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THE PRINCIPLES AND DILEMMAS OF DESIGNING DURABLE HOUSE ENVELOPES FOR THE NORTH

by

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ABSTRACT

Starting from the premise that condensation in the building envelope is a prime cause of its deterioration, the mechanisms that cause condensation are discussed and control measures explained. The conflicts that arise between some of these measures, the probability of achieving them under realistic construction conditions, and the possible need for fail-safe provisions should complete success not be achieved, are described.

INTRODUCTION

The key to durable buildings in the North is the control of water in all its phases; solid, liquid and gaseous, with particular emphasis on control of water in the gaseous phase. This is effected by controlling heat flows, and air pressures and flows. It is through an understanding of these phenomena and of some concepts of design derived from them that durable building envelopes can be created.

Obviously structural damage due to overloading can be a problem but, except for damage caused by foundation failure, the reasons for a component breaking or being displaced due to overloading are usually clear. In most cases, the magnitude of the loads that must be resisted can be estimated in advance and adequate strength built into the building either by engineering design or by conventional practice. Damage due to frost heave or the melting of permafrost is related to heat flows and can be avoided by controlling such flows. This will not be considered further here.

On the other hand, when deterioration takes place because of the effects of water the causes are not always clear and it may be difficult to select suitable remedies. In many instances precise design procedures are not available and conventional construction practice may not be satisfactory. In such cases, the designer must work with basic principles of physics. He may not be able to prove that one design is superior to another but if such principles are followed they will probably lead to the construction of a durable building. This is not exactly the sort of philosophy that one would expound to an astronaut before launching him into space in a space capsule, but in more mundane affairs it may have to suffice. If the building is needed it must be built with whatever knowledge and technology are available at the time. Failures due to deterioration can be annoying and inconvenient as well as costly to repair, but they seldom lead to injury or loss of life.

THE FUNCTION OF THE BUILDING ENVELOPE

In the vast majority of cases one builds a building to protect the occupants and contents from inclement weather. In some cases protection is also needed against animals or insects and against thieves or vandals but in most cases the initial requirement is for protection from the weather. This protection is given by separating the inside from the uncontrolled, and in most respects uncontrollable, conditions outside so that the conditions inside can be modified and controlled to some extent. The basic function of the walls, roofs and floors of the building is to effect this separation and they can collectively be referred to as the building envelope.

It is clearly impossible to keep occupants warm and dry if the wind is allowed to blow freely through the building. Unless the wind is controlled by the building envelope none of the internal conditions can be controlled satisfactorily. Thus, the first function of the building envelope is to control the flow of air. The importance of this can hardly be over-stressed, for failure to control the movement of air through, and within, the thickness of the building envelope can lead to serious building deterioration, as well as failure of the envelope to perform its intended function satisfactorily. Furthermore, the forces producing these air leaks are not necessarily those associated with strong winds. Those caused by differences in temperature can, in many cases, be of greater importance because they act steadily in one direction as long as a temperature difference exists. Such temperature differences are not only between the inside and outside of the building but also exist within the thickness of the envelope. Thus the air flows need not be right through the building envelope but can be within its thickness.

THE DURABILITY OF MATERIALS

It is natural for a designer or builder who has had a bad experience with a particular material to decide never to use it again. That, after all, is called learning by experience. The trouble is that experiences often appear to contradict each other; a material that failed on one building performs quite satisfactorily on another. Thus, as experience grows, it becomes clear that the material failed because of the particular manner in which it was used; one modifies the blanket condemnation and decides that one won't use that material in that manner again. This is an important step forward but each material in the building envelope must still be positioned so that it is not subjected to conditions that it cannot withstand.

Several factors, either singly or in combination, affect the behaviour of building materials; the three principal ones are water, temperature and ultra-violet radiation. Of these three, water is probably the most important. There are other factors, but in the absence of water they are normally harmless. Wood will rot if it is kept near the fibre saturation point in the presence of air with a temperature above about 10°C; kept dry, it will last for centuries. Similarly metals will corrode when wet but not when dry. On wetting and drying many materials will undergo dimensional changes that must be allowed for if damage is to be avoided. Finishing materials may be disfigured by water staining and, in extreme cases, ceilings may collapse under the weight of water.

The moisture content of many materials is affected by the relative humidity to which they are exposed, and mould growth can occur at high relative humidities without the material being wetted by liquid water. Thus water in its vapour phase can be responsible for physical deterioration. However the conditions appropriate for such deterioration can be changed quickly by a change in temperature or a small increase in air movement. The more serious cases of deterioration occur when the vapour condenses and soaks the materials. It is much more difficult, and takes a considerable period of time, to dry out the materials once they have been wetted; by that time irreversable damage may have taken place.

During the long periods of cold weather in the North, water may accumulate within the fabric of the building envelope as snow, hoar frost or ice. Probably little damage will occur, both because the materials will not be wetted appreciably and because the low temperatures will inhibit wood rot and corrosion. As the outside temperature moderates, the accumulated snow and ice melt, leading to severe wetting of the materials at a time when warmer temperatures allow corrosion and rot to proceed. In southern Canada some periods of relatively mild weather during the winter usually release any accumulated water and allow the materials to dry out. The southern summers also are relatively long and warm and, in most cases, give ample opportunity for drying. In the North, on the other hand, the summers may be so short and cool that water accumulated during the previous winter cannot dry out and is carried over into the following winter; this causes a progressive buildup of water in the building envelope.

If one can control the water, one will go a long way towards making a durable building. But since one cannot rely upon suitable periods of drying to reduce the concentration of water in the building envelope, the amount of water that enters must be reduced to a minimum. Any additional measures to enable water in the envelope to escape to the outdoors constitute, in effect, a safety valve. Such safety valves, or fail-safe mechanisms, should be provided, but if no water gets to the problem location there will be none to escape. A skydiver has two parachutes; one that he intends to use and one that he hopes he never has to; but if the need should arise, it is vital. So it is with designing a durable building envelope; design it so that water cannot get in, but if it should get in, provide a way for it to get out.

One can reduce the quantity of water that enters the envelope by reducing the supply of water at its source. This has only limited applicability in most northern houses, but it should not be ignored. Outside the building, water exists as rain and snow, which are not controllable. In the North fine wind-driven snow is probably the more troublesome. Inside the building, water comes from many sources such as cooking, washing, people, wet materials and the unvented products of combustion of gas-burning appliances. Water from such sources becomes water vapour carried by the air. To control such sources may require some modification of the living habits of the occupants. This is not something that the designer can control and it would be unwise to rely upon it for a permanent solution. On the other hand, provision could be made to vent moisture-producing appliances to the outdoors. Provision can also be made to increase the rate of ventilation by mechanical means when the level of humidity rises.

The principal method of controlling the accumulation of water in the envelope is to reduce the rate at which it is transferred to any location where it may cause a problem. Much of this water is deposited as condensation and so if one wants to make a durable building, it is important that the phenomenom of condensation be understood.

PSYCHROMETRY - THE PHYSICS OF CONDENSATION

Psychrometry is the branch of physics concerned with the physical and thermodynamic properties of mixtures of air and water vapour.

Water vapour is one of several gaseous constituents of air; the other principal ones are nitrogen, oxygen and carbon dioxide. Each exerts its own partial pressure in proportion to the amount of gas present; the sum of the pressures makes up the total or barometric pressure of the air.

The maximum amount of water that can exist in the gaseous state (vapour) in a given quantity of air is limited by the temperature. Thus, if any air-vapour mixture is cooled, a temperature will be reached at which it will be saturated, and if cooling is continued below this point, water will condense. If the temperature at which the air becomes saturated (the dew point) is above the freezing point, the vapour will condense to a liquid; if it is below freezing, the vapour will condense as ice in the form of hoar frost. For practical purposes, in building envelope design the ratio between the mass of water vapour actually present per unit volume of air and the mass per unit volume it can contain when saturated at the same temperature may be taken as the relative humidity of the air. It is usually expressed as a percentage. As the vapour pressures are set by the quantities of vapour in the air, the relative humidity is also given by the ratio between the actual vapour pressure and the saturation vapour pressure at the same temperature. Thus, if the temperature and relative humidity are known, the dew point temperature can be determined. First the actual vapour pressure of the air-vapour mixture is obtained from the product of the relative humidity (expressed in decimal form) and the saturation vapour pressure for the given temperature obtained from psychrometric tables. Then the dew point is located in the tables as the temperature that has a saturation vapour pressure equal to this actual vapour pressure.

A convenient way to follow the changes that take place in these inter-related phenomena is by means of a psychrometric chart, which is a graphical representation of all possible conditions within the temperature and humidity range for which the chart is constructed. One design of such a chart is shown in Figure 1. The vertical scale represents the absolute moisture content, defined as the number of kilograms of moisture per kilogram of dry air. The horizontal scale is the air temperature, scaled from -20°C to +55°C. The saturation curve (100% RH curve or dew point curve) shows the maximum amount of moisture that the air can hold at any temperature in this range. The higher the temperature, the more moisture the air can hold. For example, air at 20°C can hold six times as much water vapour as air at -5°C (Figure 2). It should be noted that at the colder temperatures the air can hold only very small amounts of water, even when saturated. The other curves are the relative humidity curves, and represent a fraction of the saturation point. At the 50% RH curve, the air holds half of the amount of moisture it could potentially hold (Figure 3). This chart is often used to calculate the dew point temperature of the inside air; from this one can calculate the required thermal resistance of an assembly (such as a window) to prevent condensation on its surface.

