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Moisture Interactions in Light-Frame Housing: A Review

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ABSTRACT: Though airchange or infiltration can significantly affect energy use, altering interior moisture can influence energy use as well as other performance characteristics. An assessment of the moisture interaction is made as related to health and comfort of the occupants, fire safety, durability and maintainability, and design and construction of light-frame housing. A discussion of significant interactions includes shortcomings and recommendations.

KEY WORDS: housing, frame construction, moisture, air infiltration, air change rates, residences, health, durability, fire safety, measurements

Of all the energy consumed in the United States, 20 percent is used in residences. More than half of this is directed to space heating and cooling [*1,2*].[2] Although the shell of a home constitutes only 19 percent of its initial cost, about 44 percent of the cost of the energy for operating a home is directly influenced by its design and construction [*3*]. As a result, much effort has gone, and currently is going, into improving the thermal characteristics of the house shell. Many of these energy-conserving practices achieve improvement in energy efficiency without affecting desirable performance characteristics of the residence. Some practices do deleteriously influence other desirable performance charateristics.

This paper selectively examines the effectiveness of various proposed moisture or air infiltration controls on such performance characteristics as livability, safety, durability, maintainability, and structural behavior. It is intended to illustrate performance advantages and disadvantages as a

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[2]The italic numbers in brackets refer to the list of references appended to this paper.

guide for researchers, designers, and builders to judge overall need satisfaction of the various techniques.

Considerations are limited to single and multifamily dwellings of frame construction because such construction constitutes three fourths of the residential construction of the United States.

Information for this report was drawn from the available literature and discussions with professionals in the housing field. The identified interactions, description of effects, and recommendations concerning the technique or practice are presented to draw attention to them and to guide improvement of the overall performance of frame residences.

Comfort, Health, and Safety

Residences are for people! This means that all techniques or practices employed in constructing residences should be developed to enhance the occupants' comfort, security, and privacy as effectively as possible compatible with cost and available technology [*1*]. Such shelter should provide continued protection from exterior elements (rain, cold, sun, snow), intrusion (theft, vandalism, noise), damage to belongings or selves (flood, fire, etc.), and noxious or infectious materials.

Heating and Cooling

Many engineered approaches to energy conservation do not consider either short-term or long-term effects on the occupants [*2*]. One influence commonly neglected is convection—drafts.

Air motion is of assistance to energy conservation and comfort when interiors are being cooled. However, when interiors are being heated, air motion continues to provide cooling to the human body and resultant discomfort. Increasing room temperature at constant absolute moisture levels is a common corrective measure. For example, circulating air at 1.5 m/s should be maintained at 27°C (80°F) in order to be equivalent to 24°C (75°F) in nonmoving air (at 20 percent relative humidity for sedentary medium-clothed occupants) [*4*]. Other reported works [*5,6*] differ in predicting this effect. Recently, extensive work with human subjects [*7*] has indicated that air circulation rates as low as 0.1 m/s (20 ft/min) can be especially discomforting when room temperature is 18°C (64°F). Also shown, however, was that tolerance improved with increasing room temperature. In any case, the influence of increasing convection is to induce a higher heating load to achieve comfort.

Humidity

Sufficient interior moisture is a requisite for human comfort and health. (It also can lead to severe problems affecting the durability and maintenance of a residence.) As a result, humidity control is essential.

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) [*4*] has analyzed the work of many researchers and developed a "comfort" chart. It reflects individual comfort as a function of temperature and relative humidity. A comfort zone, which is considered both comfortable and healthful, lies between 23 and 25°C (73 and 77°F) and 20 to 60 percent relative humidity. The most commonly recommended design conditions are an effective temperature (ET) and dry bulb temperature of 24.5°C (76°F), relative humidity of 40 percent, and air circulation rate of less than 0.23 m/s (45 ft/min).

Under winter conditions, it is claimed [*8*] that energy is wasted when humidity is added to building interiors because the latent heat of vaporization of the vaporized water must be offset. It is also clear [*4*] that raising interior relative humidity, however, permits a lowering of interior (dry bulb) temperature for the same degree of thermal comfort [*4,8*].

In humid summer conditions, on the other hand, too high a relative humidity inhibits evaporative cooling of the human being because skin surface moisture evaporates more slowly [*9*].

Several sources [*9,10*] recommend interior control of humidity for energy conservation purposes. It is known, however, that below 30 percent relative humidity, discomfort is increased and the mucous membranes tend to dry [*9,4,10*]. Above 70 percent relative humidity, the skin becomes clammy and sweat is more difficult to evaporate [*9*].

