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THE EFFECT OF SEPARATING THE AIR AND VAPOUR BARRIERS ON MOISTURE MOVEMENT IN WALLS - A DISCUSSION PAPER

by

M.C. Swinton and G.P. Mitalas*

ABSTRACT

Proper air and vapour barrier design has been the subject of thorough research in Canada and elsewhere for over 40 years. The subject still remains open for controversy despite competent research efforts and despite the simplicity of prescriptive measures currently followed to help avoid interstitial moisture accumulation problems in envelopes.

A general approach to air and vapour barrier evaluation is proposed, based on the analysis of air and moisture flows at the surface of barrier materials. Current research on heat, air, and moisture flows in envelopes is reviewed to indicate how experimental results could be used to complement the evaluation procedure.

Qualitative evaluation was undertaken of the continuous and combined air/vapour barrier placed towards the inside of the envelope. It was found that this system not only satisfies the conditions that prevent water accumulation in envelopes, but also makes the proof of that fact a trivial matter - provided air leakage does not occur. Nonetheless, since perfect continuity of the barrier does not exist in practice, the effects of air leakage must be considered, regardless of air barrier placement. It is therefore recommended that all air and vapour barrier

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systems be subjected to a more detailed performance evaluation which takes interrelated air, heat and moisture flows within walls into account.

Qualitative evaluations and review of test results reported in literature suggest that air barriers and other materials on the outer (cold) portion of envelopes should incorporate one or more features that discourage moisture accumulation. These features were identified as:

- adherence to adjacent material surfaces to discourage interstitial air flows in leakage streams;
- thermal resistance between the barrier and outdoors to promote outward gradients in vapour pressure; and
- progressive permeability to vapour, air, or both, from inside to outside to promote vapour communication with outdoors - keeping in mind rain screen principles and those of good thermal design.

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1. INTRODUCTION

A limited review of the literature on the design and performance of air and vapour barrier leads to the realization that this topic has been researched by competent people and organizations for over 40 years [1]. And still the controversy over such questions as "Should the air and vapour barriers in envelope systems consist of one or two membranes?" The fact that this topic submits to easily worded prescriptions belies the complexity of the building physics behind the prescriptions. The problem with the prescriptive measures on air and vapour barrier design is that they **define**, to a large extent, what phenomena dominate; and this, in turn, limits the test procedures to those supporting the prescription. Research methodologies that lead to the development of the prescriptive measures consist largely of experiments that validate or refute a specific prescriptive measure. Yet, innovative envelope systems, extreme weather conditions, and variable field practice can introduce phenomena not previously considered in the research work developed to support the original prescription.

In evaluating the pros and cons of one- and two-barrier systems, more than 40 years of research confirm to the fullest extent possible the value of currently accepted prescriptions, but fall short of defining the general physics needed to make a fair evaluation.

To a great extent, the literature either consists mainly of **fundamental physics**, defining test procedures and reporting research results, or of **prescriptive** approaches supported by experimental and analytical work. Both streams of research are very much needed: the first to develop the knowledge base, and the second to assist designers in specifying more durable and effective envelope systems. But the two streams need to be integrated now so that further progress can be achieved in the field of air and vapour barrier design and its evaluation.

At this stage, a general procedure is needed for evaluating the performance of air- and vapour-barrier systems. Experiments involving combinations of simultaneous flows of air, heat and moisture, such as those conducted at The Institute for Research in Construction, IRC, [2,3,4] and the University of Toronto [5], are examples of this kind of broad evaluation of their performance. The computer-modelling work at the Technical Research Centre of Finland (VTT) and of the type that resulted in the WALLDRY program developed by Scanada and RWDI for CMHC [6] are other examples of research involving a broader handling of the physics; although, the latter modelling was tailored to confirm or refute the value of a prescriptive measure (strapped siding), and cannot in its present state be used to evaluate a range of air barrier systems.

In the absence of formal evaluation procedures for air barrier systems, the following considerations are offered in an attempt to evaluate whether the air and vapour barriers should consist of one or two membranes.

