Indoor Moisture: Effects on Structure, Comfort, Energy Consumption, and Health

K.M. Kelly

ABSTRACT

This paper describes the origins of moisture. It shows how to produce, reduce, control, direct, and eliminate moisture in a building. The dynamics of moisture are outlined as related to the use of building materials and design. This paper gives detailed solutions for the cure and prevention of moisture problems, while realizing possible energy savings.

The intent of this work is to improve the quality of life, - not only the life of a building, but also its occupants and owners. For the most part, this paper is a compilation of basic scientific facts joined with scientific findings presented over the years regarding housing, health, humidity, etc., and 30 years of personal experience in solving problems in the field.

INTRODUCTION

> "The final point I want to stress here is the importance of condensation which is also a problem in semi-tropical countries -- and not only a problem in cold countries.-- Architects and engineers have to take into account that this is a common design problem in most countries. Scientists must find the solutions. Teachers must teach about this problem."
>
> M.E. Hoffman
> Technion-Israel Institute of Technology [1]

This paper presents information concerning moisture in buildings and its relation to the design and maintenance of structures. With the recent stress on the conservation of energy, the importance of understanding how moisture works has become vital. Independent interior climates may create immense thermal and vapor stress on the envelopes of buildings as the art of building continues to evolve.

THE BEHAVIOR OF MOISTURE AS IT RELATES TO BUILDINGS AND OCCUPANTS

Moisture Problems

Improper design and careless use of new materials are often the causes of moisture problems in buildings. The evolution of building construction, along with extensive weatherstripping procedures, causes moisture retention previously unknown in buildings. Modern buildings are engineered for less air leakage than those constructed in the past. Historically, houses have been

Kevin Kelly, President, Jay-K Independent Lumber Corporation, New Hartford, New York

built to have from one to two, and more, air changes per hour. Since the energy crunch, homes are being built with from 0.25 to 1.0 air changes each hour.[2] Too few air changes may result in moisture problems and, more importantly, a lack of fresh air. On the other hand, absence of moisture problems may be evidence of too many air changes, resulting in a major heat loss. Mildew, peeling paint, steam and frost on windows, rotting windowsills and casings, frost on roof boards, icicles, curling floors, curling shingles, leaking roofs, allergies, and many other problems may be the direct result of excessive moisture within the structural envelope (see Appx A).

Understanding how moisture affects comfort and health is an important aspect in the study of moisture in buildings. Knowledge of these problems, and of the interplay of various factors, will help to facilitate the cures.

Sources of Moisture

Moisture comes from living quarters. Plants, fish tanks and bowls, steam from cooking, unvented open flames, i.e., gas stoves, and kerosene heaters, humidifiers, showers and baths, mopped floors, and exhaust fans can promote moisture. Exhaust fans will draw air in through a chimney, bringing smoke, and therefore water,unless an intake vent is supplied, i.e., an open window or door.[3] Uncured fire wood, leaking pipes, occupants, dishwashers, soaking laundry, and soaking dishes contribute to moisture in a home. An average of 1 gallon (3.78 lt) of moisture daily may be added for each inhabitant.[4]

Moisture comes from the cellar. Seven times more water will come through a poor concrete floor or a dirt floor than through a good concrete floor[5], up to per 12 gal per 1000 ft^2 (45.4 lt per $92.9m^2$). Block or poured cellar walls, water in sump holes, cisterns, laundry tubs, clothes dryers, clothes drying on a line, humidifiers, cement blocks saturated with water, uncapped cement blocks, wet cellar walls, defective furnace pipes or furnaces, plugged chimneys, low stack temperatures, (see Appx B), crawl spaces, and rotting wood, (see Appx C), are possible sources of moisture.

Moisture also comes from the attached garage. Wet automobiles, wet clothes, firewood, snow-covered winter toys and equipment, and firewood each add water.

Finally, moisture comes from outdoors. Poor flashing, poor gutters, porous siding, improper grading, underground springs, leaking roofs, improperly installed louvres or vents, as mentioned in Appx D, icicles or ice dams, and warm summer air may all bring water into a building.

Another moisture cause may be rising dampness. Rising dampness is an expression for water appearing at the ground level in buildings.[6] This moisture rises from the ground in masonry construction by capillary action. The solution recommended most often for this phenomenon is to cut a horizontal crack in the exterior of the masonry and caulk it to intercept the capillary action. In many cases, though, rising dampness may not be what it appears to be. On buildings with the heating units above the ground level, the coldest spot in the building is that closest to the floor or the ground. This is where the moisture condenses, and it only appears to be rising dampness. Similarly, rotting wood sills which have never been near water may be deteriorating because of their location in the coldest area of the building.

Knapen tubes, or evacuation tubes, were used in Europe in the thick stone walls to relieve moisture. They were installed from the outside, halfway through the stone wall, slanted so that water gathered in them would drain out. Ironically, those tubes allowed the cold outdoor air to cool the stone in the area of the tube, thereby drawing moisture from inside the building, which condensed on the walls. Knapen tubes work much the same way as louvres or ventilators in the side walls or roof insulation. They allow vapor to leave, but they also cool the walls and encourage condensation and possibly promote mold growth.[7] Serious thought should be given before side wall or roof

roof insulation vents or Knapen tubes are installed.

Moisture is always present in new buildings. New plaster or other masonry, some types of foam insulation, lumber, and other components have high moisture content which may be absorbed into the interior atmosphere of the building.

Why Water Vapor Condenses

Water vapor condenses in the coldest areas of a building, not the wettest; for example, picture a cold milk bottle on a warm summer day. Water condenses on cold window panes, toilet tanks, cellar walls, garages, pipes, ceilings, and in closets. Cooking or bathing may also increase the moisture content of the air, sometimes causing condensation. Moisture also condenses when closed drapes cool window areas and when room temperatures flutuate excessively, i.e., 10°F(5°C), causing the vapor to condense in the coldest areas. When there is a decrease of air circulation, moisture may accumulate.

Vapor Flow

Water vapor flows in a fashion similar to cooking odors. Molecules of vapor equalize themselves rapidly through the whole structure just as the smell of a good stew cooking permeates the whole house. That is why absolute humidity (the amount of water in a given volume of air) will be equalized in all sections of a container or house. However, the relative humidity or rh, (the amount of water in the air compared to what the air at that temperature will hold), can vary from room to room within a house. For example, a living room at 70 F, (21.1 C), 40% rh, has the same absolute humidity as a bedroom at 60 F, (15.5 C), 60% rh, and a cellar at 50 F, (10.0 C), 80% rh; 0.65 pounds (0.297 kg) of water per 1333 cubic feet ($37.75\ cm^2$). The warmer the air, the more water it will hold (see Tab. 2); the colder the room, the higher the rh.

Why Moisture Stays in Buildings

Moisture remains inside because the building has: water-tight siding, closed dampers in the fireplace, closed louvres, inadequate ventilation, asphalt roofing, vapor retarders in the walls and ceiling, vines and shrubs close to the house, a non-porous attic floor such as exterior plywood or wafer board, storm windows, storm doors, closed windows, new insulation, or weatherstripping. Fewer people or pets in the family also mean fewer door openings, and more moisture kept inside. Any reduction of air interchange with the outdoors will cause moisture to stay within the structure.

Seasonal Problems

Water accumulates and is absorbed into the structure of buildings in the summer, fall, and winter because the wood, fabric, and plaster of the building act as a sponge.[8] The cool fall weather decreases the water-holding ability of the air and other components of the house. When the sponge (house) is being squeezed (cooled), water will appear on the windows and other cold areas. A humidifier run during the winter may keep the structure damp enough so there will be little room for additional moisture absorption in other seasons.