Noise

The transmission of a noise (undesirable sounds) to the occupants of a residence from outside a structure, or from one location to another within, should be reduced to low levels for comfort. Noise or sound transmission can be generally controlled by controlling the sound transmission properties of structural components between occupant and sound source. Normally, two paths exist for noise transmission: through or around (flanking) the components.

Structural components are often resistant to sound transfer in proportion to their overall resistance to heat transfer and air leakage [*11,12*]. Well insulated exterior stud walls, however, have been found to negligibly improve the sound transmission resistance compared to noninsulated stud walls [*11*]. Tight wall constructions did improve sound transmission resistance significantly over walls with cracks. Insulating walls and connecting interior drywall to resilient channels improved the sound transmission class (STC) for wood siding or stucco exteriors (8 to 9 dB), but negligibly for brick veneer, which had the highest STC.

Effective insulating procedures for doors and windows are also effective noise reducers and include [*11,12*] employing storm windows and doors, employing shutters [*13*] and heavy curtains, and caulking and gasketing doors or windows. Sound transmission loss correlates positively with air leakage of doors and windows [*11*].

Odor

Interior odors directly influence occupant comfort. The introduction of fresh air through vents, windows, and leaks is commonly used to control odor level. With the advent of moves toward "tighter"—leakfree—homes, the concern for odor control has grown (for example, Refs *14,15*). The introduction of outside air, of course, adds substantially to the heating and cooling load.

It has been found that as little as 0.00048 m^3/s (1 ft^3/min) of outdoor air per person is sufficient for all needs when the interior air is being decontaminated during recirculation [*4*]. ASHRAE [*4,16*] recommends no less than 0.0024 m^3/s (5 ft^3/min) per person, and another source [*17*] recommends no less than 0.0038 m^3/s (8 ft^3/min) for odor control alone. Reducing relative humidity is also found effective to decrease odor sensitivity and decreases the rate of odor release from materials.

Air change rates due to various leakages have been measured from 0.45 to 1.25 volumes per hour in residences under average winter conditions [*18*]. Air change rates of these levels could easily satisfy odor control needs, but are high heating and cooling load levels. Controlling construction for balance in natural ventilation is largely undefined.

Health

Certain conditions generated within dwellings are believed to be unhealthy [*4*]. Those found that most directly interact with energy conserving approaches are respiratory irritation, toxic product buildup, and contaminants and infectious environments.

Of most current concern to healthful conditions is the trend toward tighter homes [*14,15*]. Current United States' view is that about 0.0024 m^3/s (5 ft^3/min) of fresh air is required per person to satisfy both comfort and physiological needs [*4*]. In a conventional home, a one quarter air change per hour is said to adequately provide enough oxygen for four people [*19*]. However, oxygen required for combustion in fuel-fired furnaces also competes for the fresh air [*20*]. The carbon dioxide (CO_2) content of respirable air should not exceed 1 or 2 percent. To compensate for the human generation of CO_2 alone requires a ventilation rate of at least 0.0014 m^3/s (3 ft^3/min) for seated individuals, 50 percent higher for standing people [*21*].

A tight home minimizes loss of interior moisture (humidity)—an energy saving factor and a health benefit. Below 30 percent relative humidity, mucous membranes tend to dry [*9,10*]. Above 70 percent, the skin feels clammy and sweat is more difficult to evaporate [*9*]. As a result, maintaining interior relative humidity somewhat above 20 percent is recommended [*4*]. A level well below 50 percent also has proven satisfactory to suppress allergenic effects of pollen [*4*]. Bacteria and viruses appear to be able to survive in both humid and very dry atmospheres, so humidity control will not suppress their activity.

Security

Burglars and intruders provide a physical threat to occupants of buildings. Most gain their entrance through the doors and windows also used for moisture and air control [*22*]. Because 80 percent of such break-ins occur in residences and small businesses, special effort to increase the security of doors and windows consistent with energy efficiency and other constraints (for example, fire egress) will have impact.

Provision of windows that are effective for rapid egress during fire, yet provide security, is a current challenge in mobile homes [*22*]. Roll-shutters (lamellenstoren) have been employed in Europe to provide sun screening, security, and some thermal insulation to windows [*23*]. They are only now being marketed in the United States. It is important to note that these sturdy roll-shutters roll up completely for egress through windows during fire and are preferred for fire safety reasons to more rigidly fixed louver or iron-grille works. Well gasketed entry doors should be constructed to maximize strength yet inhibit heat transmission. Insulated steel or solid wood doors are especially effective. Any glazing in such doors should be breakthrough resistant to minimize access to latches.