2. THE FUNDAMENTALS

Review of the Fundamental Mechanism of Moisture Accumulation

Consider the control volume drawn next to the inner surface of any material in an envelope, as shown in Figure 1. (The control volume could be drawn wherever an analysis is desired). The surface of a material facing the inside is a prime location for

e accumulation, as can be deduced from analysis of the
ng phenomena:

vapour accumulation
. water accumulation
related heat transfer
air flow and related heat transfer
. reaction of materials to heat and moisture

Accumulation

er an exterior wall, originally in moisture equilibrium s surroundings, that is suddenly subjected to an increase oor relative humidity; e.g., the wall of a bathroom in someone is taking a shower.

rate of flow of water vapour from the room to a point in velope exceeds the rate of outward vapour flow at that then vapour accumulation occurs at that point. (The er mechanisms for water vapour can be diffusion or air ort.)

lly, a boundary between materials that increases the ance to vapour diffusion can cause an imbalance between the of inward and outward vapour flow at the boundary. That s then in vapour accumulation at the boundary - at least arily.

lly the accumulation is in vapour form, resulting in an se in vapour pressure locally and a change in the balance ws, i.e., the rate of inward vapour flow decreases and the f outward flow increases.

Accumulation

above process is coupled with a low temperature of the al that makes up the boundary, then the saturation vapour re may be reached before equilibrium between incoming and ng vapour flows is achieved. Subsequent accumulation is in rm of water.

Related Heat Transfer

The formation of water not only increases the temperature locally (through latent heat release) but also alters the temperature profile through the wall since all elements of the wall are thermally connected. Some adjustments in the rate of accumulation occur as a result of this change in the temperature profile in the wall, since the saturation vapour pressure is a function of temperature.

Air Flow and Related Heat Transfer

If an air stream comes in contact with the air barrier, the heat and moisture transfer mechanisms also occur between the air stream and the barrier. Convective and latent heat transfer between the air stream and the material alters the local temperature profile and hence the moisture flow.

Reaction of Materials to Heat and Moisture

Materials have an immediate and a long-term reaction to heat and moisture flow. Properties such as the thermal conductivity of materials change or appear to change with moisture flow and moisture accumulation [4]. As well physical dimensions change with changes in temperature and moisture content. The long-term fit of materials at the interfaces of assembly components is affected by the history of moisture content in the materials [7].

It is believed that most of these factors can come into play when the thermal performance of an envelope system as well as its air and moisture performance are to be evaluated. An approach to evaluating this complex set of considerations is proposed in subsequent text.

3. PROPOSED EVALUATION APPROACH

Formulation of a General Expression of the Moisture Accumulation Conditions

In general, from the principles of conservation of mass and of vapour diffusion and transport elaborated in [8], moisture accumulation occurs at any point in the envelope where:

{Influx of Vapour by Diffusion & Air Flow} > {Outflux of Vapour by Diffusion & Air Flow}

Specifically, in the control volume in Figure 1, **moisture** accumulation occurs when:

$$[(A.(\Sigma\{\mu/L\}_u \cdot (pp_u - pp_{satl})) + \dot{m}_{as} \cdot q_{in}] \cdot t >$$
$$[(A.(\Sigma\{\mu/L\}_d \cdot (pp_{satl} - pp_d)) + \dot{m}_{as} \cdot q_{out}] \cdot t \qquad (1)$$

where:

A = area of the envelope under analysis
L = thickness of the materials between the point of analysis and the inside or outside
$\dot{m}$ = mass flow rate of air
μ = water vapour permeability of each material separating the local layer from the inside or outside
pp = partial pressure of the water vapour
q = specific humidity (related to the humidity ratio)
t = time

subscripts

as = air stream passing through the control volume
sat = saturated
d = downstream (exterior)
u = upstream (interior)
l = local surface of the air barrier
in = air stream into the control volume
out = air stream out of the control volume

Conversely, water accumulation from vapour flow cannot occur if the condition of Equation 1 is not satisfied; i.e., if the left-hand expression is less than or equal to the right-hand expression, then moisture accumulation cannot occur by means of vapour diffusion or transport through the envelope.

