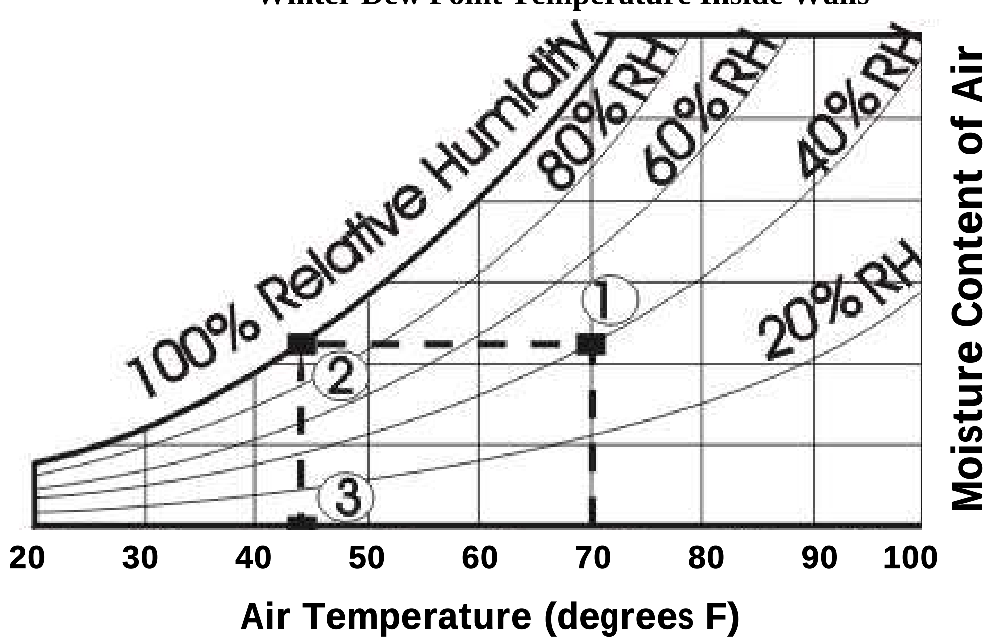


Figure 2-9
Summer Condensation in Walls

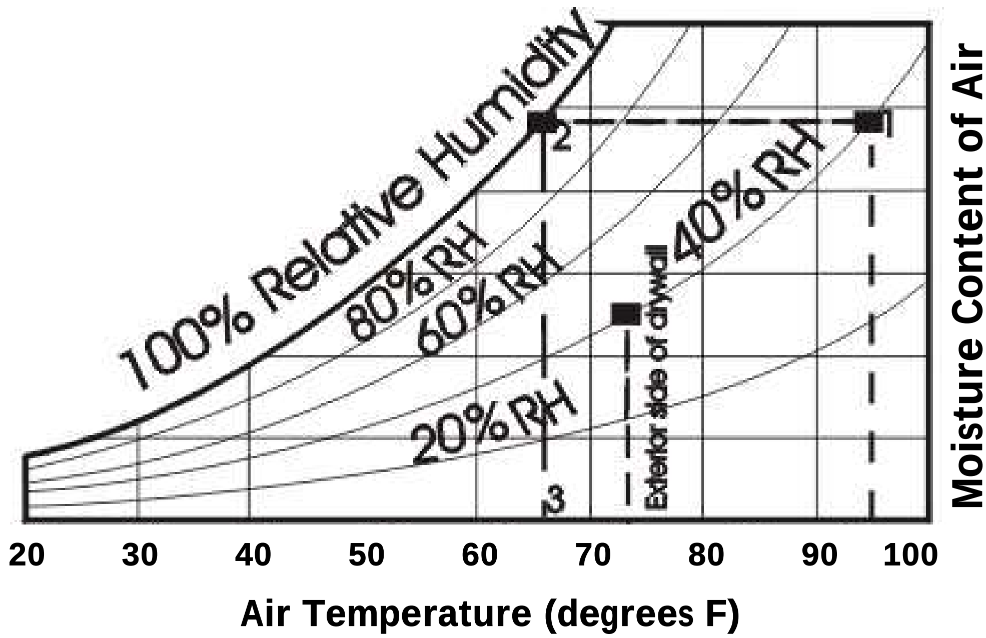


Figure 2-9 depicts a similar case in summer. If the interior air is 75°F, and outside air at 95°F and 40% relative humidity enters the wall cavity, will condensation occur on the exterior side of the drywall, which would be about 73°F? Using the psychometric chart, we find that the dew point of the outside air leaking into the wall cavity would be about 67°F. Since the drywall temperature is greater than the dew point, condensation should not form.