Fixed double- and triple-glazed windows have been found especially effective barriers to entry because of the noise generated when broken. These glazings are preferred in energy-efficient designs. However, safe egress during fire is a distinct problem with windows having fixed sashes if such a window is the only way out of a bedroom other than the door. As a result, double and triple glazing in mixed fixed and movable sashes is encouraged. Moveable sashes should provide exit areas of 0.46 m^2 (5 ft^2) with minimum dimension of 559 mm (22 in.) [*24,25*]. This use of movable versus fixed sash, each having 1.4-m^2 (15-ft^2) area, results in a 25 to 28 percent less thermally efficient window [*26*], but is preferred for other benefits. Fixed storm windows should be avoided for similar reasons [*25*].

Fire

Of the interactions investigated, none is more dramatically linked to energy efficient practices than fire safety. The majority of fire deaths yearly occur in residences, hence the concern.

Concealed open spaces are a common way for fire to spread rapidly from one widely separated room to another in residences. To prevent such fire spread, fire stops are required every 2.4 m (8 ft) within bounding assemblies [*27,28*]. Fire stops in exterior walls over 2.4 m (8 ft) high provide a thermal bridge between inside and out. The impact on heat loss is a function of area of the fire stops. Such fire stops do decrease convective motion in less than fully insulated walls, which becomes a benefit. It is presently common to vent interior and exterior walls into the attic [*29*]. This appears acceptable for fully insulated exterior walls but is questionable for uninsulated interior partitions. Such partitions can also vent a fire into the attic, aiding in fire spread.

The relative humidity maintained in a dwelling can significantly influence fire hazard. For example, wood-base products are more difficult to ignite or propagate flaming at higher moisture contents [*30*]. Fire growth in a room has been found to be suppressed with increasing humidity [*31*]. Quantification of the influence is only now underway and will have an important bearing on humidification and energy efficiency.

The insulation of buildings has been found to influence both fire growth rate and smoke and toxic gas production. In one report [*32*], a noninsulated building did not allow fire growth, whereas a fiberglass-insulated one allowed fire to spread throughout. This may be a significant finding for residences. It was also observed that heat, smoke, and gases did not escape a tight building; pressure was found to build up, providing a driving force for smoke spread [*32*].

To compartmentalize a fire, or prevent fire from entering from the outside, the structural assemblies and partitions must act as a barrier. Conventional exterior walls and bearing partitions are expected to have a fire resistance of 20 min, floors over crawl spaces 10 min, and floor-ceiling assemblies 20 min [*25*]. All of these constructions can have their fire resistance improved by increasing the use of noncombustible insulation and larger member sizes (for example, 2 by 6 studs in walls). Though increasing the fire resistance does not appear necessary for safety to life, increasing dimension to provide property protection is reasonable. With added benefit of energy efficiency, benefits should be improved. Newer panel types of stress-skin construction can be especially low in fire endurance and should be employed with caution even though they are thermally efficient and tightly constructed [*33,34*].

Durability and Maintainability

Of the energy conserving practices interactions, none is more important to the consumer than the ability to maintain the structure and life of the materials used. Among the many specific interactions found, the more significant ones relating to moisture were degradation of surface finishes both inside and out, and degradation of insulation effectiveness through moisture action.

Surface Finishes

Numerous problems with interior surface finishes are encountered that are directly influenced by energy-conserving techniques. Fungal staining of interior partitions and walls has been found in Texas homes of "tight" construction [*20*]. This might be expected to occur in closed exterior spaces, such as crawl spaces, but occurrence inside is relatively newly observed phenomenon. A second type of thermally induced staining on interior surfaces of exterior walls are those brought on by the existence of "thermal bridges" between inside and outside surfaces. The discolorations are attributed to either dust or vapor condensing on the cooler selections of the wall at the stud locations [*35,36*]. Extreme examples of the temperature difference are seen in Fig. 1 [*35*] for several stud types. Steel studs can be both significant heat loss factors as well as potential discolorant factors in comparison to wood studs. Prevention of thermal-bridge influence on staining is to provide as uniform interior surface temperatures as possible. Many solutions are possible (for example, Ref *35*). Rate of condensation of moisture on cold surfaces can be calculated when vapor pressure in the room is known [*9*]. As an extreme case, a window pane acts as a "thermal bridge," and frost or moisture condensing on it eventually melts and can run down, staining sills and walls.