Secondary Treatments

There are a number of cosmetic and localized treatments recommended as primary solutions to moisture problems, but these do not necessarily reach the underlying cause. The following treatments are often suggested:

- --Using dehumidifiers and heat exchangers
- --Installing light bulbs or heaters to warm closets
- --Washing mildew off walls and removing moss on roofs
- --Installing exhaust fans
- --Applying aluminum and/or other vapor-retarding paints

--Using insect wire for louvre screens
--Installing ice flashing and/or heat tapes
--Removing gutters
--Installing knapen tubes and/or vents in siding
--Triple-glazing windows
--Removing wet insulation
--Heating cold concrete floors
--Residing the building

Primary Solutions

To cure the problems of excess moisture in a building, the sources of moisture and reasons for the accumulation of water should be eliminated or reduced. Provide openings for attic ventilation of 1-1 1/2 in.^{2} (9.7cm^2) for each square foot (929cm^2) of attic floor space.[9] Balance this ventilation with 50% at the peak of the roof and 50% at the soffit (see Appx D); Make sure the air can circulate and eliminate the vapor retarder in the ceiling or attic insulation.

A temporary cold-weather solution is to open any two windows and storm windows in warm rooms until the water disappears from the other windows. The lumber in an average home weighs 20,000 pounds (9072 kg) dry and 26,000 pounds (11793 kg) wet. Add to this weight the absorbent ability of the furniture, clothing, and bedding for an idea of how much water a home can hold. The cold glass of the open windows will cause vapor from the exiting moisture-laden air to condense until the extra vapor in the house (a possible 2 tons or more) has departed. Although opening windows to reduce moisture sounds like a wasteful measure, Europeans have this air exchange engineered into their building codes. In England, fireplace flues are left open. In Sweden, airtight house windows have air-valve slots in each window that can be regulated to allow air intake but cannot be closed completely.[10] When the level of moisture in the house is lowered, the heating and cooling expense may decrease.[11,12,13] For example, moisture in buildings is given as the cause for 20% higher-than-normal first year heating costs in new masonry buildings in England.[14]

Warm-weather solutions involve the use of air conditioning or dehumidifiers: it is difficult and expensive to remove moisture during warm weather. Given the opportunity, natural forces will dissipate excess water in the fall and winter of the year at no cost to the homeowner.

Mechanical Solutions

There are mechanical solutions that require electricity and air movement to reduce the amount of water vapor in a structure. Air-to-air heat exchangers, although relatively new on the market, recapture 50% to 84% of the heat usually lost in air changes in a residence.[15] They remove indoor air and replace it with outdoor air. These air changers also remove pollutants other than moisture. If the moisture problem is caused from too few air changes, the air-to-air heat exchangers will also provide the fresh air required by the buildings' occupants.

Dehumidifiers will also remove moisture, but not the other pollutants often encountered in buildings with few air changes. Dehumidifiers move air and also cool it to remove the moisture. However, this cooling process results in an added electrical cost unless electricity is also used for heating.

Exhaust fans remove air if intake, such as an open window, is provided; otherwise, their value is questionable.

Cold Weather Indoor Comfort and Moisture

Cold weather thermal comfort has parameters different from warm weather comfort. The determinates of human comfort include: air temperature, air velocity, radiant temperature, and vapor pressure, in that order. Other factors include clothing, activities, floor temperature, and toe-to-head temperature variation. No one is comfortable in a draft or with cold feet. Vapor pressure (humidity) is but a minor aspect of indoor thermal comfort in cold weather.[17] Age, sex, race,[16] adaptation, room color,[17], and noise in the environment have very small, if any, influence.[18]

A person's head is his or her thermostat. Wearing nightcaps in cold bedrooms, and hats in cold weather, will help to control this source of heat loss and discomfort. Wet skin, i.e., just out of the bathtub causes a chilling sensation even in warm, 80°F (26.6°C), 100% rh. This is because water has a very high thermal conductivity--25 times that of air.[19] It carries heat away from damp buildings, clothing and the human body. A few individuals in high humidity homes (55% rh and up) have expressed the same chilling sensation while fully clothed at any temperature up to 80°F, (26.6°C). At comfortable temperatures, the effect of humidity on the feeling of warmth is small and may be neglected at temperatures below 76°F, (28.8°C).[20]

Acceptable Indoor Relative Humidity For Cold Weather

The range of indoor relative humidities acceptable for prevention of steam on windows is also acceptable for most occupants.[21] See Table 1.

A humidity gauge is not necessary. Steam on the warm side of an insulated window, or the warm side of a window with a storm sash, signifies that a house has more than enough relative humidity. In the United States, ASHRAE has set a recommended design condition of 72°F, (22°C) for winter and if humidification is provided, it shall be designed for a maximum rh of 30%.[22]

Residential Health and Moisture

Several important aspects of human health and moisture should be noted because of their relevance to this paper. In all cases, high relative humidity is harmful to the structure; in some cases, it may be harmful to the inhabitants. Mildew, a possible by-product of condensation, may aggravate allergies. The allergic individual will find that pollen allergies are reduced at a rh of under 40%.[23] In damp houses, the allergin count of dust may be higher,[24] while the occurence of dust mites is greater.[25]

If they are not kept clean, the humidifiers used to add moisture can spread harmful bacteria.[26] Although there is little scientific evidence that high relative humidity itself is conducive to respiratory illness, it has been shown to facilitate cross-infection.[27] On the other hand, it has been shown that increased rh may reduce the incidence and duration of the common cold among groups of people in a closed space--such as soldiers in a barracks,[28] and students in a classroom.[29]

Many building products and furnishings contain formaldehyde. In some cases the equilibrium concentration of this compound into the air has been found to increase in direct proportion to the water vapor content of the air.[30] Formaldehyde is found in urea-formaldehyde insulation and many other products. The United States Consumer Product Safety Commission has recently issued a ban on the use of the insulation in certain types of buildings due to consumer complaints regarding toxic effects from the formaldehyde vapors.[31] Air cleaners, disinfectants, and fabrics are other sources of formaldehyde type pollutants.[32] In fact, many household cleaners used in the maintenance of humidifiers contain formaldehyde or other toxic chemicals. Lowering the humidity in a building may decrease the severity of the formaldehyde vapors.

Air Quality

High humidity may signal poor air quality in a building. If a condensation problem persists after the production of water vapor is brought under control, the heating system is checked, and ventilation is installed, the home owner should entertain the possibility that the structure does not have a good supply of fresh air. Opening a window or preferably two in warm rooms is the first solution to this problem.

Increasing Humidity by Natural Methods

To increase humidity by natural methods, study the causes of water retention and the methods of producing water vapor naturally in a building listed in the beginning of this paper. Great care must be exercised when adding water to a building. There should be some consideration given to the balance between the maintenance of the building and the physical comfort of the occupants. Extra care must be taken as the weather becomes colder.

Selectively choose and enact one or two of the following procedures at a time until a satisfactory balance has been achieved: (1) Reduce the indoor to outdoor air exchanges by keeping windows and doors closed. (2) Do not use exhaust fans or central vacuum cleaners. (3) Weatherstrip all windows and doors, calk all spaces where cold air infiltrates into the building (see Fig. 1-4), install air tight storm windows and storm doors. (4) Insulate and install vapor retarders as required. (5) Dry clothes in the house, vent the dryer into the house. (6) Let water sit in sinks and tubs. A pan of water on the floor will give off more water than one on a table.[33] (7) Uncover dirt floors. (8) Shower with a fine spray rather than a heavy spray. (9) Supply outside air to the furnace, stoves and fireplaces.