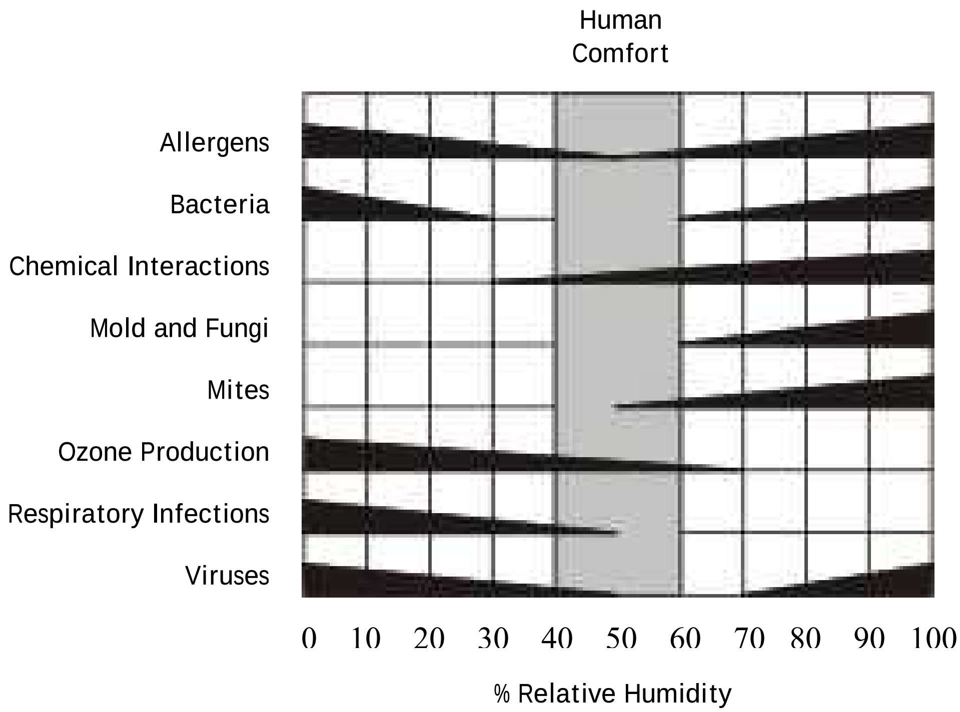
Effect of Relative Humidity

Humans respond dramatically to changes in relative humidity (RH):

- At lower RH, we feel cooler as moisture evaporates more readily from our skin.
- At higher levels, we may feel uncomfortable, especially at temperatures over 78 degrees.
- Dry air can often aggravate respiratory problems.
- Mold and fungi grow in air over 70% RH.
- Dust mites prosper at over 50% RH.
- Wood decays when the RH is near or at 100%.
- Humans are most comfortable at 40% to 60% RH.

Figure 2-10 shows that relative humidity levels in the 40% to 60% range accomplish two major goals: provide human comfort and minimize the many diverse negative impacts that occur in drier and more humid air. By controlling air leakage and properly designing HVAC systems, relative humidity levels should remain at desirable levels.

Figure 2-10
Relative Humidity Ranges



Systems in a Home

Whether the health and comfort factors of temperature, humidity, and air quality remain at comfortable and healthy levels depend on how well the home works as a system. Every home has systems that are intended to provide indoor health and comfort:

- Structural system
- Moisture control system
- Air barrier system
- Thermal insulation system
- Comfort control system

Structural System

The purpose of this book is not to show how to design and build the structural components of a home, but rather to describe how to maintain the integrity of these components. Key problems that can affect the structural integrity of a home include erosion, roof leaks, water absorption into building systems, excessive relative humidity levels, fire, and summer heat buildup.