The staining of interior ceilings and corners near the ceiling can occur when moisture condensed in attics melts and drips down [*37*]. This can be shown to be caused by either improperly vented attics or an ineffective ceiling vapor barrier. Of course, the condensed moisture had initially been on the interior of the residence and had filtered to the cooler attic where it condensed. The National Research Council of Canada has observed similar staining of the ceilings on flat-roofed homes [*38*], which appeared to be more susceptible to condensation problems than sloped roofs. Factors believed contributing to the staining problem were:

1. Interior partitions venting into the attic plenum through holes in the top plates.
2. Party walls vented into attic plenums.
3. Spaces between joists partially blocked by insulation placed over furring strips or cross bracing.
4. Stack effect due to building heating, producing an air pressure difference that promotes flow of humid air through cracks and openings into the cold roof space.

Remedies suggested were to pressurize (2.5 N/m^2) roof space using a fan,

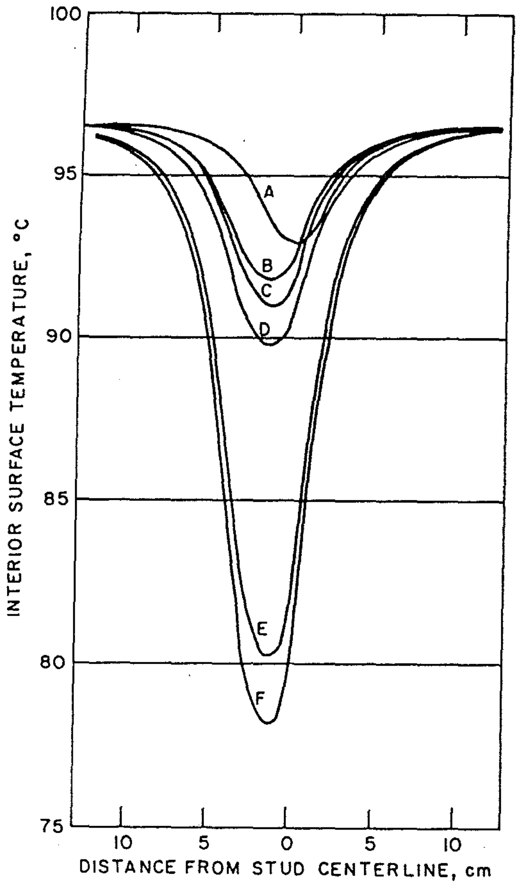


FIG. 1—*Calculated surface temperatures on the interior surface of walls when the inside/outside air temperature difference is assumed to be 100°C (212°F). The diagram gives the surface temperature at studs for a number of different alternatives using timber or steel studs* [35]. *The curves refer to:* (A) *timber stud, 34 by 120 mm;* (B) *steel stud, 6 rows of slots, web thickness of 0.6 mm;* (C) *steel stud, "stepladder" design;* (D) *steel stud, 4 rows of slots, web thickness of 0.6 mm;* (E) *standard steel stud, web thickness of 0.6 mm;* (F) *standard steel stud, web thickness of 0.8 mm. Insulation consisted of 120-cm mineral wool in all the constructions. When using standard steel studs, the surface temperature on the inside is very low regardless of the thickness of the metal.*

to seal leaks that comprise 0.02 percent of ceiling area, or to increase airtightness of ceiling construction.

Some exterior paint finishes also suffer damage due to moisture exfiltration [*37*]. An effective vapor barrier on inside walls eliminates such difficulties by inhibiting moisture transfer through the walls [*39*]. Regions of the United States for which inside vapor barriers are required are shown in Fig. 2 [*40*]. Because inclusion of an effective vapor barrier in