Other sources of water in walls, among them wind-induced rain penetration, and drying mechanisms, of which surface drainage due to gravity is but one example, have been deliberately left out of the moisture balance condition expressed in Equation 1, because the focus of this paper is on the avoidance of moisture accumulation due to vapour transfer from the interior. A similar set of conditions could be set up for exterior-sourced moisture adhering to and draining from material surfaces.

In Equation 1, q_{in} is the specific humidity of any air stream passing over or through a material surface. This may be the specific humidity of inside or outside air, or their combination, depending not only on the origins and paths of the air leaks, but also on the amount of moisture the air has picked up or dropped on its way to the surface of the material being investigated. The air flow rate, $(\dot{m})$, is a function of the leakage characteristic of the envelope and the differential air pressures acting across it.

q_{out} is the specific humidity of the air leaving the control volume; it is a resultant of the moisture transfer rate from the air stream to the material surface. Thus, q_{out} is an unknown. Again from the principle of conservation of mass, the balance of moisture in the air stream can be expressed as:

$$\dot{m}_{as}(q_{in}-q_{out}) = [A.(\mu_{bl}/L_{bl})\cdot(pp_{as} - pp_{satl})] \qquad (2)$$

where the subscripts bl is the boundary layer.

A zero or negative right-hand expression in Equation 2 signifies **no** water accumulation as a result of vapour flows from air stream to material surface; i.e., if the vapour pressure in the stream is less than the saturation pressure at the surface of the material, the air stream cannot deposit water on the surface of the material.

pp_{as} is a function of the rate of incoming air flow and the rate of vapour flow from the air stream to the layer in the envelope. It is another unknown. *q* and *pp* are linked through the following psychrometric expression, derived from [9]:

$$q = pp / (pp + 1.6078 (p_{atm} - pp)) \quad (3)$$

where p_{atm} is the atmospheric or total pressure.

Hence, the above system of equations can be solved for given material permeabilities μ and air leakage rates $\dot{m}$ to give q_{out}.

The actual evaluation of the properties of materials in the equations, i.e., the permeability μ, as they behave in dynamic heat, air, and moisture flow conditions in the envelope is not easy; it is, in fact, the subject of active research at IRC [4]. In particular, the effective permeability of the boundary layer is difficult to establish experimentally, but attempts have been made for the flow of moist air over dry wood product surfaces [6]. Flow coefficients needed to resolve the air flow rates through assemblies ($\dot{m}$ in equation 1) have been determined experimentally by Forintek for both initially green and dried wood-based assemblies [7]; for a range of building materials by AIR-INS [10]; for various siding assemblies by RWDI [6]; and for air barrier systems by IRC [11].

Difficulties, of course, remain in the application of these test results to the basic equations presented earlier; these difficulties should not deter from the utility and applicability of these equations, since much can be learned from qualitative evaluations based on these equation.

4. QUALITATIVE EVALUATIONS OF THE ONE- AND TWO-MEMBRANE SYSTEMS

The One-membrane System

If an effective air/vapour barrier is continuous, thermally close to the inside, and thermally distant from the outside (e.g., the vapour barrier is located just behind the interior finish of an insulated wall), then pp_1 is always less than pp_{sat}, as long as the interior air is not at or near saturation itself. The left-hand expression of Equation 1 is less than zero for all cases; therefore, water cannot accumulate locally from the inside. The situation is like a dam in a river, where the dam is higher than the highest level that is normally reached by the river. Such dam will spill only during floods. Similarly, water from the inside will accumulate on the vapour barrier only during saturated indoor conditions.

To complete the evaluation, the system of equations has to be applied to materials downstream of the continuous air/vapour barrier as well. This task is simple as a result of the fact that μ_{vb} (the permeability of the vapour barrier) is part of the left-hand (upstream) expression of Equation 1 for all surfaces to be evaluated downstream of the vapour barrier. In the absence of leaks, the left-hand expression of the equation is very small, even for large vapour pressure differences, and has a high probability of being less than the right-hand (downstream) expression most of the time. Thus, the condition for moisture accumulation downstream of the continuous air/vapour barrier is generally avoided, or at least minimized.