Structural recommendations

To prevent these structural problems, the home designer and builder should:

- Ensure that the footing is installed level and below the frost line. Use adequate reinforcing and make sure concrete has the proper slump and strength.
- Divert ground water away from the building through a properly designed and installed foundation drainage system and effective gutters, downspouts, and rain water drains.
- Build a quality roof and thorough exterior flashing to prevent rainwater intrusion. Install a "drainage plane" that sheds water outside (Figure 2-12).
- Seal penetrations that allow moisture to enter the building envelope via air leakage. Use fire-stopping sealants to close penetrations that are potential sources of "draft" during a fire.
- Install baffles in attics to prevent air from washing over insulation.
- Install a series of capillary breaks that keep moisture from migrating through foundation systems into wall and attic framing.

Air Barrier System

Air leakage can be detrimental to the long term energy efficiency and durability of homes. It can also cause many other problems, including:

- High humidity in summer and dry air in winter
- Allergy problems
- Radon entry (though not a significant issue in Louisiana) via leaks in the floor system
- Mold growth
- Drafts
- Excessive heating and cooling bills
- Increased damage in case of fire

An air barrier system may sound formidable, but it is actually a simple concept - seal all leaks between conditioned and unconditioned spaces with durable materials. Achieving success can be difficult without diligent efforts, particularly in homes with multiple stories and changing roof lines. Air barriers may also help a home meet local fire codes. One aspect of controlling fires is preventing oxygen from entering a burning area. Most fire codes have requirements to seal air leakage sites. There are a number of air barrier systems - all can be effective with proper installation. They are one of the key features of an energy efficient home. The basic approach is:

- Seal all air leakage sites between conditioned and unconditioned spaces:
  - Caulk or otherwise seal penetrations for plumbing, electrical wiring, and other utilities.
  - Seal junctions between building components, such as bottom plates and band joists between conditioned floors.
  - Consider using insulation that also air seals, such as foam or densely packed cellulose or rock wool.
- Seal bypasses - hidden chases, plenums, or other air spaces through which attic or crawlspace air leaks into the home.
- Install a continuous air barrier system such as the Airtight Drywall Approach or exterior house-wrap that is vapor permeable and sealed properly.

For more detailed information on sealing air leaks, see Chapter 4.

Moisture Control System

Homes should be designed and built to provide comfortable and healthy levels of relative humidity. They should also prevent both liquid water and water vapor from migrating through building components. An effective moisture control system includes quality construction to shed water from the home and its foundation, vapor and air barrier systems that hinder the flow of water vapor, and heating and cooling systems designed to provide comfort all year.

There are four primary modes of moisture migration into our homes. Each of these must be controlled to preserve comfort, health, and building durability.

Bulk moisture transport

- The flow of moisture through holes, cracks, or gaps
- Primary source is rain and groundwater
- Causes include:
    - Poor flashing
    - Inadequate drainage
    - Poor quality weather-stripping or caulking around joints in building exterior (such as windows, doors, and bottom plates)
- To solve, install a building drainage plane:
    - No roof leaks; gutters connected to drain system carry roof water away from foundation
    - Walls built with continuous drainage plane (see Figure 2-12)
    - High quality weather stripping or caulking around joints in building exterior (such as windows, doors, and bottom plates)
    - All openings through wall - for windows, doors, plumbing, lighting, etc. - well flashed and sealed to prevent rain penetration
    - Soil sloped away from home to divert ground water from foundation
    - Foundation wall waterproofed and provided with a drainage system - gravel or a gravity drain membrane
    - Foundation drain, preferably located beside the footing, to carry water away from the house