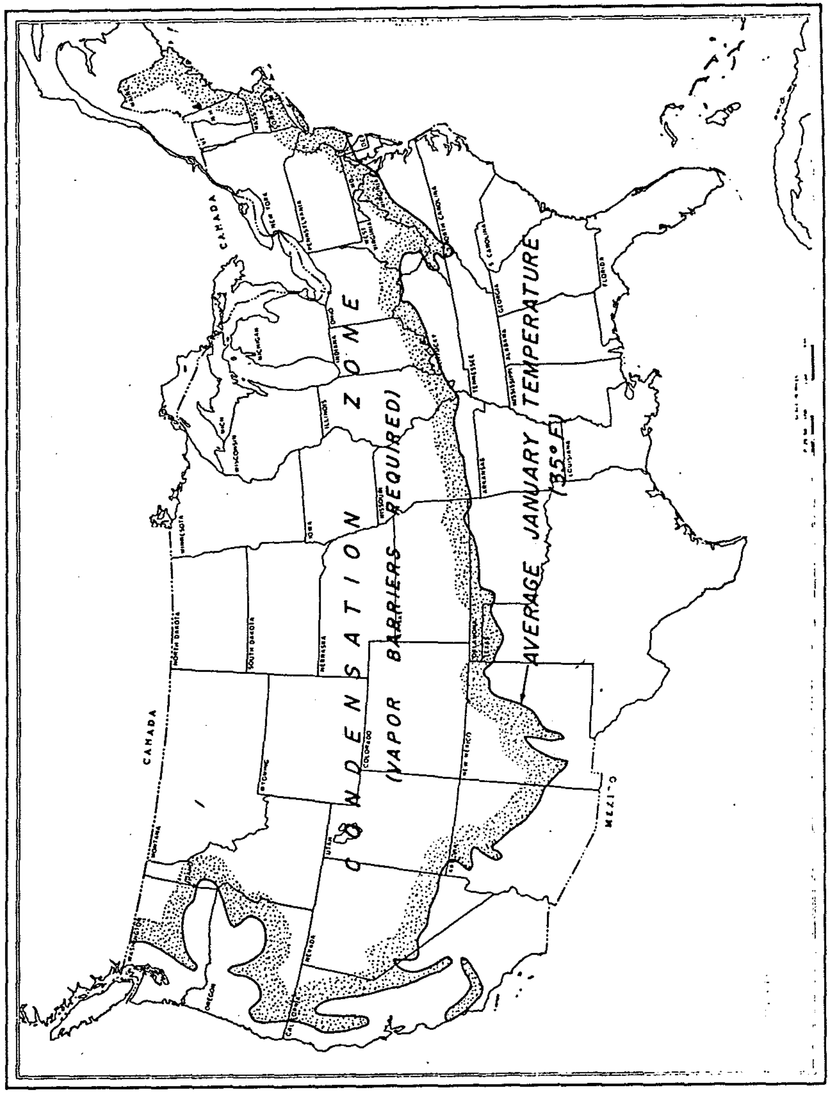


FIG. 2—*Winter condensation problems occur where the average temperature for Jan. is 1.7°C (35°F) or lower* [40].

older houses can be difficult, this situation may sometimes be remedied by enhancing flow of moisture around the exterior surfaces using "cold side venting" (Fig. 3). Venting of each stud space, at the top and bottom, permits moisture to escape before it condenses [*39,41*]. Rogers [*41*] believes that one may omit a cold side vapor barrier in southern climates if cold side venting is employed. An "open rain screen" also would appear to eliminate paint peeling [*42*].

Blistering of low permeability paints was found to occur after urea-formaldehyde foam had been foamed into a wall cavity. Much of the original water generated in the foaming process had migrated from the foam towards the sheathing-siding and was unable to escape through an oil-base paint film [*43,44*]. A more permeable paint film may not have been damaged.

Insulation Effectiveness and Degrade

Commonly employed insulations include cellulosic, fiberglass, mineral wool, vermiculites, polyurethane and urea-formaldehyde foams, and styrofoam. Fiberglass, mineral wool, and vermiculite are known to be relatively insensitive to long-term influences of moisture and heat. Urea-formaldehyde foam shrinks with age and also is subject to degradation by moisture. Styrofoam and polyurethane foam are relatively stable and impermeable enough to moisture to act as their own vapor barrier [*45*]. Cellulosic insulation is fire-retardant-treated shredded recycled newspaper or wood fiber usually employed in attic locations. Though it is considered moisture stable and able to maintain bulk density, current concerns on its use are corrosivity and smoldering tendency [*46,47*]. Fiberglass batts are also currently questioned on fire safety as the paper employed readily contributes to flame spread [*47*].

The influence of concealed condensation on insulation is potentially

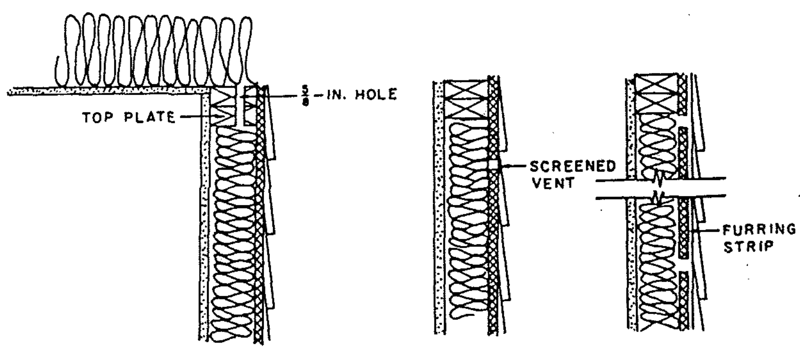


FIG. 3—*Venting of walls* [39]; left—*Into attic,* center, *right—cold-side venting.*