Therefore from our analysis of first principles elaborated in Equations 1, 2, and 3, the continuous and combined air/vapour barrier placed close to the inside of the wall satisfies the conditions that prevent water accumulation in envelopes for almost all conditions that can prevail. However, the sense of security provided by the judiciously placed continuous air/vapour barrier may lead to neglect of the design of the outer portion of the envelope, resulting in assemblies that may be especially susceptible to moisture accumulation when the continuity of the inner barrier is broken. In light of these considerations, other envelope systems should be evaluated, systems that may be more difficult to assess in terms of thermal/hygric performance, but which may be just as, or more, effective overall.

Separate Air- and Vapour-Barrier Systems

Separating the air barrier from the vapour barrier means locating the primary air barrier on the cold side of the envelope and leaving the vapour barrier on the warm side of the envelope - its traditional location. This practice has the potential advantage of being easier to make continuous, thereby approaching air-tightness more closely. This practise also protects the outer wall assembly from cold air flows through joints and fibres, thus improving the thermal performance of that assembly.

As a starting point in evaluating the moisture performance of this system, the labels air barrier and vapour barrier, should be examined. Separating the roles of the barriers in the wall into vapour and air barriers suggests that the vapour barrier is impermeable to moisture flow and that the air barrier is impermeable to air flow. Neither is true. For practical purposes, e.g., for classification of construction materials and for code specification, certain materials can be designated as vapour barrier or as air barrier or as both. Nevertheless, all materials retard the flow of air and vapour to varying degrees depending on the properties of the materials and the way the materials are assembled in the envelope. The difference between designated or primary air barrier and other materials is one of degree. As an illustration of this point, consider the profiles of pressure drop through a typical residential wall as reported by Ganguli [12], (see Figure 2). Although this wall has a designated air barrier (number 3 in the illustration), that barrier is not perfect because it does not provide 100% resistance to air flow. The sheathing offers measurable resistance to air flow under pressure, and this is significant. It shows that either the leakage rate through the wall is high, causing the measurable pressure drop across the sheathing, or that the air flow resistance of the sheathing is appreciable. A large leakage rate signifies that the air barrier is not very effective and a large moisture transport potential may be the result. Relatively tight sheathing increases the probability of long leakage paths across the face of the sheathing, since the few leakage sites in the sheathing do not necessarily line up with those in the designated air barrier and since the insulated cavity, which it encloses starts to behaves like a plenum. Long leakage paths and the plenum-like behaviour are factors which apparently encourage moisture deposition in walls, a point which will be discussed in more detail later. Therefore, the sheathing in the outer portion of such a wall should be subjected to the type of evaluation being recommended in this paper, whether it is the designated air barrier or not.

Qualitative Application of the Governing Equations

Consider an air barrier (or any plane of resistance to air flow) shown in Figure 1, and assume that room air moves over the inner surface of the barrier, or diffuses through the barrier. If the temperature of the inner surface of the membrane falls below the dew point is of room air, then according to Equations 1 and 2, there is continuous flow of moisture onto the surface of the material at a rate dictated by the vapour pressure differential:

$$(pp_{satr} - pp_{satl})$$

where subscript
r = room
l = local material surface

The above term is always positive when the temperature of the inner surface of the material is below the dew point of room air. As a result, when the temperature of the inner face of the air barrier approaches outdoor temperature on cold winter days, the probability of avoiding the condition of water accumulation on the inner surface of the air barrier is greatly diminished. Water accumulation, however, is not automatic; many mechanisms can be brought to the design of an assembly to maintain a favourable balance in Equation 1. Examination of each term in

ons 1 and 2 yields the following list of measures to
:e the potential for water accumulation:

ie vapour permeability of all materials separating the
iner face of the air barrier and outdoors should be high;

ie vapour pressure gradient between the inner face and the
itdoor air can be increased by introducing thermal
sistance between the inner face and the outdoor air; i.e.,
rge outward temperature gradient across the materials
omotes large vapour pressure gradients, when drying action
needed;

e vapour permeability of materials on the room side of the
r barrier can be kept low by using, for example, an
fective vapour barrier on the warm side;

ie vapour pressure difference between air leakage streams
d air barrier surface can be minimized by increasing the
rface temperature of the air barrier;

akage flow rates can be minimized; and

e length of leakage flow paths can be minimized to reduce
e surface area of material exposed to the air leak.