Figure 2-11
Bulk Moisture Transport

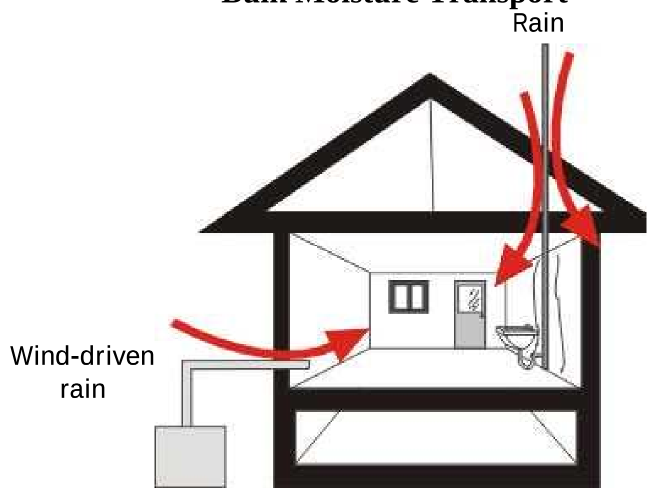
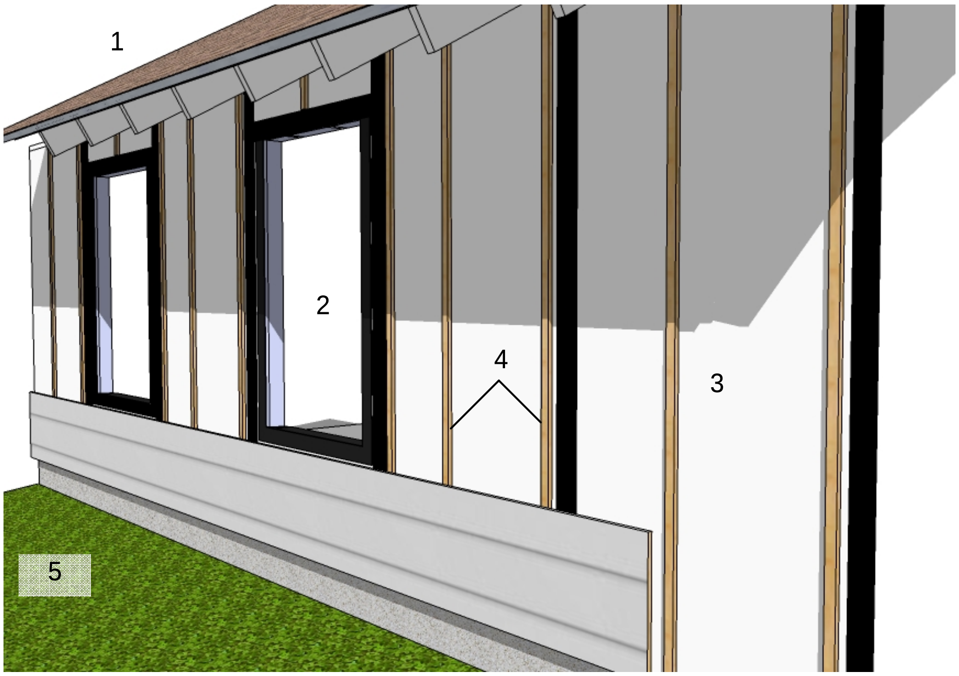


Figure 2-12
Drainage Plane



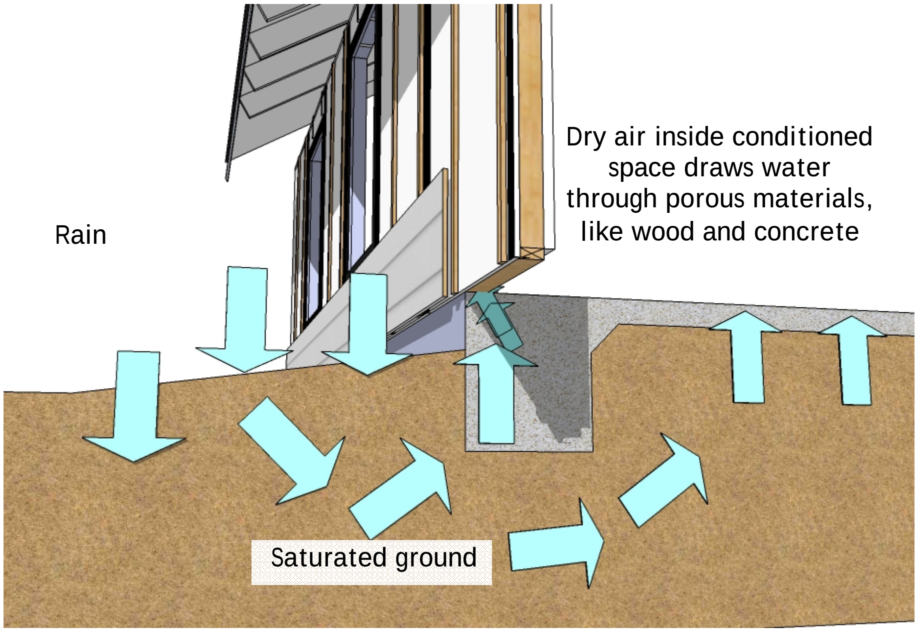
1. Design and build a durable roof with maximum overhang allowable by the International Residential Code, to shade windows.
2. Carefully flash around windows, doors, and other penetrations and seal to drainage plane.
3. Tape or seal joints in foam sheathing or house wrap to prevent water and air penetration.
4. Install furring strips between wall sheathing and siding to create a drainage plane, a ventilating air space that allows water to drain.
5. Provide a finished grade that slopes away from the foundation and a French drain beneath to keep seepage from undermining them.