Energy Savings

The cost of humidifying air is greater than any savings realized from a lowered thermostat,[34] since water is the most difficult substance to heat. It carries a specific heat of 1.0 while that of dry air is 0.25.[35] Four times as much energy is required to heat water as is required to heat dry air. Twice as much energy is required to vaporize water as is required to bring the temperature to 212°F, (100°C), increasing the energy cost further. A custom in hunting camps around the world is to open the doors in the morning when starting the fire, thus enabling the building to warm up much faster because of the low vapor content of the incoming air. Cold air heats more quickly than the damp air already in the building.

Many homes with humidifiers require dehumidifiers to counteract moisture problems caused by wintertime humidification. Both humidification and dehumidification use costly energy. There is reason to believe that decreased humidity levels may result in decreased heating and cooling costs.[36,37,38] Low relative humidity may also result in savings on building maintenance and may possibly prolong the life of roofing, siding, paint, and windows.

BACKGROUND ON THE BEHAVIOR OF MOISTURE AS IT RELATES TO BUILDINGS

The following pages give a more detailed description of the interplay among building components.

Since World War II, sheet aluminum has been widely used for roofing and siding. During the late 1940's many ice rinks were built in Canada for the old Scottish sport of curling, which requires a perfect ice surface. The buildings erected with aluminum roofing had a basic defect: moisture from the ice would rise, condense on the cold aluminum surface, freeze, then melt when it warmed, causing bumps on the ice surface.

An engineer from the National Research Council, Division of Building Research identified the problem and suggested the solution. His idea was to build a thin masonry wall on the north (cold) side of the building, designing this to be a "condensate wall".[39] At the same time, the ceiling was insulated, thus warming it. A trough to carry off water was built at the base of the masonry wall, which became the coldest area of the building. Every house has its "condensate wall". This may be window, ceiling, closet, or cellar walls.

Landslides occur every spring in the stone banks along highways, and in the mountains. Water within the stone freezes and expands 9%, with a force of up to 138 tons (135 metric tons) per 1 in.^{2} (6.5cm^2) forcing the stone apart. Nature has many destructive forces, and water, in each of its three forms, is among the greatest. When vapor condenses and freezes on the underside of a slate roof it will have the same destructive effect within the slate as it has upon the rocks in stone banks and mountains.

It is not unusual to hear people complain that their slate or asphalt roofs have deteriorated, or are growing moss on one side only. It has been found that the deterioration occurs most often on the north, or condensate wall side, because it is the coldest area. However, uneven breakdown does not always occur. Those buildings with adequately ventilated roofs usually have no problems, nor do heated buildings without insulation, because there is little or no freezing.

Evolution in the art of building occurs when simple changes are made in construction methods or materials. Insulation of an attic floor without the addition of ventilation may be the beginning of the end of a sound slate roof. Condensation will occur on the cold side followed by gradual deterioration of that part of the roof; condensation on copper roofs with soldered joints may cause electrolysis. Upon reroofing this one side with asphalt, or less conductive roofing, the coldest area will still be the condensate wall. This may be the remaining old roof (on the other side), which may cause it to deteriorate within a few years. These problems also occur in roofs with asphalt roofing.

Re-siding one side of a house to mask paint peeling problems may also warm the condensate wall, causing another wall to become the condenser, and possibly extending the problems to the other wall. In many platform-framed, insulated buildings the condensate wall is on the lee side of the house.

In the early 1940's Texas A & M University conducted an experiment to find the cause of moisture between the prime window and the storm window on the second story of homes. They concluded that wind carried cold air with a low-vapor-content against this side (see Tab. 2), which forced this dry air into the building. No condensation appeared until the wind crossed over the building, creating a negative air pressure or partial vacuum on the lee side of the building. This vacuum pulled the heated air with high-vapor content out of the building through cracks around the inner window. In this case, condensation appeared on the inner surface of the storm window because it was the first cold object the moist air contacted.

This experiment was sound but did not go far enough. If there is vapor evident at the window areas, it follows that there might also be vapor on or within most of the lee side of the building that can cause condensation within the roofing, siding, insulation, etc. A negative air pressure may also imply exagerated negative vapor pressure and thermal pressure. This in some cases may magnify potential problems.

A 1977 experiment concluded that 20% of the air loss in a house is through the electrical outlets, i.e., plugs, switches, etc.[40] (see Fig. 1) A negative air pressure on the lee side will draw air through these outlets, causing heat loss, and possibly moisture problems, in siding, insulation, and paint on this side of the structure. Even when the walls are insulated, air can usually pass through the insulation. Fiberglass insulation is used very effectively for furnace filters because air will pass through it comparatively easily, no matter how thick it is. Cellulose and rock-wool insulation also permit air movement. Blown-in foam insulation may shrink, allowing complete air passage on all six sides within a stud cavity.

The slanting rays of the rising and setting sun, reflecting off a snow covered field, may raise the temperature of plastic mouldings and weather stripping on steel entrance doors behind storm doors enough to warp the weather stripping and the moulding.[41] This heat may also vaporize water droplets behind a layer of paint, or in siding and most roofing. Water in asphalt roofing, upon vaporizing, will expand 1,500 times with a force of up to 600 lbs(1 kg) per 1 ft^2 (6 1/2 cm^2).[42] Vaporization may cause the roofing or paint to blow apart. The damage occurring in this case is the same as in the condensate wall although it is caused by evaporation rather than by freezing. To maintain a sound roof, it is advisable to have equalized vapor pressures and temperatures on both sides. Siding finished in a non-filming stain will not have vaporization problems.

One leading laboratory in the United States advocates the use of vapor retarders on the side walls, and also in the ceilings of buildings to control moisture. In the United States, the Federal Housing Authority <u>Minimum Property Standards</u> for Single Family Residences state the necessity for side wall vapor retarders, but do not require ceiling vapor retarders when enough roof ventilation is supplied (See Appx D).[43] Four walls and a ceiling wrapped in a vapor retarder do not control humidity, but merely contain it. Air containing water vapor can still pass through electrical outlets and condense, causing the siding or the paint on it to deteriorate.

Natural control of moicture in a building can be achieved by giving the excess vapor a nondestructive outlet, like the condensate wall in the curling rinks or through the ceiling. FHA specifies twice as much attic ventilation when there is no ceiling vapor retarder. Careful regulation of the production of moisture in a building, along with the removal of ceiling vapor retarders, and the addition of proper ventilation, should be sufficient to control excess moisture in that building. Some people fear that the above procedures will allow the attic insulation to become wet, decreasing its value and possibly causing paint to peel or water spots to appear on the ceiling. Ceiling insulation can become wet if there are holes in the ceiling, such as suspended ceilings, recessed light fixtures, or electrical boxes through which air laden with water vapor can pass. (Fig. 1-4). These problems signify a heat leak as well as a vapor leak.[44]

Air leakage should be eliminated. Vapor retarders slow or stop the passage of water vapor and air from one climate to another. Air retarders slow or stop primarily the passage of air from one climate to another. The separate functions of these two must be recognized. In unventilated side walls of a building there should be no air movement to have effective vapor retarders. If air passes through the electrical outlets, heat and moisture can also pass through, causing damage and possibly negating the value of vapor retarders. An air retarder such as plasterboard will allow moisture to pass through but will retain heated air in the area where it originates.

Although the drying ability of cold winter air is negligible, the volume of air produced by proper ventilation 1.5 cfm/ft^2 (1.5 m^3/m^2)[45,46,47] passing over the top of the insulation will take the moisture away. Many dairy barns, with hay piled high over the cattle areas, will attest to the value of the hay as an insulation, and the cupola above as the moisture remover.