deleterious. Because the thermal conductivity of most materials increases with increasing moisture content or temperature—polyurethane is one that does not increase with temperature [*4*]—minimizing moisture presence is desirable to maintain insulative capacity. To control concealed condensation, one of several measures [*4*] has been recommended (*a*) providing a vapor and air barrier to limit vapor entrance into the cavity, (*b*) ventilating the building to reduce interior vapor pressure, or (*c*) ventilating the cavity to remove vapor that has entered.

There is some published evidence [*46*] and unpublished National Bureau of Standards (NBS) research results that show, for typical wood-frame walls during winter outdoor conditions, moisture accumulation occurs predominately within the exterior siding and sheathing. The insulation remained comparatively dry. Such an occurrence would largely negate any concern over moisture accumulation within insulations if found more generally true.

A wall having mineral wool insulation with both surfaces permeable to airflow can increase the U-value for the wall 50 to 100 percent (depending on the cold side temperature) [*47*].

Flat roofs evidently incur insulation degrade more readily than pitched roofs because of moisture entrance potential from the top (leaks) and bottom [*48–51*]. Sealing both surfaces leads to buildup of moisture in the insulation between unless vented [*48*]. An "airtight" barrier is considered essential below such insulation [*49,51*] in order to maintain insulative value. A permeable outer layer is advocated by Cornish [*51*] if venting is not possible. (It is also believed that increasing the amount of roof insulation dramatically shortens the life of most roof membranes [*50*].)

Other

Moisture levels within wood products above 20 percent are conducive to their decay. Hence, moisture condensing within walls, floors, and roofs can lead to decay of the wood elements.

It would appear [*29,52*] that increasing the thickness of a polyethylene vapor barrier from 2 to 4 mils or greater provides a more effective vapor barrier and produces a barrier that is more durable in construction of a building and with time. Maintaining vapor barrier continuity is, of course, important.

Design and Construction

Architectural

The infiltration of air can, to a great degree, be controlled by exercising care in the siting and design of housing. Such simple techniques as providing continuous nonpenetrated surfaces normal to the prevailing wind in winter, and providing fins or vanes to enhance formation of a static boundary layer at the exterior surfaces [8] can be very effective. Such methods can be intuitively applied, but controlling infiltration by quantifiable design techniques still requires development [53]. The simple technique of decreasing the ratio of exterior surface to enclosed volume of housing would also naturally decrease leak occurrence. The mobile home with its high exterior-surface-to-volume ratio [54] in comparison to the low ratio for multifamily townhouse construction are typical examples. Window ventilation without having the window contribute significantly to energy loss is a particularly challenging problem [53].

Simplicity in assembly of housing components should contribute much to providing infiltration free exteriors as well as allowing easy maintenance for the owner. Such simplicity should also enhance an improvement in quality of workmanship to minimize penetrations.

Many papers are available to guide designers in minimizing condensation or moisture problems in housing [39-41,45,51,52,55,56]. Most provide design details proven effective.

For northern dwellings of older construction having no vapor barrier in the exterior envelope, maintaining inside relative humidities less than 40 percent during winter has been found to minimize the occurrence of moisture condensation [46,57]. It could be concluded that to minimize the winter occurrence in any dwelling in northern climates due to breaks in the barriers, interior relative humidities should not much exceed this level.

Several construction details have impact upon infiltrating air and moisture movement. One of these is the requirement to have fire stops in walls between stories [27]. A fire stop also will stop ventilation of moisture unless special care is taken to vent to the outside. This is a special consideration for first story exterior walls in two-story structures. For insulation batts to provide an effective vapor barrier (unquantified), experts in construction agree that the stapling of the batt tab to the narrow stud face is more effective than stapling to the side of the wide face [58], but it creates an uneven surface to nail drywall too. Hence, most recommend stapling at close intervals along the wide face. This practice appears to be one requiring improvement by developing a new technique. Corners of homes present a location where infiltration can magnify heat loss. Care in placement of wall studs at corners should be taken to facilitate insulating and leak sealing. Double framing (that is, a double row of studs to form a wall thicker than (102 mm) (4 in.)) can be very effective at reducing corner leakage or cutting penetrations [59]. But again, fire stopping and ventilating double-row-of-stud construction require innovation for application in more than single-story dwellings.