For example, suppose that the air in a room is at 23°C and 50% RH; what would be the dew point temperature of the air? First, plot the intersection of the inside air temperature with the measured relative humidity (Figure 4). Second, move horizontally to the left to intersect the 100% RH curve. Third, project the intersection downward until it intersects the temperature axis once more, at about 12°C. This is the dew point temperature of the inside air. Therefore, if condensation appears on the surface of window glass, the temperature of the glass must be below 12°C.

Conversely, with an outside temperature of -40°C and a 25 km/hr wind and with a room temperature of 21°C, the inside surface temperature of the centre of a double glazed window will be about 0°C; then the maximum room relative humidity before condensation occurs on the window is about 25% (Figure 5). Since the glass temperature will be lower near the bottom and the thermal bridge effect of spacers in sealed glazing units will lower the temperature further, extensive ice formation on double glazed windows is inevitable. Even triple glazed windows under the same conditions will have a surface temperature of about +7°C, with lower values at the bottom. Thus the only practical way to prevent condensation on windows in the North is to blow warm dry air over them, i.e. to reduce the relative humidity locally. Since there is no "free lunch", this solution involves the extra cost of an increased heat loss through the windows but this may be a small price to pay for windows free of condensation. There is also the danger of introducing thermal stresses in the glass that may break it.

HOW DOES CONDENSATION OCCUR IN THE ENVELOPE?

For many years the response to the problem of water condensing in the building envelope has been to specify that a vapour barrier be installed on the warm side. Unfortunately just what mechanisms for vapour movement were to be controlled by the vapour barrier were not made clear, but any standard for a vapour barrier material defined it on the basis of its ability to resist the diffusion of vapour. No mention was made of the need to control air movement and as a consequence, many systems that contained a vapour barrier failed to eliminate condensation.

It is now recognized that vapour diffusion is a relatively weak mechanism for moving water vapour into or out of the building envelope as compared to the movement of vapour by a current of air. Nevertheless it will be discussed first in order to clarify the function of a vapour barrier before proceeding to a discussion of the more important subject of air leakage.

Diffusion

When there is a difference in concentration of water vapour between two points, there will be a corresponding difference in vapour pressure. This will cause a flow of water vapour from the point of higher concentration to the lower, without any corresponding flow of air. When a vapour pressure difference exists between two sides of a material, the water vapour will diffuse through the material at a rate determined by the vapour pressure difference, the length of the flow path, and the permeability to water vapour of the particular material.

Vapour flow by diffusion through a building envelope because of a difference in vapour pressure is very similar to heat flow because of a temperature difference, but with one major distinction. The maximum possible vapour pressure at any location is set by the saturation vapour pressure at the location. Thus if the vapour pressure gradient through the envelope, given by consideration of the inside and outside vapour pressures and the vapour flow resistance of the various materials, calls for a vapour pressure at any point that is above the saturation vapour pressure at that point, then condensation will take place. This will reduce the vapour concentration at all locations until the vapour pressure is reduced to the saturation vapour pressure. To prevent this situation from arising materials with high resistance to vapour flow (i.e. vapour barriers) are added near the high vapour pressure side to depress the vapour pressure gradient to below the saturation vapour pressure gradient. At the same time, materials with low resistance to vapour flow (e.g. breather membranes) are used on the low vapour pressure side.

If the envelope is built following these principles, to ensure that condensation as a result of vapour diffusion does not take place even under the most adverse conditions, there will always be a reserve of vapour diffusion capacity to dry out any water that may accummulate from any other cause. This would rule out the use of some materials as sheathing despite their otherwise desirable properties. The situation is not, however, one to which rules of thumb should be applied without thought. Insulating materials with vapour permeabilities that would preclude them from being used as sheathing will also raise the temperature of the inside face of the sheathing. This will raise the saturation vapour pressure at that location, which will help to keep the saturation vapour pressure above the vapour pressure dictated by considerations of continuity of vapour flow. Such materials could still be used provided that a highly impermeable vapour barrier is used on the high vapour pressure side.

Vapour diffusion is not a very powerful mechanism for moving water vapour into the envelope but, because of the long periods of cold in the North, it should not be neglected.

Air Movement

In many respects all the various constituents of air act together as though only one gas were present. The temperature of the oxygen will not be different from that of the nitrogen, and when a current of air moves the carbon dioxide, it will also move the water vapour. This uniformity of temperature and movement among the various constituents was implicit in the discussion of psychrometry and condensation; where the air went, the water vapour went too; when one was cooled, so was the other.

Because of the small amount of water vapour that cold outdoor air is capable of holding (see Figure 2), it frequently has a high relative humidity, 80% RH or more. When it is warmed up to the building temperature, its RH drops to less than 10% and it will be considered very dry although nothing has actually changed except its temperature (A to B, Figure 6). Water will evaporate from many sources within the building, including the occupants and their various activities, and from damp materials within the building, and will raise the moisture content of the air (B to C, Figure 6). Now, since the air in the building does not remain stagnant but must be changed to provide needed ventilation, this humidified air must make its way back to the outdoors, and since during cold weather it will undoubtedly have a higher moisture content than it can carry at the outdoor air temperature, there is great potential for condensation to take place. The trick in making a durable building is to ensure that this condensation does not take place where it will be harmful.

If the building envelope is completely sealed, then all of the air change will take place through specially provided openings, probably via a mechanical ventilation system. If the outlet duct from such a system terminates on the outer surface of the envelope, or is heavily insulated to its extremity, the outgoing air may remain above the dew point and condensation will not take place in the duct itself. In such a case, the condensation will be in the form of fog in the outdoor air, which may collect as hoar frost around the ventilation outlet. The effect of wind pressures on the inlet and exhaust ducts may make it undesirable to terminate the exhaust duct on the surface of the building envelope, but this question will not be considered further here.

In practice, buildings are seldom completely airtight and some leakage takes place through the envelope. Until relatively recently, this leakage was relied upon to provide the ventilation air and also the air required by combustion appliances, such as furnaces and stoves. Only in the last few years have attempts been made to reduce the air leakage of buildings as an energy economy measure; this has been advocated for years as the key to building envelope durability. The installation of exhaust fans to improve air quality in bathrooms and kitchens by exhausting contaminants from these locations, and the ducting of clothes dryer exhausts to the outdoors, all tacitly assume that openings are available to allow air to enter. With tighter building envelopes, the major available opening may be the chimney that is intended to exhaust the products of combustion from a furnace or a fireplace. Such chimneys may then be backdrafted, especially at start-up or low burning rates, and the products of combustion drawn into the building. However this subject is also outside the scope of the present discussion of building durabilty.

What must be recognized is that there is a balance between the quantities of air entering and leaving the building. Air entering in winter is cold and has little moisture in it, whereas air leaving will be warm and will, in most instances, be considerably more moist. Should this warm moist air leak out through the building envelope, it will pass through regions that are progressively colder. At some point it will come in contact with a component in the envelope that is below its dew point. When this happens, some of the water vapour in the air will condense (C to D to E, Figure 6). How much will condense will vary with the circumstances. If the leakage path is short and direct, the air may flow rapidly to the outdoors without much vapour condensing; just as it does in an exhaust duct from a fan. On the other hand, if the air follows a tortuous path and flows over the inner surface of the sheathing, for example, there will be ample opportunity for it to be cooled to the temperature of the sheathing and large quantities of vapour will condense.

The foregoing discussion assumes that the air flow is right through the building envelope from inside to outside, and this is probably the major type of air flow that causes condensation. However, a convective air flow that moves warm humid air from inside the building, cools it by contact with the colder portions of the envelope, and then leads it back into the occupied spaces, can also lead to condensation. This is a point to be considered when choosing a location for the air barrier.

AIR PRESSURES ON THE BUILDING ENVELOPE

For air to move from one location to another, there must be a force to move it and a passage along which it can move. Eliminate either one and the air stays where it is. The forces that may move air into and through the envelope are the differences in air pressure, which can be produced in a variety of ways.

Wind

Wind blowing on the building will produce a complicated distribution of pressures and suctions. Fortunately, with regard to the movement of moisture into the building envelope, it is not necessary to describe them in detail. It is only necessary to recognise two or three basic principles in order to get a general picture of the wind pressure distribution. The wind will be deflected over, under and round the building, and wherever there is a change in direction or in the speed of flow, there will be a change in air pressure. If the change in direction is convex towards the building there will be an increase in pressure; if it is concave towards the building, there will be a reduction in pressure. This will, in general, produce an increase in pressure on the windward face of the building and a suction elsewhere (Figure 7). Similarly, if the air flow has to speed up to get the volume of air that approaches the building through a passage of reduced size, then a suction is created as pressure energy is converted to kinetic energy. With an elevated building the reduced passage under the building can be seen clearly, but there are similar invisible reductions over and round the building. Some distance away from the building the air can be considered as flowing on undisturbed, and this position of undisturbed flow can be taken as the outer, invisible wall of the reduced air flow passage (Figure 8). (It is this speeding up of the air flow through the invisible passage over the top of an airplane wing that creates the necessary reduced pressure on the wing to keep the plane in the air.) Details of wind load coefficients on structures are given in the Supplement to the National Building Code of Canada, together with procedures for the calculation of the maximum wind-induced loads on buildings.