Cutting one or two slashes in a plastic bucket of water will effectively empty the water from the bucket. On the other hand, slashing cuts in a ceiling vapor retarder will not effectively allow vapor to pass through it. Slashing the vapor retarder in the insulation will not do much for a vapor problem because vapor, unlike water, is in the gaseous state. Water vapor in a room is always in motion. Various pressures, i.e., barometric pressure, thermal pressure, and vapor pressure, are continually acting on the air and the vapor to equalize the interior and exterior pressures.[48] Small amounts of vapor will be drawn through a vapor-permeable ceiling and through slashes in the vapor retarder as long as the insulation above remains dry, but not nearly enough to solve a major moisture problem. A vapor retarder in the ceiling can be compared to a piece of glass on the top of a fish bowl; water vapor cannot go through either one. Beads of liquid form on the underside of the glass on the fish bowl. In a building with a ceiling vapor retarder, the beads of water do not appear below, but the vapor remains in the air below, searching for other ways to escape. The vapor retarders should be removed to allow the ventilators above to be completely effective. Needless to say, it is advisable to remove ceiling vapor retarders before adding more insulation to a house.

<u>Comfort</u>

"It's not the heat, it's the humidity." This is a common expression heard on hot, humid summer days. Hot weather comfort is enhanced by reducing humidity, therefore we see the widespread use of air conditioning, which removes water vapor from air as it is cooled. Many publications including the September 1981 <u>Readers Digest</u>, advise the use of high humidity to enhance cold weather <u>comfort and energy</u> savings.[49] For the most part, however, this publicity is based on comfort perception experiments conducted in 1923.[50] The conclusions were declared erroneous by the project director at a later date.[51]

Scientists have been studying moisture and its relation to human comfort for many years. One of the earliest and best known studies was done at Harvard University in 1923 by Dr. C. P. Yaglou.[52] In this test, people walked into rooms heated to various temperatures and humidities and gave immediate impressions as to what they considered most comfortable. These impressions led to the conclusion that higher humidity was preferred by a majority of the subjects. In 1947, after further experiments in comfort, by himself and others, Dr. Yaglou wrote an article stating that the first findings needed more evaluation. He realized that the feelings of discomfort in the room with low relative humidity were related to other conditions of the experiments.[53]

Since 1947 the field of comfort research has been greatly expanded. Physicians, physiologists, psychologists, and mechanical engineers are cooperating to define all factors relating to the physical comfort of individuals in every mode of work, in all the climates of the world. Since the revision of ASHRAE comfort standards in the 1970's, the effect of humidity level on thermal comfort has not been emphasized. The winter heating energy consumption should be lower for the house with lower humidity.[54]

<u>Icicle Control and Energy Savings</u>

Icicles and ice dams form on the edge of a roof because the heat beneath the snow on the roof melts the snow. The source of heat can be either the low angle rays of the sun striking the gable ends of the building or leakage from the heated rooms below by conduction or convection.[55-56] Heating engineers anticipate that up to 50% of a building's heat loss is through air leakage. Ceiling-to-attic air leakage is directly responsible for many icicles. Air, therefore heat, moves through block ceilings, board ceilings, suspended ceilings, and cracks in unsealed board walls. These should always be capped with a subceiling or wall of a solid, airtight, vapor-porous material such as plasterboard. Air also moves through holes for electrical wires, ceiling lights, electrical boxes, stairways, hatch covers (Fig. 1-4) and unsealed cement blocks. Open spaces from the cellar such as spaces around chimneys, laundry chutes and around the side walls in balloon-framed houses can conduct air.

Balloon framing of buildings, invented in 1832 and widely used until the middle of the 20th century, used studs running from the cellar to the attic allowing air to move through the spaces created between them. These spaces should be closed at the top and the bottom with an airtight material. The widespread use of balloon framing has been discontinued because of the fire hazards it created.[57] The use of steel studs may recreate the chimney aspects of balloon framing, in some instances, making them less-than-ideal construction material. Present day envelope houses may also recreate the hazards of balloon framing.

Heat is also lost through the cavities of cement and cinder blocks where airflow permits vertical transfer.[58] Heat enters an attic by convection and/or conduction from the chimney, vent stacks, (Fig. 1-5), exhaust fans, heat ducts and pipes, and exhaust fan ducts.

Each of the previously mentioned sources of heat from the house to the attic must be controlled or eliminated. The roof must be completely ventilated, (See Appx D), to eliminate the heat buildup in the attic. When this is done, snow on the roof will not thaw until the snow on the street melts. Ice dams will not develop. There is a danger, however: closing all of the air leaks in the house may cause a moisture problem or may make an existing problem worse.

CONCLUSION

The previous pages have described some of the changes that can occur when proper thought is not given to the use of materials and design in buildings. The Pantheon, in Rome, Italy, built almost 2000 years ago, has a 28-foot (8.5 meter) hole in the roof. It has supplied this building with enough fresh air to prolong its existence. Wooden churches in northern Scandinavia have survived over 1000 years, possibly because of the permanent ventilation supplied by the steeples. "Materials and structure which in themselves are excellent can, if used in the wrong place, cause damage to the surroundings."[59]

Throughout the centuries there has been a change in building envelope construction materials; animal skins, straw, wood, concrete, stone, asphalt and others. The evolution of building design and materials is more rapid and visible than the evoluton of homo sapiens. A constant international vigil must be kept on the developments in this field to maintain a balance between form and function.

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APPENDIX A

CHECK LIST

Indoor steam and frost on windows and mildew are signs that a building has too much water. Three points regarding this condition have to be addressed.

1. Where does the water come from?

2. How do you stop producing it?

3. How do you eliminate the excess water?

The following are reasons for water to form in a structure: *Because there are:*

Cold areas	Cold pipes
Cold windows	Cold toilet tanks
Cold closets	*Or there are:* pulled drapes,
Cold walls	a yo-yo thermostat,
Cold ceilings	or cooking (spaghetti)

The following are reasons for water to stay in a structure:

Watertight siding
Closed dampers in fireplaces
Closed louvres
Asphalt shingles
Vapor barriers in walls
Vapor barriers in ceilings
Vines and shrubs close to building
Storm windows
Storm doors
Closing air leaks
Closing windows
Closing doors
Losing residents, children, cats and dogs

In the cellar, water comes from:

Cellar walls and floors
Dirt floors
Cracked concrete floors
Water in sump holes
Laundry tubs
Cement blocks, wet cellar walls
Humidifiers
Cisterns
Clothes dryers
Clothes drying on a line
Defective furnace pipes
Defective furnace
Firewood
Rotting wood
Plugged chimney
Crawl space

In the living quarters, water comes from:

Occupants
Plants
Fish tanks
Vaporizers
Showers, baths
Floor mopping
Exhaust fans
Firewood (uncured)
Leaking pipes
New Occupants (babies, retirees)
Unvented open flames
Cooking, gas cooking
Kerosene heaters
Dishwashers
Soaking laundry; dishes

In garages, water comes from:

Wet automobiles, wet clothes, sleds, etc.

Outdoors, water comes from:

Rising dampness
Poor flashing, poor gutters
Porous siding
Improper grading
Leaking roof
Outdoor air in summer
Improperly installed vents

To eliminate water and stop the problems, consider all of the preceeding and do the following:

Ventilate the attic with one inch of ventilation for each one foot of attic floor space, "balanced" ventilation, 50% at the soffit and 50% at the peak.

Remove the vapor barrier in the attic insulation.

A short run solution is to open two windows and storm windows in warm rooms until the water on the other windows disappears.

The heat bill will go down.

Fans, dehumidifiers and heat exchangers remove vapor, but, require constant expense.