ve discussion is consistent with the considerations
ng dew point and air barrier continuity referred to in
ides on the subject [13,14,15,16,17]. For air barriers on
er portions of walls, however, the dew point condition
realistically be met in cold winter weather, and air leaks
ansport room air to the barrier surface cannot be
ced completely. Therefore, the relative magnitudes of the
n equations 1 and 2 must be the focus of the evaluation
it is the determinant of the effectiveness of the
s just listed. Therefore, for air barriers that can be
ently below the indoor dew point the orders of magnitude
following must be examined in detail:

- the ratio of the rate of moisture flow to the material surface by air transport to the rate of moisture flow outward through the material by vapour diffusion

- the degree and duration of the excursions of the material surface below the dew point temperature of the air stream and above the ambient temperature.

The first factor is a function of material properties and air tightness of the wall assembly, the second is a function of the thermal location of the barrier within the envelope and the environmental conditions in which the envelope system is expected to perform. (Although environmental conditions are not the focus of this paper, they do play a key role in the overall result). The degree to which the material properties have to be tailored to perform properly is a strong function of the degree and duration of moisture flow imbalances. The time factor t in Equation 1 is very important. Ultimately, a statistical review and a characterization of the environment (weather and indoor conditions) have to be made, since systematic extremes in conditions, such as consistently high indoor RH, prolonged cold, and prevailing winds, increase the **duration and magnitude** of an imbalance, and thus determine the quantity of water accumulated.

Evidence from Tests

The way in which materials retard, deflect and diffuse air flow and vapour flow in walls has been the subject of intense research at IRC for many years [1,2,3,4,11,12,13,14,15]. Recent experimental studies at IRC [3] have shown that the degree of communication between the inside surface of the sheathing in wood frame walls and the outdoor air is a key factor in promoting dry cavities; that is, the right-hand terms in Equation 1 gain importance under systematic air leakage of room air through the cavity. Vapour transfer resistance of the sheathing materials was cited as a key factor that resulted in the observed differences in performance observed.

:ests also showed that the overall accumulation in a cavity unfavourable periods; i.e., during cold weather, is very naller than the total moisture passing through the cavity. ι terms of Equation 1, the difference between influx and : of moisture; i.e., the water accumulation, is very much : than either the influx or the outflux. The accumulation s the result of a relatively small imbalance between large suggesting that small changes in either term could have effects on the order of magnitude of the accumulation.

laboratory, Timusk [5] compared the performance of various ntial wall systems with respect to their ability to resist accumulation in the outer portion of the wall under .ons of forced air leakage. These tests confirmed the ance of the temperature excursion from the dew point of the surface of the exterior air barrier. However, somewhat singly, the tests showed no systematic favouring of high bility materials in the outer portions of the walls. In the air barrier material with the lowest permeability fared ι these tests by virtue of its insulation value and related nner-surface temperature. This would suggest that for very ir leakage rates (forced in this case for purposes of rating differences in performance over short periods), the .on terms in Equation 1 are so small that they become ificant, regardless of the material. The deposition rate is .y determined by the right-hand expression of Equation 2, dominates the diffusion term. The only property-sensitive : Equation 2 (once the variability of leakage rate is .ted) is pp_{satl} - the local surface saturation pressure, .s a function of surface temperature. The surface ature is, in turn, a function of the distribution of . resistances of materials in the envelope. These test s lead to the conclusion that for high leakage rates ι the envelope, exterior air barriers could benefit from ed thermal isolation from the outdoor air. But these show only one side of the equation. For lower flow rates, .l permeability becomes a factor - especially during drying ons. As well, the accumulated quantities of water and ice d by Timusk are not directly comparable in absolute terms.