Wind pressures (positive or negative) on the outside of a building will be transmitted to the inside through any major openings in the building envelope. Thus where a door, for example, is open on the leeward side of a building, the force to be withstood by a wall on the windward side will be the sum of the positive pressure on the outside and the negative pressure transmitted to the inside via the open door (Figure 8). This is of great importance when designing an air barrier.

Temperature

Differences in air pressure are also caused by differences in temperature. When considering the building as a whole, this is generally referred to as stack effect, although there will also be pressure differences between the room and the envelope and within the envelope itself. Stack effect or convective air flows are not so dramatic as wind forces but they may be much more damaging to a building since they act steadily in one direction over long periods of time. This is particularly important in the North because of the long periods of cold.

When air is heated it expands, so each cubic foot of heated air is less dense than the same volume of unheated air. If two columns of air of equal height, one warm and the other cold, are placed side by side, the denser cold air will exert a greater pressure at the bottom than will the lighter warm air. It will undercut the warm air, causing it to rise; this produces the familiar draft up a chimney, with cold air entering at the fireplace, being heated and leaving at the chimney pot. During cold weather a similar action occurs in buildings, although the inside-to-outside air temperature difference is much less than in a chimney: air flows in at the bottom, is warmed, rises and flows out at the top.

Since air flows from high to low pressure areas, the pressure outside must be higher than that inside at the bottom and lower than that inside at the top. Thus, the pressure difference through the building envelope changes from positive to negative at some point in the height of the building and there must be a level at which this pressure difference is zero. A plane through the points on the building perimeter of zero pressure difference is called the neutral pressure plane. If there are openings at the top and bottom of equal size, they impose an equal resistance to flow and the pressure differences through them are therefore of equal magnitude. For continuity of air flow, the pressures at top and bottom must be equal in magnitude but opposite in sign and the point of zero pressure difference, and thus the neutral plane, will be at mid-height.

With real buildings the openings in the envelope will seldom be uniformly distributed from top to bottom, but in all cases the inflow must equal the outflow. If the openings at the bottom, for example, are larger than those at the top, a smaller pressure drop would be required through them relative to the top openings to give the same flow. The neutral pressure plane would be lowered. Similarly if the openings at the top are larger than those at the bottom, the neutral pressure plane would be raised.

Ventilation Systems

A ventilation system must create pressure differences, at some points, between the inside of the building and the outside. Air must be drawn in somewhere and an equal volume must be exhausted somewhere else. With a natural ventilation system, the wind and temperature induced forces (stack effect) are used to create the necessary air flow; with a mechanical ventilation system, fans are used to do this. Depending upon the design of the system and the way it is operated, a mechanical ventilation system can create either a positive or a negative pressure on a building. If there is an excess of exhaust over supply, then the extra air required will be drawn in through some of the openings in the building envelope; the neutral plane will be raised. This will prevent moisture-laden air from infiltrating into the building envelope, which is good from the point of view of building durability, but it creates the possibility of chimneys being backdrafted, as mentioned before, and it may also cause cold drafts to enter the building at uncontrolled points. To stop such drafts, the system could be designed with an excess of supply over exhaust. This, however, forces warm moist air out of the building into the envelope, with the almost certain result of condensation and building deterioration. Since it is this possibility of rapid deterioration that one is trying to avoid, this too is an undesirable system.

In view of the possible problems, both with a suction on the building and with a pressure, it is desirable to design a ventilation system with balanced supply and exhaust. This is not an easy matter, since the performance of the system may vary with wind and temperature effects on the intake and exhaust ducts. There will also be intermittant effects of special purpose fans, such as clothes dryer exhausts, and of chimney draft that will be difficult to integrate into an overall ventilation system. The actions of the occupants in opening doors, windows or vents and in changing the settings of dampers will also affect the operation of the system. In any case, because of stack effect, the ventilation system can balance pressures through the envelope at one level only.

Considering all of these factors, it is difficult to determine in advance the pressure differences across the building envelope or even to be sure of the direction in which they will act. In general, however, during most of the period of cold weather, when condensation may accumulate in the building envelope, there will probably be an air pressure inwards at the bottom of the building and outwards at the top.

Since it will be more or less inevitable that, for long periods of time, there will be an air pressure tending to move air outwards from the building at some locations, and since this air will probably have more water vapour in it than it can carry at the outside temperatures, the only way to stop condensation within the building envelope is to eliminate all of the holes through which it could leak into the envelope. In other words, to be durable the building envelope must be made air-tight; this is a formidable task.

Formidable or not it must be tackled. It is not a case of energy conservation, nor of the comfort of the occupants, but of the durability of the building itself. Fortunately energy conservation and comfort are additional benefits derived from an air-tight building.

VAPOUR BARRIERS, AIR BARRIERS AND AIR-VAPOUR BARRIERS

For many years the term "vapour barrier" has been used to describe a specific element that has a high resistance to the diffusion of water vapour under the action of a vapour pressure difference. More recently, the comparable term "air barrier" has been used to describe an element that stops the movement of air under the action of an air pressure difference; it does not necessarily have to meet the vapour diffusion requirements of a vapour barrier. The term "air-vapour barrier" is used to describe an element that both stops the movement of air and has the characteristics of a vapour barrier. Unfortunately, since polyethylene film has been used extensively as a vapour barrier, all three terms tend to conjure up visions of its use in all cases. This is certainly one possibility, but it is not the only one.

To reject the use of the term air barrier and just to talk about air-tightness has some drawbacks, since it is necessary to define the position within the thickness of the building envelope at which one wishes to stop the passage of air. One could talk about the plane of air-tightness to signify the location, except that it need not be all in one plane, even within one component, and in fact has to be continuous on all faces of the building.

It is preferable to use the terms air barrier, vapour barrier and air-vapour barrier, provided it is clearly understood that they do not imply the exclusive use of thin flexible membranes. Many materials can be used, ranging from coats of paint to solid concrete slabs, provided that they fulfill the required functions.

There is also the question as to what actually constitutes the air barrier. Is it the air-impermeable item itself, even if that item cannot resist the air pressures without support? Or is it the combination of the air impermeable item and its supports? If the former, then bubble gum is an air barrier and one must specify how it is to be supported. If the latter, then one must not rule out the use of thin membranes in conjunction with suitable supports, as opposed to those materials that have adequate strength on their own.

The former definition will be used in this dissertation, since it allows for greater flexibility in design. Materials can be selected for their individual properties and ability to perform specific functions. They can then be combined with other componants of the envelope that may be required for other purposes, without those other componants being defined as forming part of the air barrier itself. For example, wood studs are required in the wall of a house to form part of the structure that supports floors and roofs. They do not have to be defined as forming part of the air barrier, despite the fact that they are one essential part of the support for a polyethylene film that provides the air-tight layer in the wall.

It is essential that the loads that will act on the air barrier be recognized and suitable support be provided for all its components. The air barrier and its structural support must act together as a system.

Not only must the strength of any particular material be considered, but also that of its attachments to its supports or the structure of the building, or to other components of the air barrier. For example, a sheet of polyethylene may be strong enough to withstand the air pressures when backed by wood studs at 600 mm spacing, but it may rip off the top and bottom plates and at points of overlap if it is just stapled into place. It may also rip off the staples when the wind direction changes and it is being blown away from the studs rather than back against them. It should always be remembered that strong suctions will be acting on a building as well as positive pressures. Joints between components must be just as strong as the components themselves and must retain that strength for the life of the building. Thus caulking may need a backup support or to be clamped between rigid components. An adhesive tape may dry out and lose its adhesion after a period of time.

Characteristics Required of an Air Barrier

What then are the functions of the air barrier? The most obvious requirement, but at the same time the one that is most difficult to fulfill, is that it should be complete. All the various items and materials that go to make up the air barrier must be joined in some way that will stop the passage of air. In most cases, the air barrier is buried in the thickness of the building envelope and so its completeness cannot be verified after construction. For this reason, it is sometimes argued that the inside finish should form the air barrier. This has some merit, for any damage to it can be seen and repaired. However this presupposes that the occupants of the building recognize that the inside finish is the air barrier and realize its importance. This is unlikely to be the case with most occupants and while the inner surface is easy to repair, it is also easy to damage.

The second essential function of the air barrier is that it must be strong enough to withstand the maximum air pressures from the combined effects of wind, stack action and ventilation. The prime function of any building is to stop the wind from blowing through it and the air barrier is the component in the envelope that has to do this. This requirement applies equally to all components of the air barrier: the glass in the window, a sheet of plastic, tape over a crack or caulking in a joint.