Caulking around door and window casements with a flexible compound on the interior of the house has been proven to reduce air infiltration and moisture change [19]. Caulking around electrical outlet boxes is also recommended because of potential penetration of the vapor barrier [40].

Structure

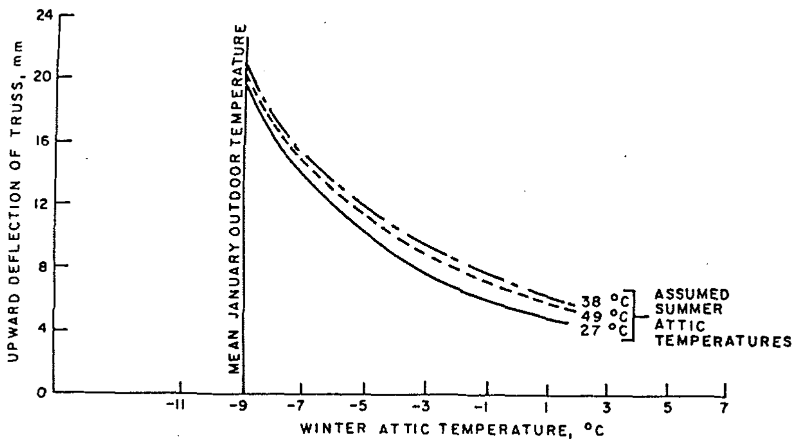
A few structural effects are possibly induced by moisture or air infiltration.

A most curious problem is the bowing upward of low-pitched roof joists and roof trusses in winter [60,61]. The upward bowing of roof trusses and joists in conventional and mobile home residences has been observed to result in cracks from 12.7 to 25.4 mm (½ to 1 in.) wide developing between interior partitions and the ceiling. An explanation of the phenomenon has been lacking, but a tie to temperature and moisture differences in the structural elements has been considered the cause. Suspected contributory influences are the embedment of joists and the lower chord of roof trusses in insulation and the lack of a vapor barrier at the ceiling.

Tuomi and Temple [61] experimentally found that joists with slopes-of-grain greater than 1:16 would deflect about 25.4 mm (1 in.) over a 3.65 m (12-ft) span with a moisture differential of 22 percent between top and bottom edges. The joists, however, were also sawn from small logs and therefore had considerable juvenile wood included. Because the shrinkage of juvenile wood exceeds that of older wood, it is suspected that this factor also played a role.

Plewes [60] analytically examined the upward deflection of Howe roof trusses and mobile home roof trusses due to linear changes in chord length caused by moisture and temperature differences (Figs. 4 and 5). Plewes assumed 102 mm (4 in.) of insulation was emplaced along the bottom chord. It is noted that the deflection of the Howe truss is between 10 and 20 mm (0.4 and 0.8 in.) and of a mobile home truss 20 and 23 mm (0.8 and 0.9 in.) at attic temperatures of −10°C (14°F). If the slope of the Howe truss is decreased, greater upward deflection results. A 9.1 m (30-ft)-span Howe and Fink truss (assumed pin connections), having 6:12 slopes and a moisture content difference between the top and lower chords, were analyzed by Schaffer with resulting upward deflection of 0.24 and 0.3 in., respectively. Decreasing the slope to 3:12 for the Fink truss increased the estimated upward deflection to 12.7 mm (0.51 in.) in keeping with Plewes' [60] analysis. Because there are many houses in which upward deflection is not evident, there must be other factors unexplained to date. It is likely, however, that not embedding the joists and truss elements would alleviate the problem but would add to complexity and cost of construction.

In general, the drier the wood members are kept (as low as 6 percent moisture content) the higher are the strength properties [62]. As a result,



Location—Lethbridge, Alta.
Mean January temperature −10°C (14.5°F)
Mean January relative humidity 71 percent
Mean July temperature 18°C (65°F)
Mean July relative humidity 50 percent

FIG. 4—*Calculated deflection of timber arch—truss roof of mobile home* [60].

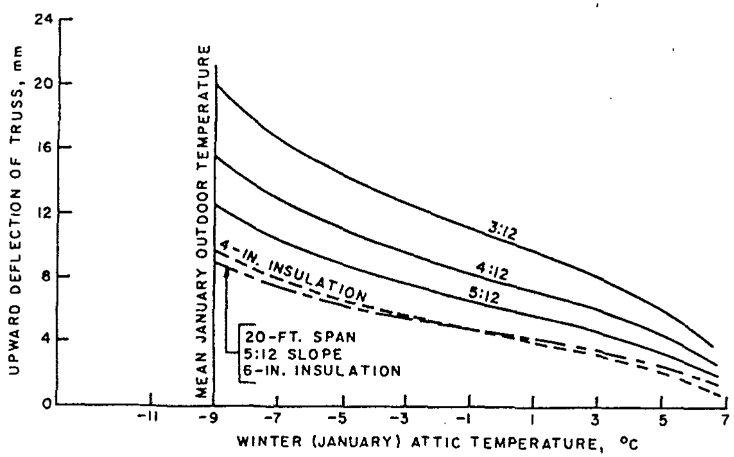


FIG. 5—*Calculated upward deflection of timber (Howe) trusses (July to January, location—Montreal, Effect of slope, span and insulation* [60]. *Note base case—span 28 ft, 6 in.; slope 5:12; and Insulation 6 in.) (Conversion factor—1 ft = 0.3048 m, 1 in. = 25.4 mm).*

minimizing concealed space condensation can materially improve the stiffness of wood studs, joists, and paneling. To minimize structural decay, accumulations of condensed moisture in wall, roof, and floor assemblies must be avoided.

Recommendations

Comfort, Health, and Safety

It is clear that engineered approaches to energy conservation can have an effect on thermal comfort of occupants.

High humidity levels can be uncomfortable and can lead to moisture-induced technical problems when air is not forcedly circulated. Maintaining a relative humidity of 30 (±5) percent provides both healthful and comfortable conditions in winter. This level should be considered as that desirable with minimum energy use. This level also minimizes the occurrence of moisture condensation in walls and roofs. Air circulation rates compatible with both thermal and humidity comfort may be selected from available guides.

About 0.0024 m^3/s (5 ft^3/min) of outside air per person is needed for odor and other physiological needs in dwellings. This is about one eighth air change per hour for a 93 m^2 (1000-ft^2) house with three occupants. Existing dwellings have variable infiltration levels of fresh air and tighter dwellings are under construction. It is not clear how dwellings can be designed to control infiltration for optimum comfort and energy use.

A minimum level of fresh air is needed for health maintenance and satisfaction of combustion needs in residences. Ventilation or infiltration levels of 0.0024 m^3/s (5 ft^3/min) per person provides adequate oxygen to satisfy physiological needs. Additional air for combustion purposes is calculable and must be added to personal requirements to obtain the total ventilation level. Means of controlling home construction to limit infiltration is a research need. Maintaining relative humidities somewhat above 20 percent and below 40 percent is desirable. A level less than 40 percent should minimize the occurrence of moisture condensation in wall and roof assemblies.

Window design strategies to balance needs for security, egress, and thermal efficiency are required. In bedrooms having single windows and one entry door, the single window should have moveable sash of a minimum area of 0.46 m^2 (5 ft^2). Hardware should provide security yet be simple to operate in fire panic conditions. Storm windows should not be fixed over movable or fixed sashes for windows needed for rapid fire egress.

A tight dwelling can be considered more of a fire hazard than those with higher air exchange rates. A tight dwelling allows toxic gases to build rapidly and diffuse rapidly throughout the structure. It is smoke and the toxic gases generated which kill the majority of people involved. However, air exchange rates would be required to be in excess of those consistent with practical energy conservation. Controlling interior humidity at upper levels would decrease combustibility of furnishings, and decrease both risk of fire and its rapid spread.

Durability and Maintainability

Tight construction and thermal bridges can lead to discoloration of interior surfaces. When residences are tight, circulating interior air should inhibit fungal staining. Attic ventilation is needed to prevent excessive moisture accumulation in attic cavities in cold climates to keep melting condensation from discoloring ceiling panels. Venting interior and exterior walls into attic plenums presents a special hazard preventable by adequate attic venting.

A vapor barrier near the warmer, inside surface in cold climates will inhibit moisture degradation of insulation effectiveness. Flat roofs need special care. Residential vapor barriers should be increased in thickness to at least 4 mils in order to improve durability.

Design and Construction

Several architecturally controlled factors minimize air infiltration, but the effect of each is largely unquantified. Reducing the surface-to-volume ratio is a natural approach. The stapling of insulation batts between studs requires improvement in order to maintain interior surface smoothness yet provide an effective vapor barrier. Care must be exercised in the installation of fire stops in outer walls to maintain adequate ventilation.

The upward bowing of mobile home and conventional home roof trusses in winter is a phenomenon requiring further analysis and correction. The influence of thermal bridges in walls can be reduced by incorporating clips for attachment of interior surfaces or emplacing insulation panels at exterior surfaces. The practices require an assessment of how wall rigidity and strength are affected.

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