Rather, once the accumulation has stopped, the duration of drying of the accumulated moisture under more favourable conditions becomes the focus of comparison. Equations 1 and 2 can be used for the comparison, provided the drainage of surface water is taken into account.

Evidence from Computer Simulations

Scanada and RWDI were commissioned by CMHC to evaluate the effectiveness of using strapping behind the siding of walls. That work, which resulted in the WALLDRY computer model [6,18], can be cited as an exercise in evaluating the system of equations (Equations 1, 2, and 3) for a discontinuous air barrier system located on the outside of walls; i.e. tightly mounted siding. It was found that tightly installed, impermeable siding could start acting like an air/vapour barrier so that under heavy moisture load from a saturated inner wall, moisture accumulation would occur on the inside surface of the siding during some periods of the year.

Simulations further showed that strapping had the effect of allowing more outside air to dilute the moisture approaching the siding from the interior of the wall, thereby reducing the local pp_{as} of Equation 2 at the inner surface of the siding. For the weather locations studied, the depressed pp_{as} at the inner face of siding resulted in uniform drying of previously wet siding. Ventilated attics work on the same principle - diluting the moisture content of the air leakage streams with drier outdoor air. The key with this approach is to introduce enough outdoor air to achieve depressed vapour pressure of the leakage stream, without compromising other design considerations.

5. APPROACH TO TROUBLE AVOIDANCE

Although the above analysis is qualitative in nature, and cannot be conclusive on the subject, a number of directions in design have been identified to be promising avenues to avoid long-term, systematic water accumulation in the outer envelope. These are:

1. Review of the climatology and operating conditions to identify **systematic** trends:
   - prolonged periods of extreme cold,
   - strong winds in persistent directions,
   - high indoor RH (by design or by accident,)
   - generally low neutral pressure plane, and
   - pressurized interior space.

2. Review of the anticipated air-integrity of the envelope system in place, considering such factors as the effects of

   - damage during construction [19],
   - difficult detailing at hidden corners, joints, utility penetrations [13],
   - material deflection and permanent displacement due to wind loading [11],
   - drying and related shrinkage of materials, and effects on the air permeability of materials [7], and
   - relative movement of materials due to differential rates of thermal expansion and contraction.

3. Introduction of elements to the outer envelope design that will foil mechanisms of failure in the integrity of the air barrier most of the time. For example:

   - minimize material interface designs that allows interstitial flow of air leakage; for example, the use of air barrier membranes that adhere to adjacent materials and combined insulating air barriers discourage such flows, and may be less likely damaged by wind loads,
   - progressively more permeable or less air-tight materials from the interior to the exterior to promote vapour communication with the outdoors,
   - larger temperature gradients between the inner surface of the air barrier and outdoors by

introducing a thermal barrier on the outside of the air barrier, and

- decoupling of air permeable insulations from wind induced air flows through them, for thermal effectiveness.

4. Introduction of elements that will cope with failure when it has occurred; e.g., plan for drainage down and out, while isolating materials that suffer permanent degradation when exposed to water and freeze/thaw cycles.

5. Satisfaction of code requirements.

6. CONCLUSIONS

For proper air and vapour barrier design, prescriptive measures should continue to be used until ultimately replaced by a performance evaluation system that accounts for all of the interrelated factors, including imperfections in assembly, variations in material properties (vapour permeability, air permeability, and thermal resistivity), and the conditions in which the envelope is expected to perform. A framework, based on analytical techniques supported by tests, has been proposed here for performing such evaluations. Current testing and computer-modelling programs being developed at various laboratories and institutions support such evaluation procedure.

For the time being, separating the air and vapour barrier does not appear to introduce fundamentally insurmountable problems. Although in theory the combined air/vapour barrier system may be effective, and easily proven to be effective, all air- and vapour-resisting materials and assemblies in the outer portion of walls should be subject to the same moisture performance evaluation.