The strength requirement of the air barrier also relates to the third requirement, that it be durable. The structure of the building is expected to last for long periods, usually the useful life of the building, without needing repairs. The air barrier is the principle defence against deterioration of the building envelope because of undesirable concentrations of water, and so is almost as important as the structure. Thus it should be required to have an equal durability. Clearly it will not be durable if it does not have sufficient strength, in all its components, to withstand the loads imposed on it.

A fourth requirement is that the air barrier be adequately stiff or rigid; a requirement that relates to three factors. First there is the previous requirement for durability; an air barrier that is constantly flexing back and forth may become brittle and crack or work loose from its fastenings. Second, a flexible air barrier may dislodge insulation that should be in contact with it and so create spaces in which room or outside air may circulate. It may compress a mineral wool insulation behind it thus, temporarily at least, reducing its thermal resistance. Third, pressure equalization must be maintained in a space behind the wetted facade as a means of controlling rain penetration. Pressure equalization will occur under steady wind loads even though the air barrier may be completely flexible. With fluctuating wind pressures, however, air will be constantly pumping in and out of this supposedly pressure-equalized space, and water may be forced inward. Just how much stiffness is adequate has not been determined as yet, but clearly an unsupported flexible membrane is not stiff enough.

LOCATION OF THE AIR BARRIER

Simply to say that the building envelope must stop the exchange of air between the outdoors and the inside of the building is not enough. Problems can still arise if either room or outdoor air flows into and back out of the envelope without any through leakage at all.

Because of the temperature differences between the room and the outer portions of the wall, convective air flow may take place. Warm moist room air could enter a wall at a high level, be cooled by contact with the colder portions of the wall and return to the room at a lower level (Figure 9a). If this air is cooled to below its dew point temperature, some moisture will condense within the wall. While there is some evidence that this does occur, the severity of the problem has not been established. With the extended periods of cold in the North, it could be serious. Nor is it known by how much the effectiveness of the insulation is reduced, although clearly there must be some reduction.

Similarly cold outdoor air can enter a wall at a low level, be warmed by contact with the warmer portions and return to the outdoors at a higher level (Figure 9b). In this case no condensation can take place in the moving air stream since it is being warmed, not cooled. In being warmed, however, it will cool the inside panel and if this is cooled to below the dew point temperature of the room air, condensation will occur on the room side of the interior finish. The forces producing this convective air flow from the outside are identical with those producing a convective flow from the inside, since both are produced by the same temperature difference. On the other hand, much larger air flows can take place within the insulated cavities of the envelope because of wind action. Condensation and even ice formation on the warm side have resulted, which indicates a great reduction in the effectiveness of the insulation. Thus stopping air from leaking into or out of the building is not enough to ensure a durable building. Convective and wind-induced flows through and around the insulation must also be stopped. These requirements, which are additional to the basic one of stopping through air flow, create a dilemma as to the correct location of the air barrier in the thickness of the building envelope.

Just as condensation in the envelope as a result of through air leakage (exfiltration) must be prevented by stopping the air leak so must condensation as a result of a convective flow be prevented by stopping the convective flow. This can be achieved in either of two ways. The holes on the warm side of the insulation through which the room air enters and leaves the envelope can be closed off by what can be called a "convection barrier" (Figure 9a); or the spaces in the envelope on the cold side of the insulation that provide a passage for the convective flow can be eliminated. This can be achieved by installing air impermeable insulation in full contact with the sheathing. This is not a matter of sealing the joints between the boards or panels of insulation; to do that is to attempt to make a convection barrier out of the insulation.

To stop wind-induced air flow through or around the insulation requires that either the insulation be covered with an air-impermeable layer on the outside or that the insulated cavity have no exit through which the air could leave. The first solution is an obvious one and since the function of the covering is to stop the wind, it could be called a "wind barrier", or alternatively a "weather barrier", since the total exterior covering must also keep rain and snow out of the building envelope. The second solution is akin to a box that is sealed on all faces except for an opening on the windward face. Since there is no opening through which the wind could leave the box on the leeward side, it will not enter on the windward. A small amount of air will enter the box to pressurize it to the wind pressure but thereafter there will be no air flow.

Thus to stop air movement through or into and out of the building envelope, the need for three different sorts of barrier has been identified (Figure 10):

- an infiltration/exfiltration barrier to stop through air leakage;
- a convection barrier to stop convective flow from the room;
- a wind barrier to stop the wind from blowing through or round the insulation. (This will also stop convective flow from outside).

To stop condensation resulting from convective flow, the convection barrier must be located where it will be kept above the dew point temperature of the room, i.e. near the warm side. To keep the wind out of the insulation, the wind barrier must be outside of the insulation. To stop through air leakage only, the infiltration/exfiltration barrier can be located anywhere through the thickness of the envelope. Clearly then, the infiltration/exfiltration barrier can be combined with either the convection barrier or the wind barrier, and since the first function of the building envelope is to stop the uncontrolled flow of air into and out of the building, the combined pair of barriers can be called the prime air barrier. Since it does not matter where the air barrier is located, as far as stopping through air leakage only is concerned, its location will be determined by consideration of the factors that may cause condensation, including the likelihood of achieving continuity under realistic construction conditions on the site.

When choosing a location for the air barrier, the designer should consider three interrelated factors:

- the probability of being successful in preventing condensation;
- the consequences of failing to do so;
- the possibility of drying out such moisture as may collect in the envelope before it can do any harm.

To prevent condensation, room air must not enter the envelope; thus both through leaks and convection currents must be stopped. This would argue for combining the convection and the infiltration/exfiltration barriers to form the air barrier, which would thus have to be located near the warm side of the envelope. Unfortunately with conventional construction, it is difficult to ensure that a barrier in this location is complete and air-tight round the various components, structural and otherwise, that may penetrate it. These difficulties can be overcome with suitable details, but construction becomes more difficult and costly and there are many opportunities for mistakes. These problems can be reduced by using less conventional designs, such as double stud wall construction for houses, that bring the structure inside the major portion of the envelope, and by locating the air barrier outside of the structure, with adequate insulation outside of it to keep it above the dew point temperature of the room. There may still be some problems with attachment of the outer portions of the envelope but these can usually be overcome in ways that maintain the integrity of the air barrier.

The alternative approach is to combine the infiltration/exfiltration barrier with the wind barrier, and to locate this air barrier on the outside of the building envelope immediately behind the outer cladding. Such a location usually provides a much simpler uninterrupted surface to be sealed. Attachment of the cladding need not damage the air barrier. With house construction, nails securing the siding, for example, will penetrate the air barrier but will automatically plug the holes to stop air leakage. An air barrier on the outside will be subjected to a much greater range of temperatures and so greater strains will be imposed on the materials, which may lead to premature failure. With a flat or nearly flat roof, an air barrier on the outside would mean that the roof membrane would also be on the outside; this would rule out the use of a protected membrane system, which uses a membrane, and thus an air barrier, on the warm side of the insulation. With pitched roofs, the air barrier can be outside of the roof sheathing but underneath the shingles, with the insulation in contact with the underside of the sheathing. With elevated floors, there would be some problems of carrying the air barrier over the foundation supports, if it were located on the outside. However, with such floors and a platform type of construction, it is not difficult to carry an air barrier located on the warm side of the floor assembly out to the outer edge to join with an air barrier on the outside of the wall.

If the air barrier is located on the cold side of the insulation, then to prevent condensation on it, it is necessary to provide a separate convection barrier located near the warm side. Ideally such a convection barrier should be air-tight, but the big difference between a convection barrier and an air barrier is the magnitude of the forces that act on it. The air barrier, as the prime means of stopping the uncontrolled movement of air into and out of the building, must withstand the maximum combination of wind and other air pressures acting on the building. The forces acting on a convection barrier, on the other hand, are quite small. Thus strength is not a major factor. But the convection barrier should be complete, which reintroduces problems similar to those encountered in making a complete air barrier on the inside. How complete it must be has not been established, but any convective flow that may take place will continue so long as there is a temperature difference to produce it. In the North, this could be for long periods of time. The alternative to a complete convection barrier is to eliminate the spaces for air circulation. It is not known whether or not an air-permeable insulation such as fibre glass will solve the problem if it completely fills the insulated cavity but there is always the possibility of misplaced insulation leaving a void on the cold side.

Therefore it is difficult to be sure that condensation will not occur in the envelope no matter where the air barrier may be located. On balance, the greatest probability of success may be obtained with an air barrier located far enough out from the warm side to eliminate penetrations by the structure and other items but with sufficient insulation outside of it to keep it above the dew point temperature of the room air. Because of uncertainty about many factors, including site construction conditions, it is as well to err on the side of caution and to have as many factors as possible working in favour of success.

The severity of the consequences of failing to prevent condensation in the envelope will vary with the amount of water that accummulates and the length of time that it remains before the material dries out again. The amount of water that accummulates depends upon many factors, as discussed earlier. The rate of drying out depends upon the availability of drainage, ventilation and diffusion.