APPENDIX B

Furnace and Chimney Moisture Problems

The smoke developed by burning a gallon (liter) of fuel oil or kerosene contains over one gallon (liter) of water. Burning 100 cubic feet (2830 mm^3) of gas develops over 1 gallon (3.79 lt) of water. Wood, paper and all other combustibles produce enough water to put at least one, and up to five, gallons of water into the smoke going up a chimney daily during the heating season.

A low stack temperature may result in water condensing in the chimney and appearing at the base of the chimney. Other problems that may mean an abundance of water are: rusty pipes in the plenum, rust in the pipe from the furnace to the chimney, or rust in the fire box.

A damper which is opened excessively may cool the smoke so much that the draw of the chimney may not be effective. This may cause the by-products of the fire, including H_2O to remain in the structure.

Pilot lights have traditionally kept the fire box warm during the damp summer months. Electronic ignition now will allow condensation in the cold fire box especially when central air conditioning is used. This could hasten the process of rust.

The most common furnace moisture problem is that of a plugged chimney. Any of the above problems can also occur in chimneys for water heaters and fireplaces as well as furnaces. Any fuel that needs a chimney, needs the chimney cleaned occasionally; gas, oil, wood, etc.

APPENDIX C

Rotting Wood, Mold and Mildew

Mold, mildew and rotting are lower forms of plant and animal life, and they give off H_2O when they are alive as do other living things. Mold, decay or rotting of wood is caused by wood-inhabiting fungi. These fungi are parasites which are classified as molds, stains or decay. These parasites have four requirements for development including oxygen. For the most part, wood does not rot under water. A second necessity is a temperature between 50°F (10°C) and 90°F (32.2°C). Below 40°F (4.4°C) and over 90°F (32.2°C) their growth practically stops.

Thirdly, wood must be damp or wet to be damaged by fungi. Wood picks up moisture in equalibrium with the relative humidity of the air around it. High rh air (90%, or more,) or condensation, contribute to the conditions conducive to rotting wood. Drying wood to below 20% moisture content by weight and maintaining a moisture content lower than that should prevent fungi damage.

The sapwood sections of wood supply the fourth ingredient necessary for rot, i.e., food. It provides carbohydrates[60] and lacks the toxic resins and other extractives which may discourage fungi.

The description of absolute humidity defined earlier will give an idea of how there can be condensation in the coldest areas of a building even when there is only a 40% rh in another area of the same building. The condensation in these cases can accumulate to the point of causing rotting (possible structural damage) or mildew (health problems).

APPENDIX D

Ventilation

The Minimum Property Standards published by the Federal Housing Authority of the United States contain the most definitive description of ventilation requirements for housing in the United States. However, due to changes in energy conservation and construction methods there is a need to revise some of these rules.

Table 4-3.1 states ventilation requirements in square feet. This should be changed to square inches so that it matches the markings on manufactured louvres. The formula could require one square inch of free ventilation area for each one square foot of attic floor area, regardless of the use of vapor retarders.[61] In addition, all ventilation should be balanced with 50% at the soffit or lower section of the roof and the other 50% at the apogee or peak of the roof.[62] (Ventilation at two levels has a number of factors in its favor. Air-pressure, thermal bouyancy, i.e., hot air rising, and wind, all tend to move air upward and out. Louvres on the same plane will function best when the wind is blowing in the proper direction.)

A Norwegian study found that flat roofs could be effectively ventilated with ventilator ducts located above the insulation and oriented in the same direction as the prevailing winds.[63] Research in the field of ventilating flat roofs might be encouraged, since there are few current studies on this subject.

In addition, standards should state that all flooring above the insulation (attic floors) must be vapor permeable. A formula for the use of non-permeable flooring could be devised to eliminate future problems.

When calculating ventilation area, caution must be taken when using screen or louvers. See Table 2.

TABLE 1

PROPER HUMIDITY (for a house at $70^{\circ}F$)	PROPER HUMIDITY (for a house at $22^{\circ}C$)
$-20^{\circ}F$ or below not over 15% rh	$-30^{\circ}C$ or below not over 15%rh
$-10^{\circ}F$ to $-30^{\circ}F$ not over 20% rh	$-24^{\circ}C$ to $-20^{\circ}C$ not over 20%rh
$0^{\circ}F$ to $-10^{\circ}F$ not over 25% rh	$-18^{\circ}C$ to $-24^{\circ}C$ not over 25%rh
$10^{\circ}F$ to $0^{\circ}F$ not over 30% rh	$-12^{\circ}C$ to $-18^{\circ}C$ not over 30%rh
$20^{\circ}F$ to $10^{\circ}F$ not over 35% rh	$-6^{\circ}C$ to $-12^{\circ}C$ not over 35%rh
$20^{\circ}F$ and up not over 40% rh	$-6^{\circ}C$ and up not over 40%rh

TABLE 2
Ventilating Areas Increase Required if Louvers and Screening are Used in Crawl Spaces and Attics[64]

Obtructions in ventilators - louvers and screens	To determine total area of ventilators, multiply required net area in square feet
1/4 inch mesh hardware cloth	1
1/8 inch mesh screen	1-1/4
No. 16 mesh insect screen (with or without plain metal louvers)	2
Wood louvers and 1/4 inch mesh hardware cloth	2
Wood louvers and 1/8 inch mesh screen	2-1/4
Wood louvers and No. 16 mesh insect screen	3

Few vapor retarders are completely effective.[66] All ceiling or roof insulation should have an area above it providing fresh moving air to pass over the insulation. All roofing should have a layer of air moving underneath it. This can be accomplished by the proper use of vents and louvres.

TABLE 3

Humidity Table
lb of water per 100 lb of dry air
Kg of water per 100 Kg of dry air

Air Temp.		Relative Humidity Per Cent						
F	C	100	80	60	50	40	30	20
100	37.8	4.3	3.5	2.6	2.2	1.7	1.2	.87
90	32.2	4.1	2.5	1.9	1.6	1.2	.93	.62
80	26.6	2.2	1.8	1.4	1.2	.90	.68	.45
70	21.1	1.6	1.3	1.0	.83	.65	.48	.32
60	15.5	1.05	.85	.65	.54	.42	.32	.21
50	10.0	.78	.62	.47	.39	.31	.23	.15
40	4.4	.53	.42	.33	.27	.21	.16	.11
30	-1.1	.35	.28	.22	.18	.14	.10	.07
20	-6.7	.24	.19	.15	.12	.09	.07	.05
10	-12.2	.17	.13	.10	.09	.07	.05	.03
0	-17.8	.11	.09	.07	.06	.04	.03	.02