Capillary action

- Wicking of water through porous materials or through small cracks.
- Primary sources are from rain or ground water.
- Causes include:
  - Water seeping between overlapping pieces of exterior siding
  - Water drawn upward through pores or cracks in concrete slabs
  - Water migrating from crawlspaces into attics through foundation walls and wall framing
- Solved by completely sealing pores or gaps, increasing the size of the drainage planes (usually to a minimum of 1/8 inch), or installing a waterproof, vapor barrier material to form a capillary break.

The foundation system should include a drain pipe surrounded by a gravel bed covered by a filter fabric to prevent dirt from stopping up the drain. In addition, install a layer of 10-mil polyethylene under concrete slabs and footings. Use sill sealer between concrete foundation walls and sill plates. Lapped wood siding should be primed on the back. In addition, the wall system should have an air space behind the siding and a continuous drainage plane behind the air space, such as 30-pound roofing felt installed shingle style.

Figure 2-13
Capillary Action



Air transport

- Unsealed penetrations and joints between conditioned and unconditioned areas allow air containing water vapor to flow into enclosed areas. Air transport can bring 50 to 100 times more moisture into wall cavities than vapor diffusion.
- Primary source is water vapor in air.
- Causes include air leaking through holes, cracks, and other leaks between:
  - Interior air and enclosed wall cavities
  - Interior air and attics
  - Exterior air and interior air, adding humidity to interior air in summer
  - Crawlspaces and interior air
- Solved by creating an Air Barrier System.

Vapor Barriers or Vapor Diffusion Retarders

A vapor barrier or vapor diffusion retarder (VDR) is a material that reduces the rate at which water vapor can move through a material. The older term "vapor barrier" is still used even though it may inaccurately imply that the material stops all of the moisture transfer. Since everything allows some water vapor to diffuse through it to some degree, the term "vapor diffusion retarder" is more accurate.

The ability of a material to retard the diffusion of water vapor is measured by units known as "perms" or permeability. A perm is equal to one grain of water vapor at 73.4°F (23°C) passing through a square foot of material per hour at a differential vapor pressure equal to one inch of mercury (1 grain/square-foot*hour*inch-of-mercury). Any material with a perm rating of less than 1.0 is considered a vapor retarder.

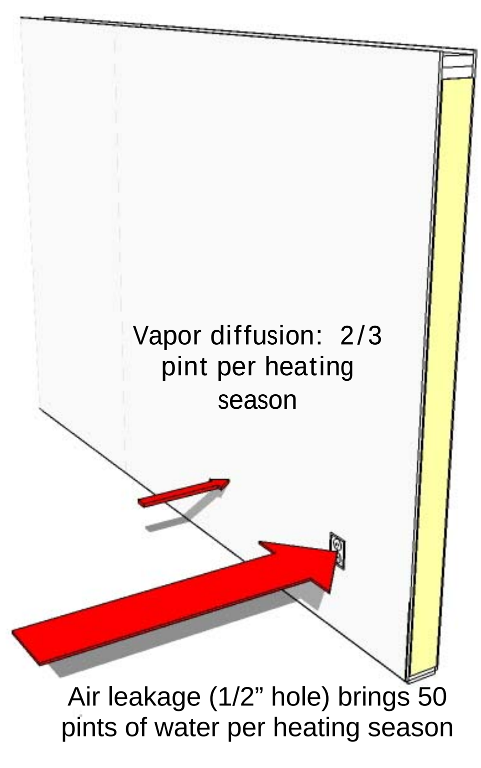
Vapor Diffusion

- Water vapor in air moves through permeable materials.
- Primary source is water vapor in the air.
- Causes:
  - Interior moisture permeating wall and ceiling finish materials
  - Exterior moisture moving into the home in summer
  - Moist crawlspace air migrating into the home
- Solution: proper installation of a vapor retarder.