With long periods of cold weather, considerable quantities of water can accummulate as hoar frost or ice, to be released at one time when conditions moderate. The quickest way to get rid of this water is to drain it out; in fact it is difficult to stop it from draining, since it will leak out through any available passage. Such passages may, however, lead inside the building, resulting in water damage to the interior finish or contents of the building. Drainage will remove ponded water but not water absorbed in the materials. The most effective way to remove absorbed water is by ventilation. Relatively dry air passing into and out of the wetted cavity can pick up moisture and carry it away. This movement can take place in one of two ways: most conventionally by the passage of air right through the cavity but also by a pumping action of air into and back out of the cavity. A flow of air through the cavity requires two holes and a pressure difference; it is the more effective method. The pumping action requires only one hole and a fluctuating pressure, which could be caused by wind gusts or by changes in temperature in the cavity. Drying by diffusion can take place either to the outside or to the interior of the building, depending upon the differences in vapour pressure and the vapour permeabilities of the materials. It is, however, a relatively slow mechanism for drying and in view of the short periods of warm weather in the North, it is unlikely to be a reliable method of drying out more than small quantities of water.

In summary, a complete air barrier on the warm side eliminates condensation in the envelope but may be difficult to achieve under practical construction conditions. In the event of failure to prevent condensation, both drainage to the outside and ventilation of the outer cladding can be provided. On the other hand, the insulation must be protected against the intrusion of the wind. This can be achieved with a complete air barrier on the outside, where it is usually easier to achieve completeness than on the inside. Some action must then be taken to prevent convection currents from inside circulating in the envelope. When the air barrier is on the outside, neither drainage to the outside nor ventilation of the inner surface of the air barrier, where the condensation will occur, is possible. Only diffusion is available as a drying mechanism. Protection of the insulation against wind intrusion is provided automatically.

Possibly the best of both worlds can be achieved by a design that locates the air barrier on the outside of the structure and outside all other items that would otherwise penetrate it, but with a balance of insulation inside and outside the barrier to keep it above the dew point temperature of the room air. One drawback for northern construction conditions is that the insulation must be installed from the outside before the outer cladding can be applied.

THE WIND BARRIER

If the air barrier is not located outside of the insulation, then some further action must be taken to stop the wind from blowing through or around the insulation. The insulation never forms the outer surface of the building but is always located behind some form of exterior cladding. In many cases, however, this cladding is not air-tight, either because in conventional construction there is no attempt to make it air-tight, or because holes have been made in it deliberately, for pressure equalization as a rain screen or for drainage. Thus one cannot rely upon the outer cladding to keep the wind out of the insulation.

An obvious way to keep the wind out of the insulation is to cover it with an air-impermeable layer. This, in effect, makes a second air barrier. This will reduce through air leakage, since such defects as there may be in each barrier will not, in all probability, be opposite one another. Given two perfect air barriers, the air pressures to be resisted by each will be reduced. The inner barrier will carry the internal pressures from wind suction, stack effect and ventilation equipment, while the outer one will carry the external wind loads. However since perfection cannot be relied upon in practice, it will still be necessary to design both barriers to carry the full combination of air pressures from all mechanisms.

A further factor is the need to provide for the drying of the envelope should any water accummulate within it, either by condensation, or by rain or snow penetration. As discussed earlier, this can be achieved by drainage, by ventilation and by diffusion. Both drainage and ventilation require at least one hole connecting the insulated space to the outdoors. Diffusion requires that the vapour permeabilities of the materials on the outside be high enough to give a rapid rate of drying to remove the moisture during the short northern summers. Such a requirement would rule out the use of plywood as exterior sheathing, since it is equivalent to at least a Type 2 Vapour Barrier as defined by the CGSB standard for vapour barriers.

If some provision must be made to remove water from within the envelope, drainage and a limited amount of ventilation should be the prime methods of doing so and diffusion should be relied upon only as a secondary method. This, of course, means that the wind barrier cannot be made air-tight and alternative means must be adopted to stop the wind from blowing through the insulation and destroying its effectiveness. The alternative that is available is that the insulation must be in a dead-ended compartment, preferably with only one drainage hole connecting to the outdoors. With stud wall construction, the studs themselves may provide the necessary compartments to restrict the lateral flow of wind (Figure 11). With double stud walls, or those with horizontal furring or strapping outside of the air barrier, there is no such compartmentation. The same is true of roofs other than flat roofs and cathedral ceilings, with no furring at right angles to the joists. In such cases special steps must be taken to divide the insulated cavity into compartments. The next question is how large can a compartment be or at what locations on the envelope must there be divisions?

With small cavities, such as 600 mm stud spaces, only one drainage hole should be required. With larger cavities, several holes may be required and these holes may be subjected to differing wind pressures that would promote air flows through the insulation. Divisions must be provided to control these flows and so wherever there is a rapid change in wind pressure, there should be a barrier to stop lateral air flow. Referring back to the discussion on air pressures on the building envelope, wherever there is an abrupt change in direction on the face of the envelope, there will be a rapid change in wind pressure. Thus there should be dividers at the corners of the building, at the junction between the wall and the roof, and, in those cases where the wind can blow under the house, between the wall and the floor. Localized changes in direction, such as for projecting bay windows, probably do not need a division at each corner; the whole should be treated as one compartment. Curved surfaces have no clearly established locations for dividers but one at every 15° change of direction should be reasonable, except for very short radius curves, where a minimum spacing of about one metre could be adopted. Even on plane surfaces there are variations in wind pressure, so additional dividers should be provided every ten metres or so along a long surface and preferably between one and two metres from a corner to accommodate the relatively rapid changes in air pressure near these abrupt changes in direction. There are no clear-cut rules for determining the correct location for dividers other than at each major abrupt change in direction in the surface of the building envelope. Beyond that the designer must consider the possible wind flows around the building and act accordingly.

CONCLUSION

The control of water vapour so as to prevent condensation is the single most important factor contributing to the durability of the building envelope. It is at least equal in importance to structural aspects such as wind and snow loads, and to foundation design to control uneven movements.

Of all the aspects of moisture control, the control of air movement through and within the envelope is paramount. If there is no movement of air from inside the building to locations that are below the dew point temperature of the air-vapour mixture, then condensation within the envelope will be limited to the small amounts that may be deposited by diffusion. Should there be a flow of cold outside air within the envelope sufficient to cool the air barrier to below the dew point temperature of the inside air-vapour mixture then condensation will occur on the warm side of the air barrier. Such an air flow, whether it leads to condensation or not, would greatly reduce the effectiveness of the insulation. Without condensation, however, this is an economic problem of increased heat loss rather than of building durability, although it could affect the comfort of the occupants because of colder interior surfaces.

Three types of air movement must be controlled: a through leakage of air from inside to out; a convective flow of warm moist air from the room to a location within the envelope that is below its dew point temperature; and a flow of outside air through or around the insulation, by convection but more often because of wind forces. Inward leakage from the outside is largely a problem of increased heat loss and comfort rather than of durability unless it carries fine snow or rain with it.

Since the prime function of the building envelope is to stop the wind from blowing through the building, the barrier that stops the through air leakage can be designated the prime air barrier. Its precise location is still subject to debate. If it is to prevent through air leakage it must be complete and completeness is easier to achieve on the outside, where there are fewer items that must penetrate it. But, if the air barrier is on the outside it will be subjected to wide fluctuations in temperature which may overstress it, and at some times, it will be below the dew point temperature of the inside air. If this air can reach the air barrier, water will condense on it. Locating the air barrier on, or near, the inside will overcome these problems. Probably the most desirable location for the air barrier is outside the structural components of the envelope and all piping or wiring, but with sufficient insulation outside of it to keep it above the dew point temperature of the inside air. No matter where it is located, it must be strong enough and be sufficiently well supported to withstand the combination of air pressures to which it may be subjected.

If the air barrier is positioned on or near the warm side of the envelope, then there will be no problem of convective air flow of warm moist air into the envelope and back to the room. There is, however, the need to provide a wind barrier to keep cold air flows out of the insulation. Conversly, this cold air flow will be eliminated if the air barrier is located outside of the insulated portion of the envelope; in this case convective air flows from and back to the room will have to be prevented, either by a convection barrier near the warm side or by air-impermeable insulation installed with no air space between it and the cold air barrier.

Vapour diffusion is not considered to be a major problem, but it should not be neglected. A vapour barrier of low permeability should be combined with the air barrier if it is near the warm side of the envelope, or with the convection barrier if the air barrier is on the cold side. Ideally the relative vapour permeabilities of the various components of the envelope should be chosen, in conjunction with their thermal properties, so that the saturation vapour pressures at all locations will be higher than the corresponding vapour pressures set by considerations of continuity of vapour flow. Under these circumstances, there will always be some potential for drying to the outside of any moisture that may enter the envelope by any other mechanism.

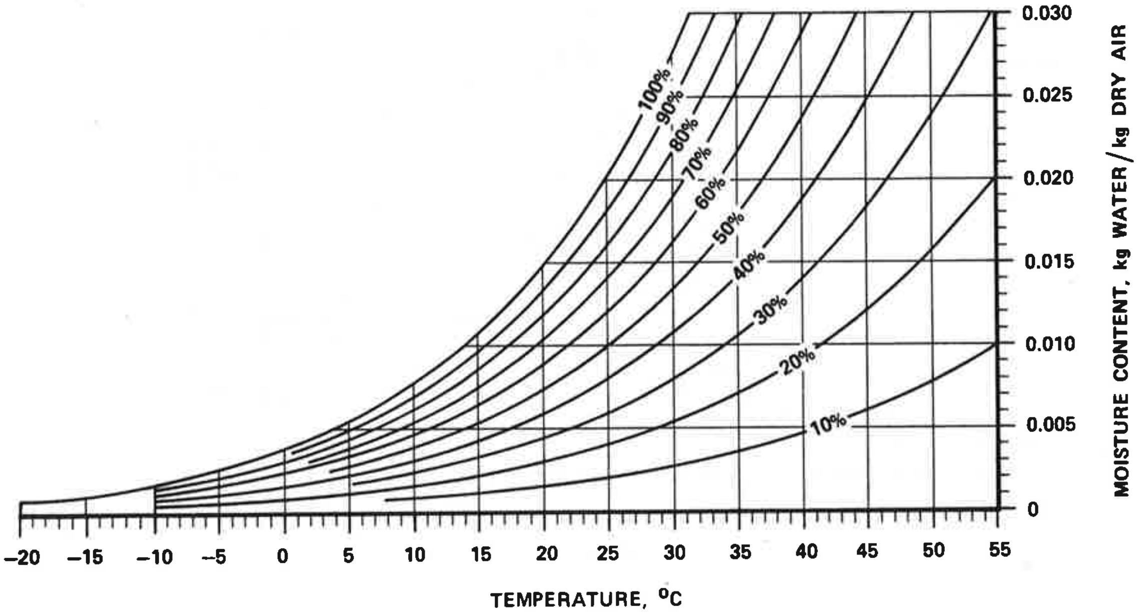


FIGURE 1

PSYCHROMETRIC CHART

BR 6638-1

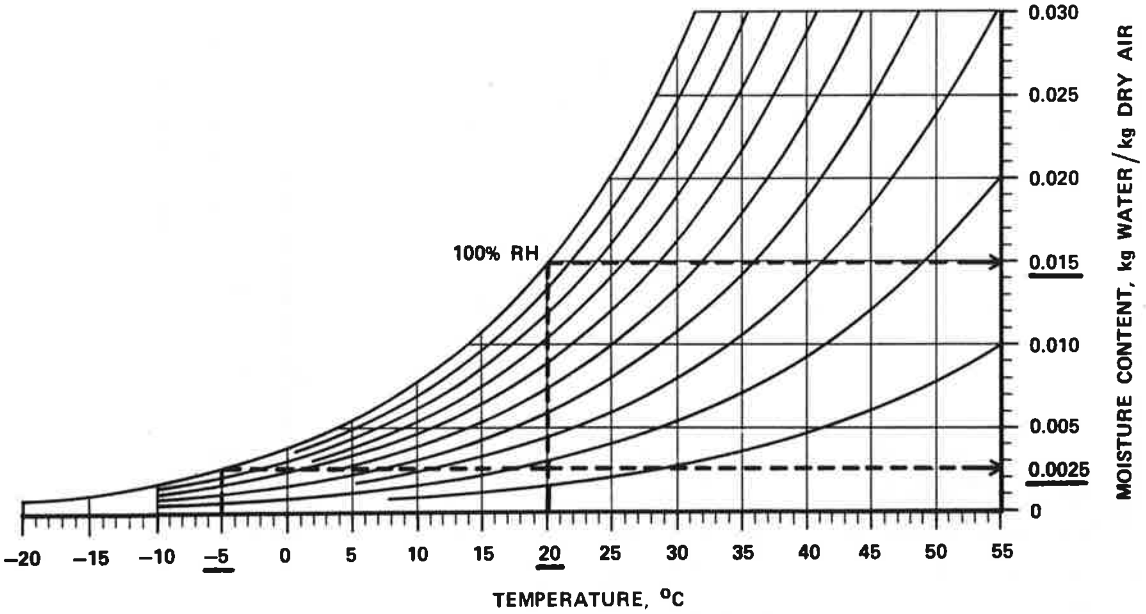


FIGURE 2

DETERMINATION OF MAXIMUM MOISTURE CONTENT OF AIR

BR 6638-2

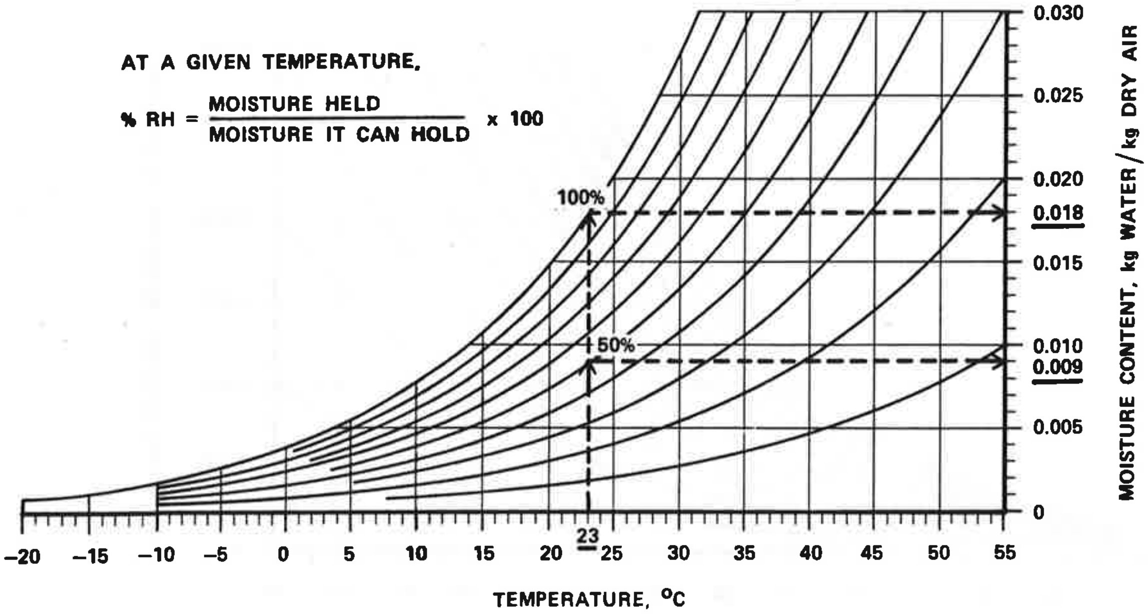


FIGURE 3

DETERMINATION OF RELATIVE MOISTURE CONTENT OF AIR

BR 6638-3

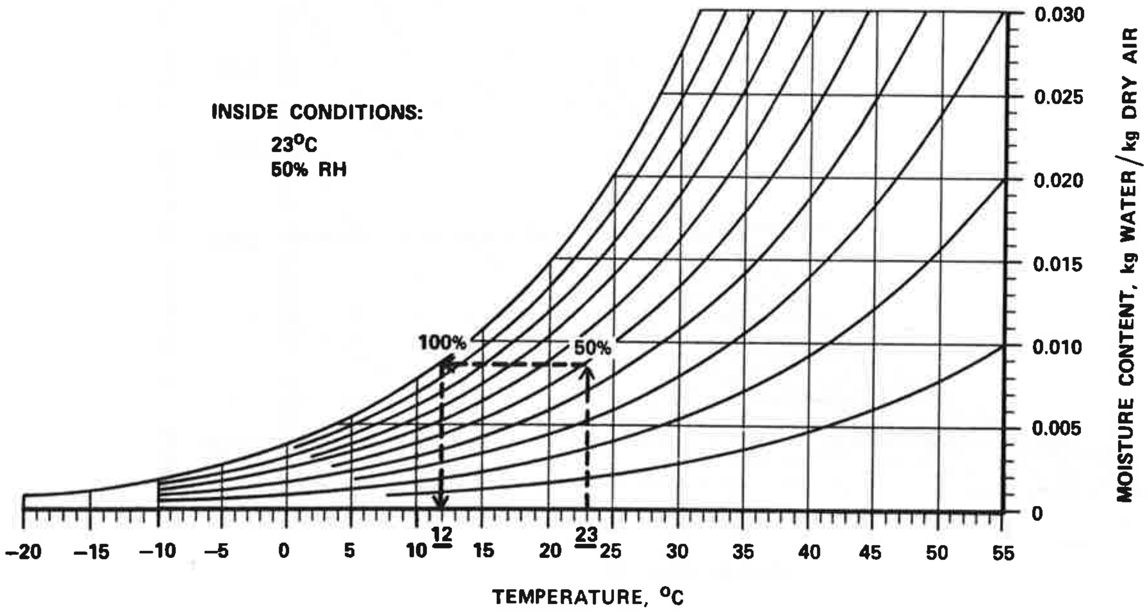


FIGURE 4

DETERMINATION OF DEW POINT TEMPERATURE

BR 6638-4

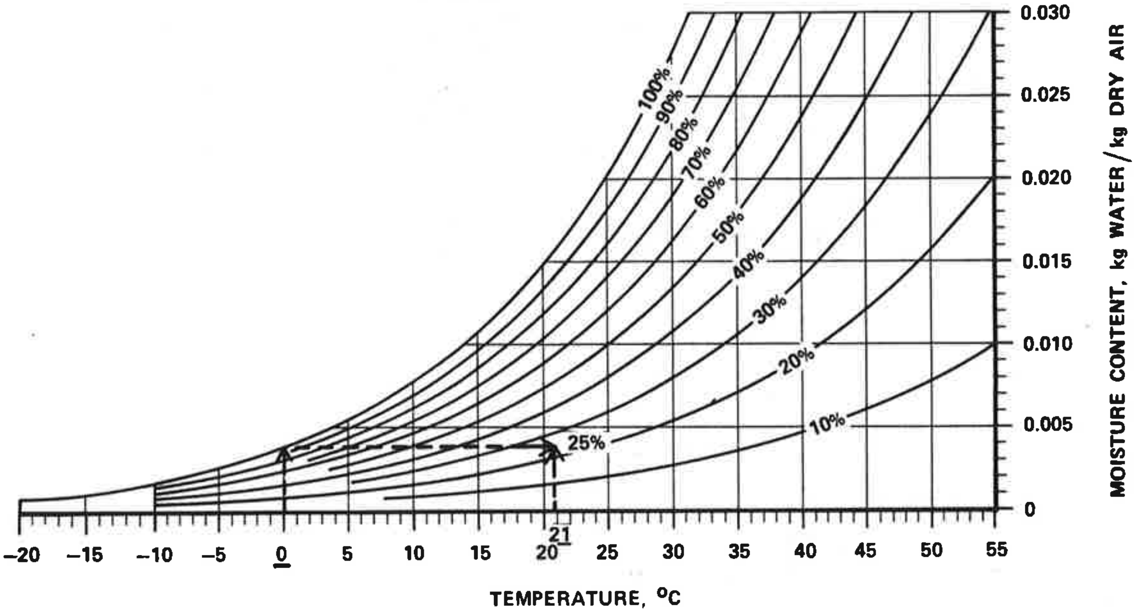


FIGURE 5

DETERMINATION OF MAXIMUM ROOM AIR RELATIVE HUMIDITY TO AVOID CONDENSATION ON A COLD SURFACE

BR 6638-5

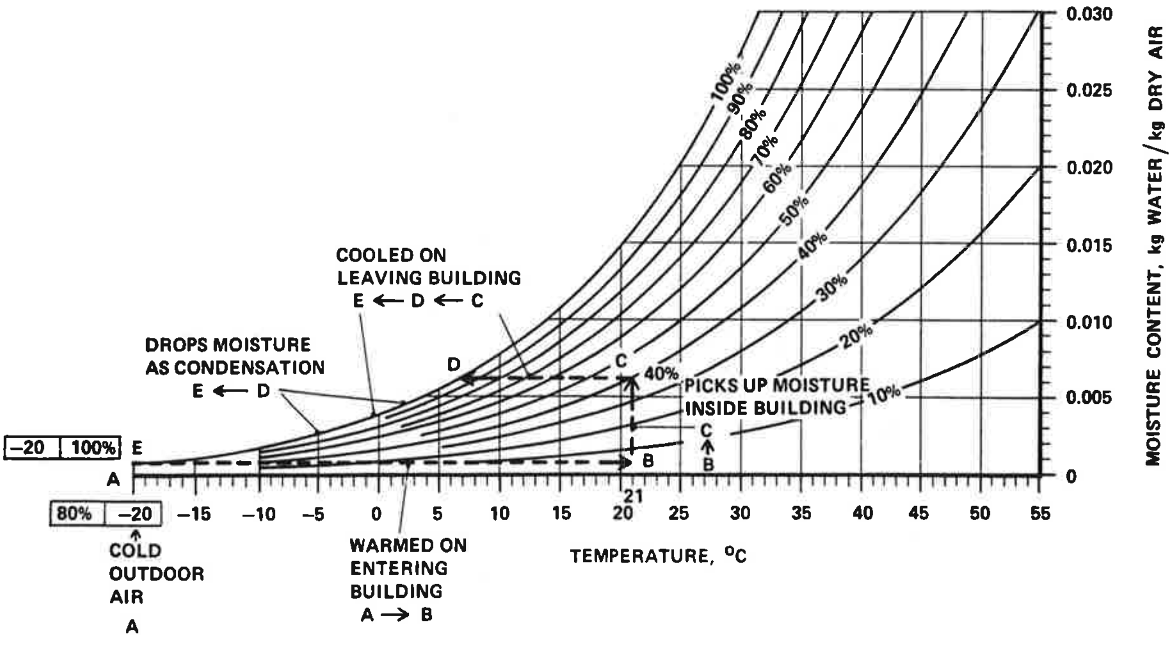


FIGURE 6

CYCLE OF AIR MOVEMENT INTO AND OUT OF A BUILDING LEADING TO CONDENSATION

BR 6638-6

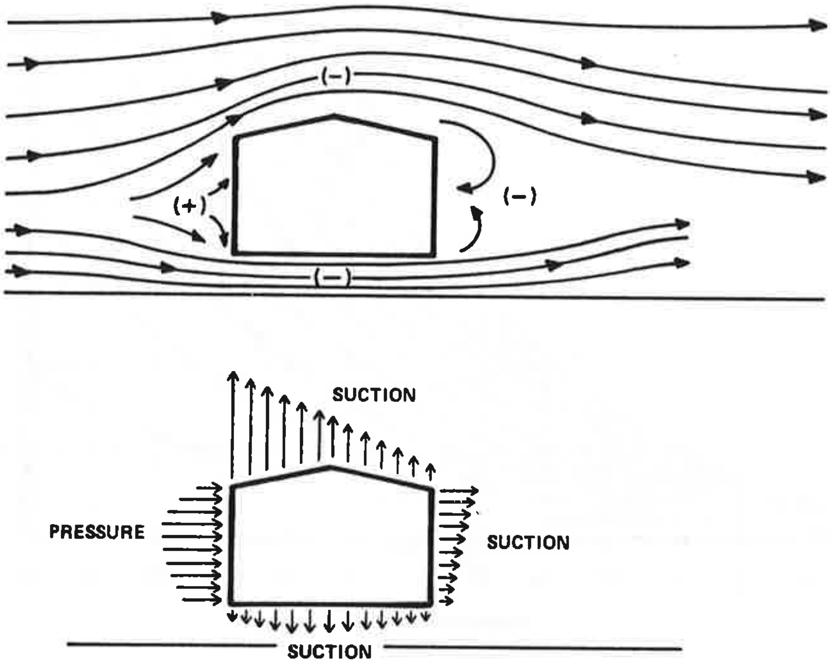


FIGURE 7

AIR FLOWS AND PRESSURES ROUND A BUILDING

BR 6638-7

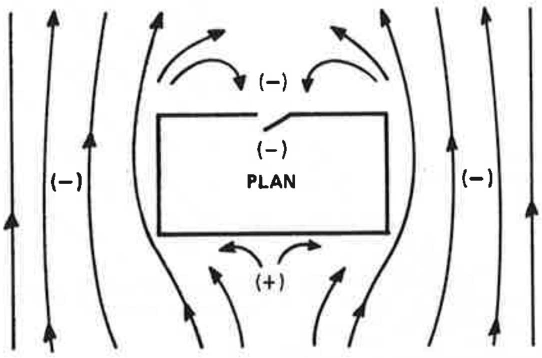
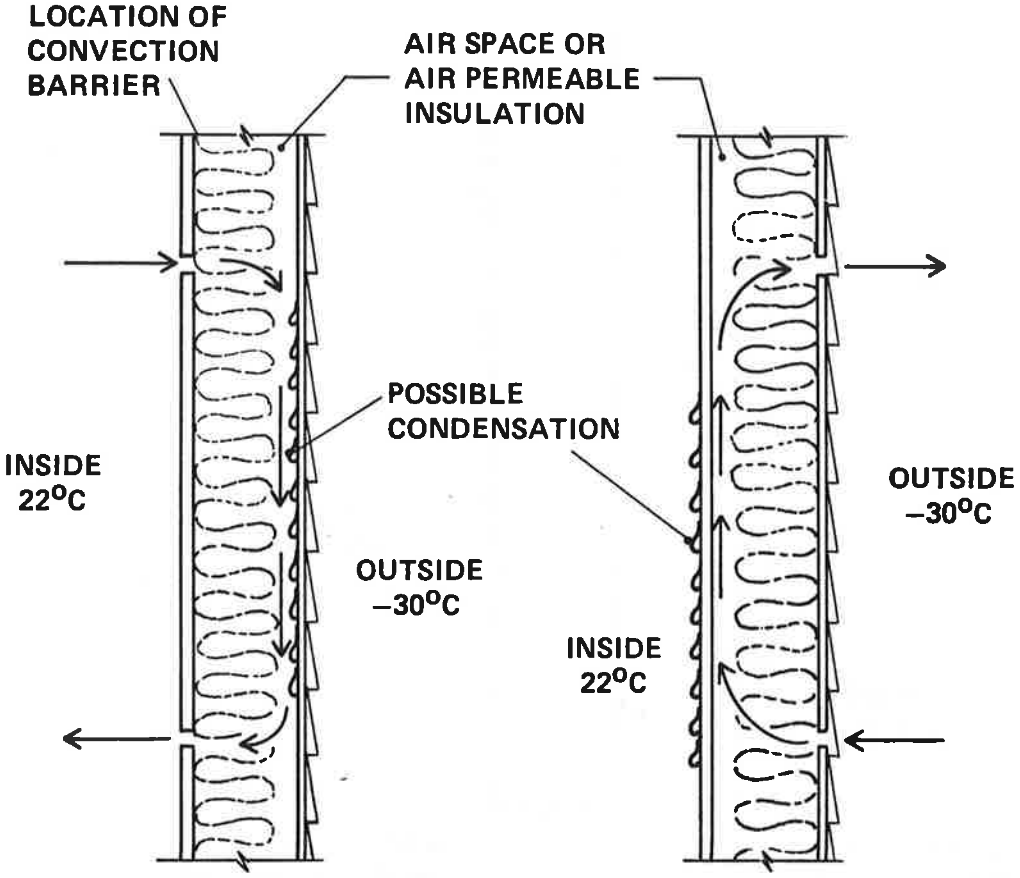


FIGURE 8

AIR FLOWS AND PRESSURES ROUND A BUILDING

BR 6638-8



(a) WARM AIR CONTACTS COLD OUTER SURFACE

(b) COLD AIR COOLS WARM INNER SURFACES

FIGURE 9

POSSIBLE CONVECTIVE FLOWS WITHOUT THROUGH AIR FLOW

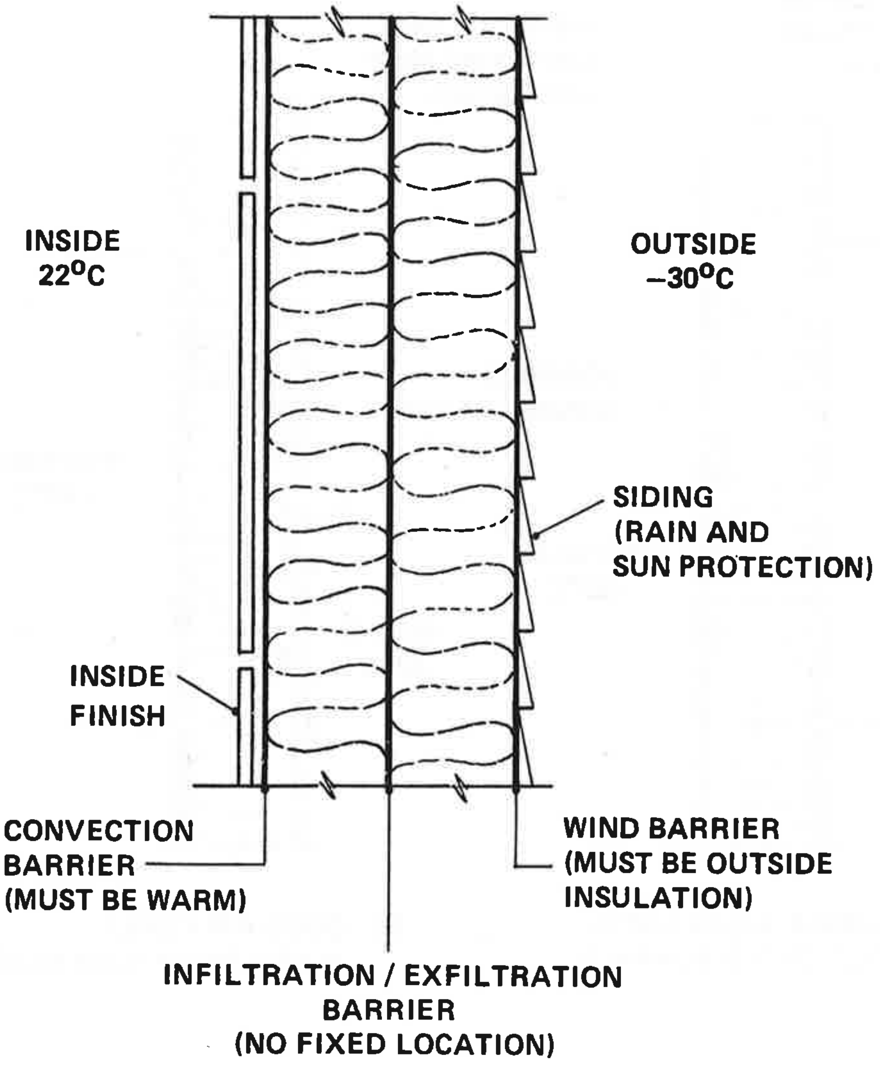


FIGURE 10

BARRIERS NEEDED TO CONTROL AIR FLOWS IN THE ENVELOPE

BR 6638-10

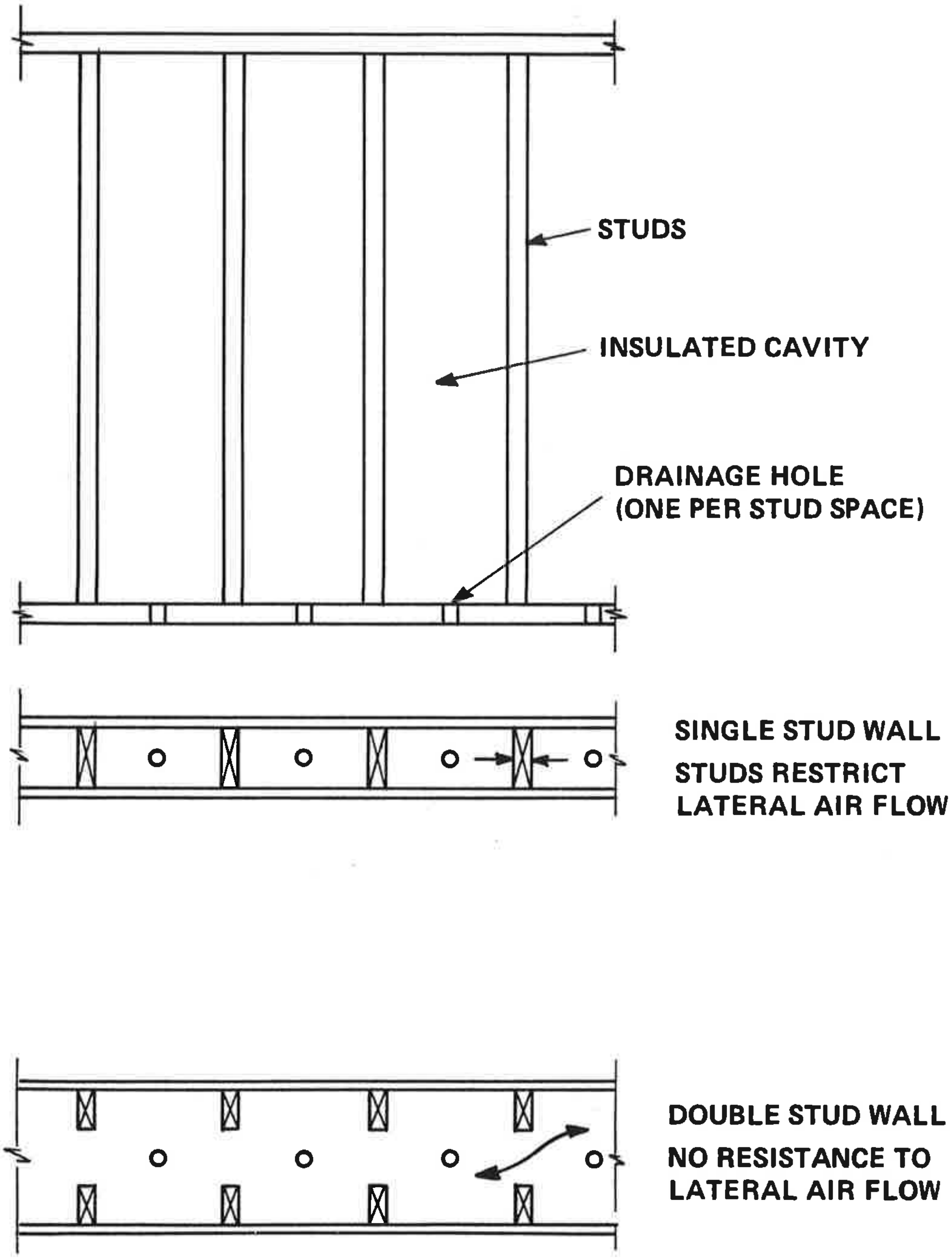


FIGURE 11

COMPARTMENTATION OF WALL SPACE

BR 6638-11

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