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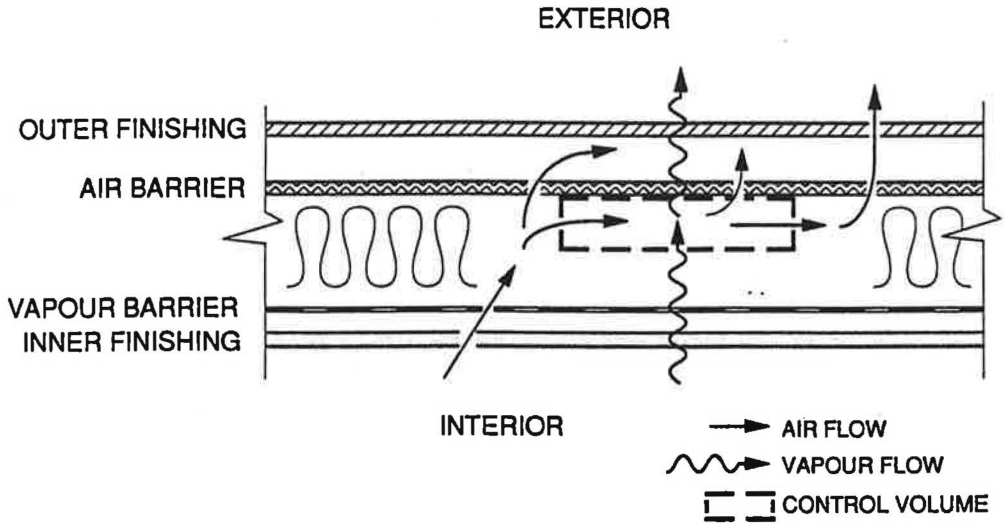

FIGURE 1

SCHEMATIC DIAGRAM OF A WALL SECTION: CONTROL VOLUME FOR ANALYSIS

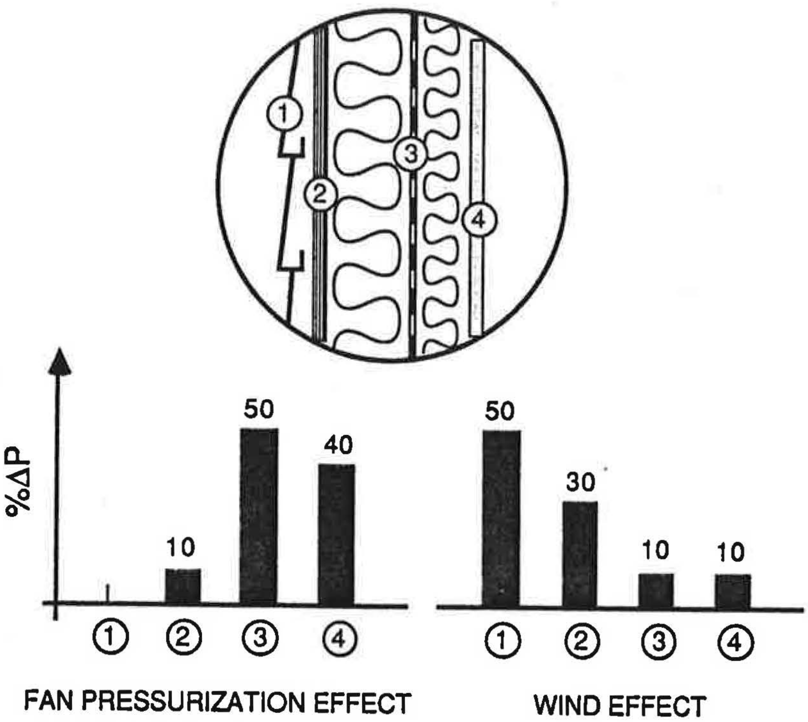

FIGURE 2

AIR PRESSURES ON A WOOD FRAME WALL (REPRODUCED FROM GANGULI [12] FIGURE 6. – BSI'86)