Vapor barriers are not recommended in Louisiana

Winters are mild so interior vapor barriers are not necessary; exterior sheathing materials usually serve as partial vapor barriers in summer. Wall systems without vapor barriers can dry to the inside of the home in summer and to the outside in winter. An exterior "drainage plane" is required as shown in Figure 2-12 above.

Figure 2-14
Typical Water Vapor Transport
(100 square foot wall)



Moisture Problem Example

The owner of a residence complains that her ceilings are dotted with mildew. On closer examination, an energy auditor finds that the spots are primarily around recessed lamps located close to the exterior walls of the building. What type of moisture problem may be causing the mildew growth, which requires a relative humidity over 70%? In reality, any of the forms of moisture transport could cause the problem:

- Bulk moisture transport - the home may have roof leaks above the recessed lamps.

- Capillary action - the home may have a severe moisture problem in its crawlspace or under a slab. Via capillary action, moisture travels up the slab, into the framing lumber, and all the way into the attic. If the attic air becomes sufficiently moist, it may condense on the surface of the cool roof deck and drip onto the insulation and drywall below.

- Air transport - unsealed recessed lamps are quite leaky; if relatively warm and moist air is leaking into the attic, and the roof deck is cool, the water vapor in the air may condense and drip back down onto the sheetrock. The moisture moves through the gypsum and mold can grow. This is the most likely explanation.

- Vapor diffusion - the home's ceiling may not have an adequate vapor barrier in the vicinity of the recessed lamps, resulting in excessive vapor flow into the attic. Although this situation is highly unlikely in Louisiana, the true cause may be a combination of the above problems.

Figure 2-15
Drying to the Interior

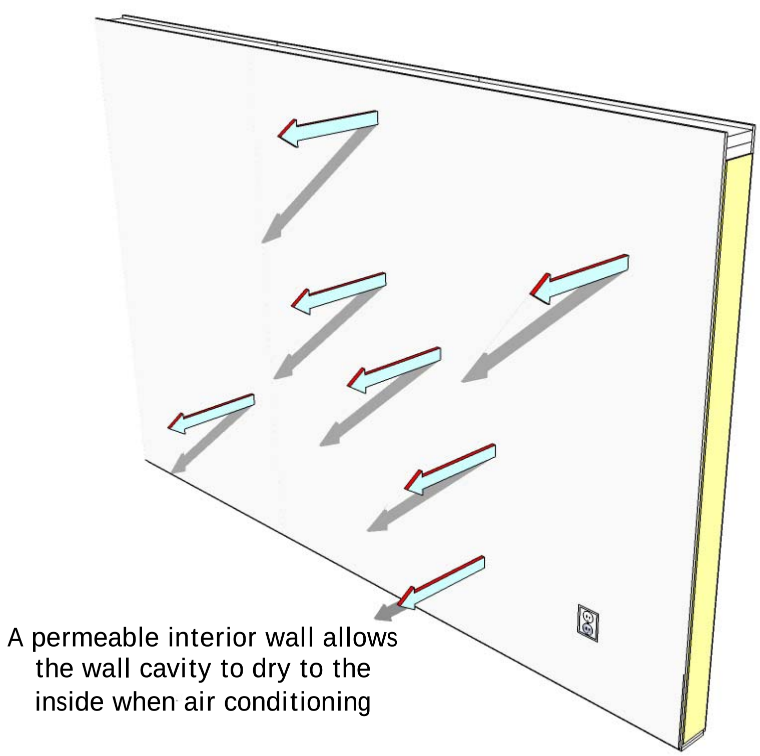


Table 2-1
Building Materials and Their Perm Ratings

Material	Perm Rating*	Vapor Retarder?
½" Gypsum Wallboard	38.0 – 42.0†	No
Latex Primer	7.0 – 10.0†	No
7/16" Oriented Strand Board	0.77 – 3.48††	Sometimes
1" Thick Extruded Polystyrene	0.40 – 1.60††	Sometimes
Kraft Paper Facing	1.0†	Yes
2-mil Polyethylene Film	0.06 – 0.22††	Yes
Alkyd-based or vapor retarder paint	< 0.05††	Yes
1-mil Aluminum Foil Laminate	< 0.05††	Yes
Plywood with exterior glue	0.70	Yes
DuPont™ Tyvek® DrainWrap™	50	No
*grains/[hr·ft2·in.Hg], 7000 grains = 1 pint of water †Tested at Johns Manville Technical Center ††Solplan Review, November 1999 http://www.jm.com/engineered_products/wallcoverings/moisture.pdf		