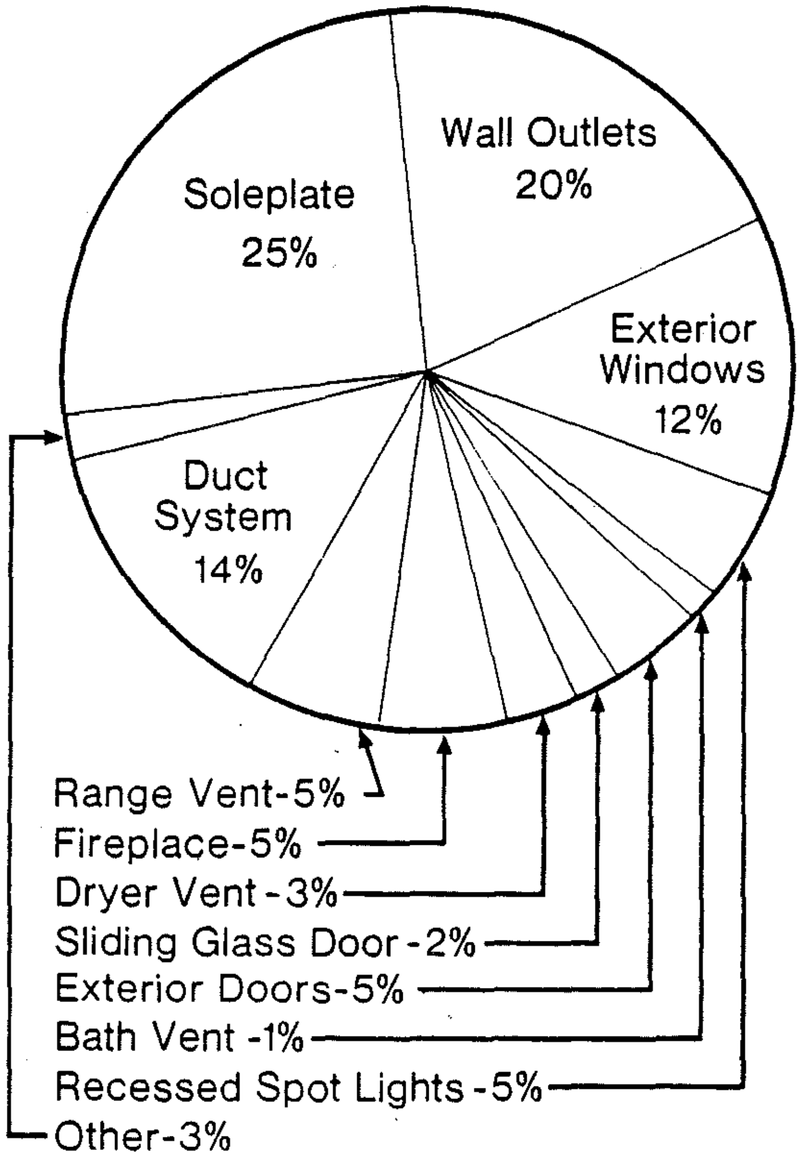
EXAMPLE:

For 85%rh it can be seen that air at 70^{o}F (21.1^{o}C) can hold 6 1/2 times more water as at 20^{o}F (-6.7^{o}C).

100 pounds (45.36kg) of dry air equals 1,333 ft^{3} (37750mm^{3}) of dry air at 70^{o}F (21.1^{o}C), 29.95 (Hg) barometer. This is equal to the amount of air in a room 11ft (3.35m) wide, 16ft (4.88m) long, and 8ft (2.44m) high.

Cold air holds less moisture (absolute humidity) than warm air. Although its relative humidity may be high, it will pick up much more vapor when warmed and still be at the same or lower rh. Hot air is thirsty air.

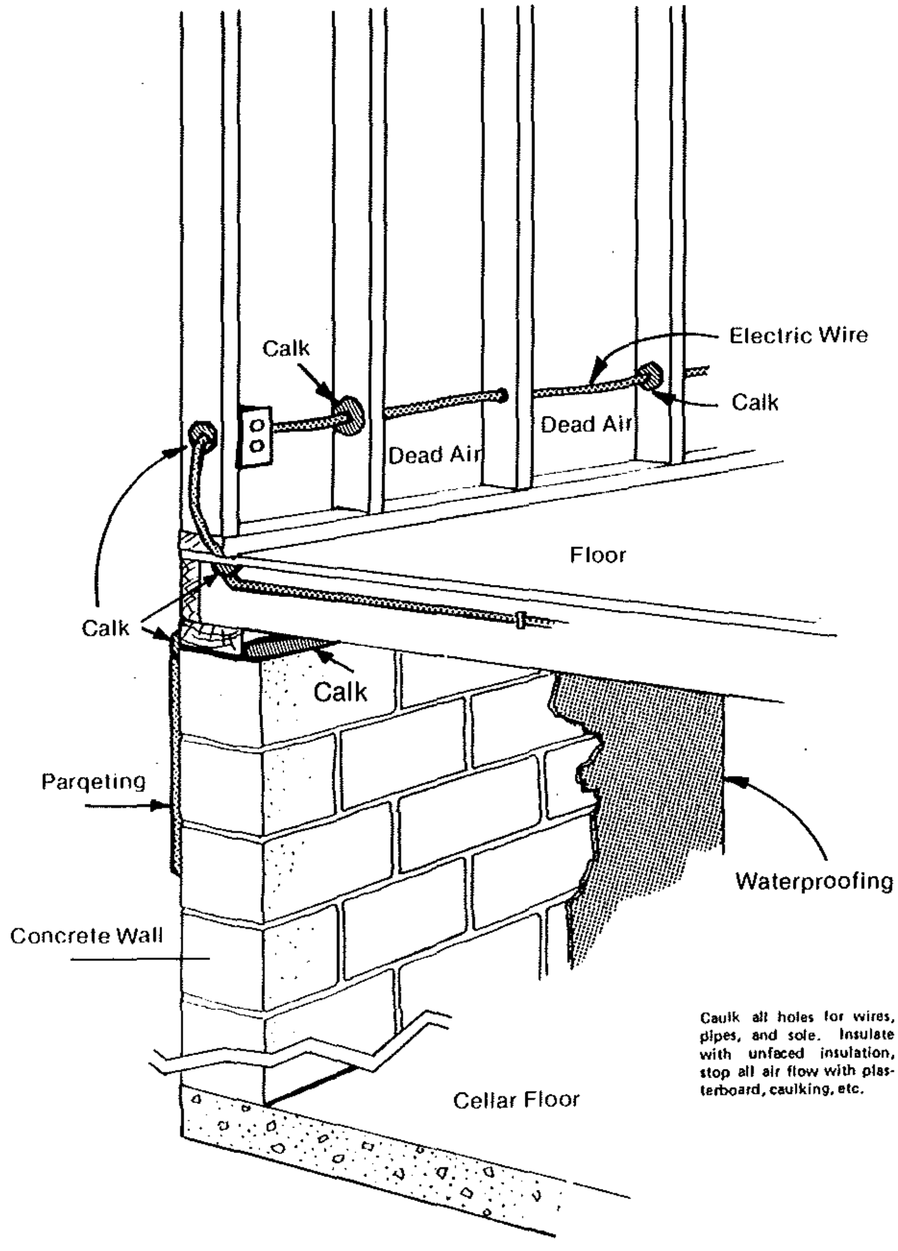
FOR AVERAGE HOME OF 165.4M² (1,780 SQ. FT.)



Not included in this study are the cement blocks commonly used in the construction of the cellar walls. When not painted or pargeted, they are extremely porous and are responsible for serious air and heat leaks.

Air leakage may account for up to 50% of the heating/cooling costs in a building. The leakage may also contribute to unseen condensation with-in the structure. Closing of these leaks may increase the vapor held within the structure. Control of, and direction for, this vapor then becomes a necessity.

Figure 1. Air leakage test results for average home of 1780 ft² (165.4 m²)



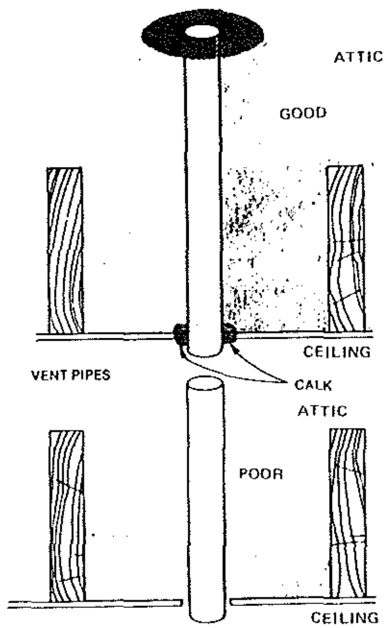
When the air flow has been controlled, the 14% air loss from the heat in pipes will be more apt to stay within the house.

Waterproofing the inside or pargeting the outside above ground will stop air and moisture flow through cement which is porous. This may have as much value as R 11 insulation.

Care must be given in insulating cellar walls that the earth on the outside does not freeze, expand and crack the concrete walls.

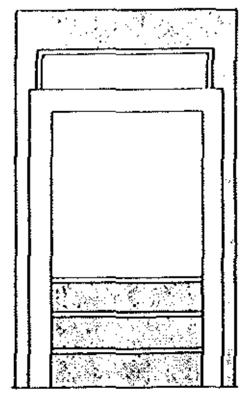
Use storm windows on cellar windows.

Figure 2. Air and heat loss in a cellar

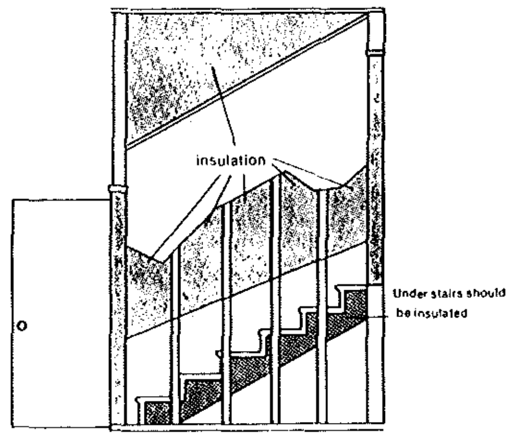


Spaces around all pipes and wires into the attic area should be caulked. For icicle control it may be necessary to wrap pipes in insulation.

VENT PIPES

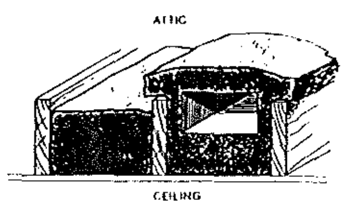


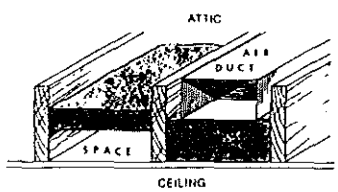
Insulate stairway



ATTIC STAIRS

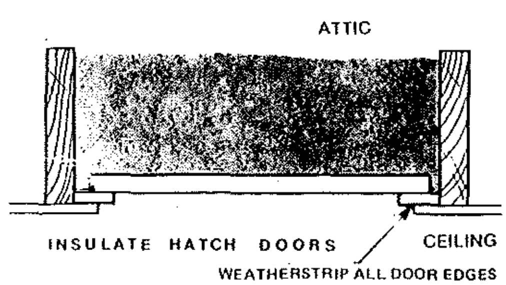
There are air leaks around the door, through the electric outlets in the walls, and through the cracks in the stairs. The door should be weather stripped and insulated; the walls and the underside of the stairs insulated. A trap door, insulated and weather stripped can be built over the whole opening. Cover the keyhole.





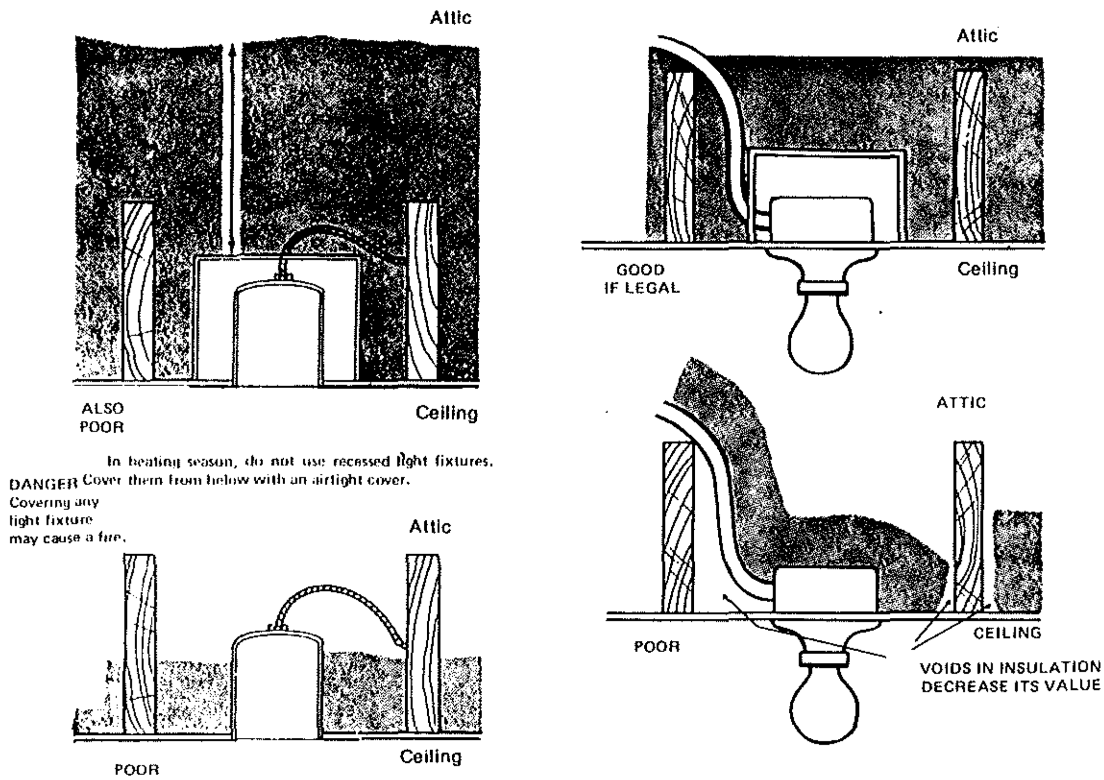
There is air loss through the joints in the piping and conduction heat loss in other areas. Tape all joints in pipes in the attic, cover with double the R value of the other attic insulation.

Currents of heated air circulate under insulation unless there is a solid airtight surface in contact with the insulation. Push all insulation down against the ceiling.



Air leaks around the edges of both hatch doors and disappearing stairways should be weather stripped. Disappearing stairways should have an insulated box built above them.

Figure 3. Air loss



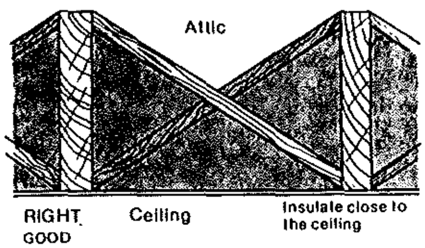
The United States National Electrical Code (section 410 66) states: "Thermal insulation shall not be installed within three inches of the recessed fixture enclosure, wiring compartment or balast and shall not be so installed above the fixture as to entrap heat and prevent the free circulation of air unless the fixture is approved for the purpose.[65]"

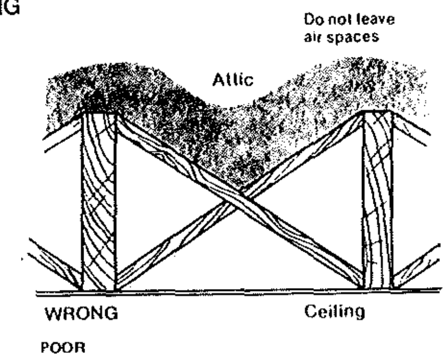
There is air loss around light and electric outlets. Check codes and each fixture before insulating. Seal all air leaks only if legal.

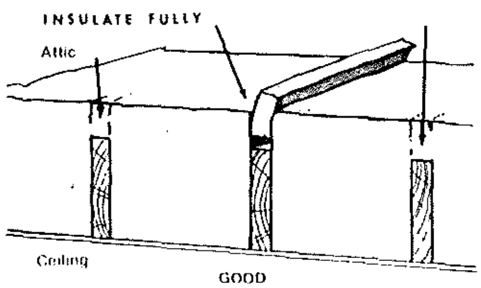
The physical characteristics of wood change when it has been heated to a high temperature many times. It becomes highly combustible. The wood in the vicinity of chimneys and other areas subject to extreme temperatures may spontaneously ignite.

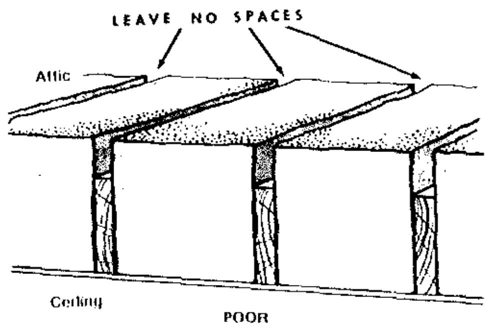
Figure 4. Air loss

BRIDGING

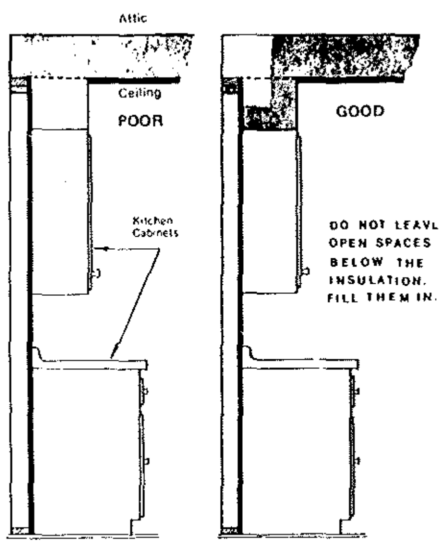








Cold will be conducted through the ceiling joists causing dirt or dark spots on the ceiling below if not fully insulated.



This also occurs in lowered ceilings, around bathtubs, stair wells and in other areas of a building.

SOFFITS WITHOUT CEILINGS

Figure 5. Heat loss

Discussion

S. Tuma, Dept. of Energy/National Resources, Springfield, IL: What is your feeling on not putting a vapor barrier on the ceiling, but having one on the side walls? Wouldn't a total barrier throughout the side walls of the house be better, and then be careful to keep inner humidity medium to low?

K.M. Kelly: We believe that there should be no vapor retarders in the ceiling when the ventilation in the roof is adequate. That is, one square inch of ventilation for one square foot of attic floor area and the ventilation is balanced, with 50% at the soffit and 50% at the peak of the building.

Warmside side wall vapor retarders are advisable. Actually keeping the indoor humidity low 10-30% in winter is probably the ultimate answer.

J.T. Norris, Lilco, Mineola, NY: The author's statement that relative humidity is not important to human comfort is not true.

Kelly: My comments referred to thermal comfort, not human comfort. Relative humidity is not an important aspect of the thermal comfort in winter, i.e., cold weather at normal indoor temperature of $70^{o}F(21^{o}C)$[1]. As early as 1960 Messrs. Koch, Jennings, and Humphreys of the ASHRAE Research Laboratory in the United States, found that thermal comfort perception is only slightly dependent on humidity.[2] In 1971, O.B. Rasmussen, of the Technical University of Denmark, found in tests involving 250 individuals, that man is almost incapable of judging air humidity at normal temperatures and humidities.[3]

In a study of over 600 office workers in Sweden, published in 1975, it was found that complaints of dry air were the same in humidified office buildings as in buildings without added humidity. In addition, there is no evidence that increasing the humidity decreased complaints.[4] Additionally, P.O. Fanger suggests having a low humidity in shops, public offices, etc., as the lower humidity decreases thermal discomfort under certain circumstances.[5]

These are examples of experiments determining the parameters of thermal comfort with regard to temperature and humidity perception in cold weather. Actually, as you imply, some aspects of human comfort are related to the relative humidity. In experiments in Denmark it has been found that, in most cases, static electricity or shocks will decrease drastically at relative humidity of 30-35% or above. Flooring materials, polishes, and finishes are partially responsible for shocks.[6] More study is required in this field.

Another aspect of human comfort is odor perception. Odor perception decreases as the relative humidity increases when the odor generating source is independent of water vapor. Cooking and smoking are two such cources. Odor generation intrinsic to relative humidity such as paint, odors, linoleum odors, and formaldehyde vapors may decrease as the relative humidity decreases.

Another cold weather human comfort problem relates to dry throats and nasal passages. Cracked lips and cracked nasal andthroat mucosa are often blamed on dry low vapor pressure air. Cold winter outdoor air, regardless of its relative humidity has a much lower vapor pressure difference between the human body and the surrounding cold winter air as do potted plants. Many of the popular adult liquid refreshments are also diuretics, making them incapable of fulfilling the body's needs for water. Coffee, tea and cola, among others, take water from the body tissues just as dry air does. Water in the mouth, not in the air, may possibly be the best medicine for cracked lips, dry throats and dry nasal membranes.

Finally, the American practice of daily bathing may open the pores and speed the departure of water from the body in addition to removing protective natural body oils and also drying the skin.

Human comfort has many aspects, a few of which have been addressed in this paper. With this information, I have attempted to illustrate many effects of relative humidity on human comfort. Perceived comfort differences among individuals may be partly due to the above factors rather than being totally dependent on temperatures and humidity.

R.A. Wiley, Bonneville Power Admin., Eugene, OR: Have you considered recycling the latent heat of water vapor (970 Btu/lb) through the use of a dehumidifier (COP-1.6) instead of throwing that energy away through pushing the water vapor into the ventilated attic where it may condense on cold surfaces causing moisture damage?

Kelly: I find it difficult to give a quantitative answer to the first part of this question. As far as I can determine, the efficiency of dehumidifiers is calculated at a temperature of 80°F and 40% relative humidity.

970 Btu/lb equates to approximately 2¢ per recovered lb. if electric heat at the cost of .062¢ per KWH is used. Since in central New York the cost of gas, oil, or wood is less than electricity, the return would probably be only about 1¢ per recovered pound. A daily 16 lb. recovery might result in a perceived savings of approximately 16¢ to 32¢. Because of the variation in recovery efficiency due to the location of the machine, the temperature, and the relative humidity of the ambient air, we find it difficult to recommend dehumidifiers for the purpose of saving money. I would like to see further work in this area.

Regardless of these points, people do use dehumidifiers but their operation needs 65°F or above temperature which is seldom found in cellars and is sometimes not found on the first floor of houses in the winter.

Bge 300 of the May 1981 Consumer Report mentions that it is inconvenient to empty the water pans of dehumidifiers. It continues that dehumidifiers are as noisy as room air conditioners and that their best location for operation is in the center of a room. Mechanix Illustrated, May 1980 pg. 52, mentions that dehumidifiers need to have the water container cleaned once a week to prevent the accumulation of bacteria and molds. These are some of the disadvantages.

Extensive research has disclosed many health problems with humidifiers and air conditioners. Although no problems have been identified directly with dehumidifiers, they are closely related to the other appliances.

Humidifiers, dehumidifiers and air exchangers, etc., are good for the homeowner who doesn't mind fussing with them and for buildings which have no other solution. However, I believe that nature should be allowed to do the job whenever possible.

In answer to the final point in your question, I have not found any instances of, or documentation of, condensation problems in attics that are ventilated according to the specifications described in this paper. The only exception to this would be attics that have air leaking into them from heated rooms.

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