Thermal Insulation System

Thermal insulation and energy efficient windows are intended to reduce heat loss and gain due to conduction. As with other aspects of energy efficient construction, the key to a successfully insulated home is quality installation. Substandard insulation not only inflates energy bills, but may create comfort and moisture problems. Key considerations for effective insulation include:

- Install R-values equal to or exceeding the International Residential Code of 2006 or the latest update version implemented and presently in effect.
- Do not compress insulation.
- Provide full insulation coverage of the specified R-value; gaps dramatically lower the overall R-value and can create areas subject to condensation.
- Prevent air leakage through insulation - in some insulation materials, R-values decline markedly when subject to cold or hot air leakage.
- Air seal knee walls and other attic wall areas and insulate with a minimum of R-19 insulation.
- Support insulation so that it remains in place, especially in areas where breezes can enter or rodents may reside.
- Consider installing a radiant heat barrier; especially in homes whose roofs receive sunlight in the summer and have less then R-30 insulation.

Comfort Control System

The heating, ventilation, and air conditioning (HVAC) system is designed to provide comfort and improved air quality throughout the year, particularly in winter and summer. Energy efficient homes, especially passive solar designs, can reduce the number of hours during the year when the HVAC systems are needed. These systems are sometimes not well designed or installed to perform as intended. As a consequence, homeowners often suffer higher heating and cooling bills and more areas with discomfort than necessary. Poor HVAC design can also lead to moisture and air quality problems.

One major issue concerning HVAC systems is their ability to create pressure imbalances in the home. Duct leaks can create serious problems. Even closing a few doors can create situations that may endanger human health. Pressure imbalances increase air leakage, which may draw additional moisture into the home. Proper duct design and installation helps prevent pressure imbalances from occurring. HVAC systems must be designed and installed properly, and maintained regularly by qualified professionals to provide continued efficient and healthy operation. See Chapters 7 and 8 for a detailed discussion of this subject area.

Duct Leaks and Infiltration
Forced-air heating and cooling systems should be balanced - the amount of air delivered through the supply ducts should be equal to that drawn through the return ducts. If the two volumes of air are unequal, pressure imbalances may occur in the home, resulting in increased air leakage and possible health and safety problems. For more information on duct sealing, see Chapter 8.

Carbon Monoxide
Consider a home that has been built to airtight specifications - an air barrier system success. However, the home's ductwork was not well sealed - a HVAC system failure. It has more supply leakage than return leakage which creates a strong negative pressure inside the home when the heating and cooling system operates. The home has only a single return in the main living room. With overnight guests in the home, many of the interior doors are kept closed.

When the system operates, the rooms with closed doors become pressurized, while the central living area with the return becomes significantly depressurized. Because the house is very airtight, it is easier for these pressure imbalances to occur. The home has a fireplace without an outside source of combustion air. When the fire in the unit begins to dwindle, the following sequence of events could spell disaster for the household:

- The fire begins to smolder, producing increased carbon monoxide and other harmful pollutants.
- Because the fire's heat dissipates, the draft pressure, which draws gases up the flue, decreases.
- The reduced output of the fire causes the thermostat to turn on the heating system. Due to duct pressures and closed interior doors, the blower creates a relatively high negative pressure in the living room.
- Because of the reduced draft pressure in the fireplace, the negative pressure in the living room causes the chimney to backdraft - the flue gases are drawn back into the home.
- Backdrafting may generate considerable carbon monoxide and cause severe, if not fatal, health consequences for the occupants. This example is extreme, but similar events occur in dozens of Louisiana homes each year. The solution to the problem is to eliminate the causes of pressure imbalances and install an external source of combustion air for the fireplace, a set of tightly fitting doors and a carbon monoxide detector.

Systems are Interdependent
It must be remembered that a house is a complex system of smaller systems. Each of these smaller systems can not only affect the performance of the house in general, but they can also affect the other systems within the house. Understanding these systems will help the homeowner and builder make educated decisions about which systems to use. The following chapters provide more detailed information on these individual systems and their effects.

Notes: