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COMPUTER MODEL CALCULATIONS ON THE PERFORMANCE OF VAPOR BARRIERS IN CANADIAN RESIDENTIAL BUILDINGS

A.N. Karagiozis, Ph.D. M.K. Kumaran

ABSTRACT

The performance of vapor barriers in typical residential walls is investigated through numerical analysis. A two-dimensional heat, air, and moisture transport model that simulates transient effects is used. Two series of calculations are performed. In the first series, the wall is exposed to constant boundary conditions, representative of typical heating periods, for a fixed interval. In the second series, the exterior conditions are chosen to be representative of three Canadian locations, Vancouver, Winnipeg, and Ottawa. In each series, six different levels of vapor resistances are imposed. Each of these cases is simulated for each location for a two-year period.

All results indicate the influence of convective flow within the insulation in the wall cavity to direct moisture to the upper part of the wall. In the absence of a vapor barrier, this results in localized moisture accumulation at the interface of the insulation and the exterior sheathing. Depending upon the severity of the winter conditions, different levels of water vapor resistance that avoid localized moisture accumulation are identified at the three different geographic locations. At all locations, for all cases, for the interior boundary conditions chosen to be representative of a comfort level, the moisture accumulated during the heating season, due to diffusion, dries out in the summer and avoids any cumulative effect, year after year. The preliminary results show that, for Vancouver weather conditions, installation of a vapor barrier at the interior of the assembly may not be necessary to stop vapor diffusion. At Winnipeg, a type II vapor barrier may prevent any localized moisture accumulation due to diffusion. At Ottawa, it may not be necessary to install even a type II vapor barrier; instead, an interior coating of paint with a third of the vapor resistance of a type II vapor barrier may function equally well. These preliminary calculations, however, neglected the effect of driving rain, solar radiation, and wind effects. In order to develop definite design guidelines, many series of calculations including all these effects should be carried out.

INTRODUCTION

It is known that unintentional water entry into typical Canadian wall constructions can lead to destructive consequences (Hutcheon 1963). Moisture entry into the wall structure can be caused mainly by two processes: vapor diffusion and moist air leaking inward or outward (being more important for cold climates) through the building envelope. This study is concerned with moisture transport due to vapor diffusion only. However, it has long been recognized that moisture transport due to air leakage can be more serious than that transported by pure diffusion processes (Rousseau 1983; Latta 1976). Moisture transport by diffusion occurs under the influence of a vapor pressure gradient acting across the wall structure. The rate of moisture flow is dependent upon the magnitude of the vapor pressure gradient and the vapor permeances of the component layers of the wall assembly. Additional factors are inarguably the overall integrity of the building material (i.e., cracks and openings), the interface contact, and surface moisture resistances. In general, for a given permeable structure, the greater the vapor pressure difference across a wall assembly, the greater will be the rate of diffusion. The moisture movement is almost always outward from the building envelope during winter (heating season) and can be inward or outward during the summer (cooling season). With current construction practices in Canada, houses are better insulated and more airtight, resulting in colder and warmer regions within the wall structure and higher indoor relative humidities. If the vapor pressure and temperature are, respectively, high and low enough in a material layer, then a thermodynamic change of state occurs and moisture vapor changes into the liquid state (water) or even into a solid state (ice). The condensation within the concealed wall structure can thus be a highly localized effect.

To control this moisture flow into the wall structure, vapor barriers have been devised. Vapor barriers are materials or systems that adequately retard the transmission of water vapor across the wall assembly, offering a high resistance to the diffusion of water vapor. Indeed, in the National Building Code of Canada (NBC) it is a code requirement that "a vapour barrier protection shall be installed on the warm side of the insulation" (NBC 1990). The need is critical where insulation systems operate below freezing conditions. This requirement was enacted in the 1940s due to the noticeable damage attributed to high moisture levels in the walls. Concealed water condensation within the insulation system can also significantly alter the thermal effectiveness of the insulation. The thermal conductivity of condensed water can be 15 times greater than the

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insulation material. If below-freezing conditions occur, then the thermal conductivity can be further increased. The phase-change effects also will add to the heat transport, which could be of serious concern for designs of advanced energy-efficient housings.

Due to higher indoor relative humidities, especially with the use of humidifiers for increased levels of human comfort, vapor barriers are incorporated near the warm side (interior) of the wall structure. This is generally advocated as a safe design principle, since the entry of moisture is restricted closer to the source, which is normally the higher vapor pressure side. However, only a limited number of studies have been documented (ASTM 1976; Latta 1976; Hutcheon 1963; Burch and Thomas 1992) that discuss the performance of vapor barriers. Indeed, all studies only considered one-dimensional heat and moisture flows, and most of these studies, with the exception of the latest, drew conclusions based on the use of the steady-state one-dimensional Glaser method (Glaser 1959) or its simple extensions (Trethowen 1979). Thus it has become apparent that a systematic, at least two-dimensional, transient heat, air, and moisture transport investigation is required before effective guidelines can be deduced. The following will attempt to address some of these issues using a state-of-the-art analytical method.

Objectives of Present Study

The present work is concerned with the hygrothermal performance of a typical Canadian residential wall structure subjected to six selected vapor barrier conditions. The first objective was to assess the hygrothermal performance of these selected vapor barriers when exposed to constant interior and exterior boundary conditions. This is essential since consultants tend to use such conditions, based on mean values, for design purposes. The second objective was to determine the long-term hygrothermal performance of the wall structure for each of the selected vapor barrier cases while subjecting the exterior boundary to temperatures and vapor pressures from weather data. The weather data used are representative of Canadian climates, ranging geographically from the west coast and the middle and eastern parts of Canada. These objectives were met through intensive numerical analysis.

The Numerical Analysis

The computer model used for the analysis is a general research tool for moisture transport analysis of residential building walls, i.e., lightweight constructions. It models the two-dimensional heat, air, and moisture transport processes through multilayer building envelopes. The transport equations are based on temperature, pressure, and water vapor pressure as driving potentials. Darcy's flow equations with Boussinesq approximation for incompressible fluids are used for the convective flows. The balance equations are discretized using a finite-difference technique. The model has been applied to several different heat, air, and moisture transport problems, including airflow leakages (Kohonen et al. 1985, 1987), crack flows (Ojanen and Kohonen 1990), exfiltration of indoor air (Ojanen and Kumaran 1992), and dynamic walls (Morrison et al. 1992). The two-dimensionality of the model permitted only cross sections of the wall structure to be modeled. Thus corners, the encasing wood studs, and other three-dimensional effects were not included in the analysis.

A residential wall structure, 2 meters high, as shown in Figure 1, was used in the current investigation. The wall construction, from the inside of the envelope to the outside, consisted of an interior-grade 12-mm gypsum board, one of the six vapor barriers listed in Table 1, a 150-mm-thick glass fiber insulation (density = 20 kg/m^3 or 1.25 lb/ft^3), and 12.7-mm chipboard. (Case 5 given in Table 1 corresponds to the threshold requirement for a vapor barrier achievable with a kraft paper. Case 6 is an extremely good vapor barrier achievable with a polyethylene film. Case 3 corresponds approximately to a coating of oil-based paint and case 2 to a coating of latex paint.) No exterior siding was modeled.

For one set of calculations, the wall assembly was simulated as exposed to an interior temperature of 20°C and water vapor pressure of 900 Pa (RH = 38.5%) and an exterior temperature of −10°C and 100 Pa (RH = 38.5%) water vapor pressure for 360 hours. For a second set of calculations, weather conditions of the cities of Vancouver, Ottawa, and Winnipeg, from geographical locations as shown in Figure 2, were used; the exterior (outdoor) ambient dry-bulb temperature and the vapor pressure at time intervals of one hour were used as inputs to the model.

The heating degree-days for the three locations, below 18°C, according to climatic information for building designs in Canada (NBC 1977), are, respectively, 3007, 4763, and 5889. The interior boundary condition was maintained constant at 20°C with a vapor pressure of 900 Pa (RH = 38.5%). Moisture transport was assumed to take place by diffusion, though currents of natural convection within the porous glass fiber insulation were modeled. The vapor barrier and the interior gypsum board were grouped together and simulated as additional resistances to moisture and heat flows.

Grid-independent results were produced using 60 nodes in the horizontal direction and 30 nodes in the vertical direction, and hence a 60 × 30 grid was used for all simulations. The material properties, such as dry density, heat capacity, thermal conductivity, air permeability, vapor permeability, and the sorption isotherms and their functional dependence, if applicable, on temperature and/or moisture content, were extracted from the property data base included in the model. Solar-driven moisture, wind pressure effects, direct rain effect, interface effects, and liquid water moisture movement are not accounted for in the current investigation. The results were post-processed, and the

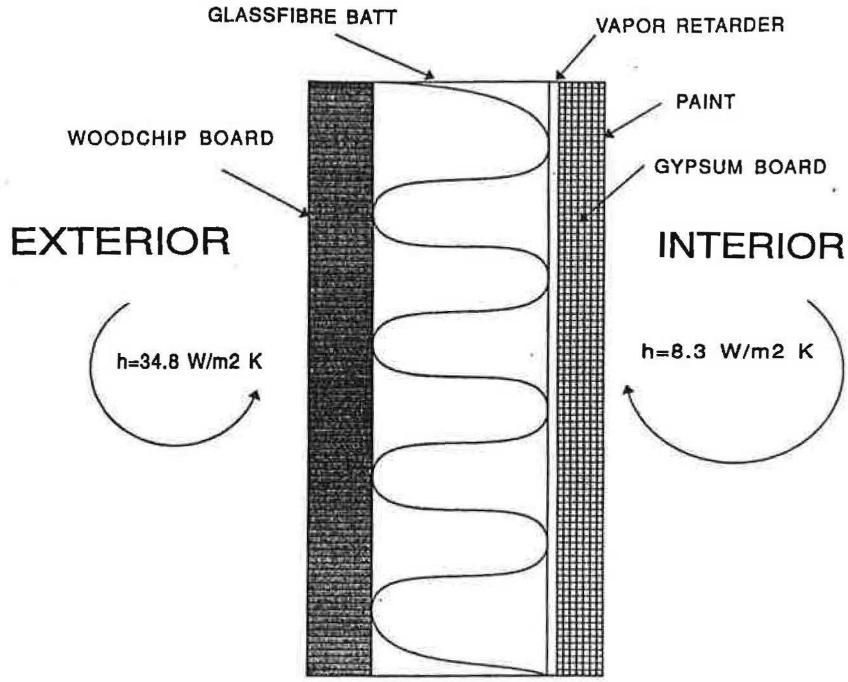

Figure 1 *Multilayer wall cross section.*

TABLE 1
The Six Vapor Barrier Cases Investigated in the Current Work in the Order of Decreasing Vapor Permeance

Case	vapor barrier
1.	Plain gypsum board
2.	Gypsum board + A paint with permeance of 400 ng/(m^2.Pa.s) (≈ 7 perm)
3.	Gypsum board +A paint with permeance of 200 ng/(m^2.Pa.s) (≈ 3.5 perm)
4.	Gypsum board +A paint with permeance of 100 ng/(m^2.Pa.s) (≈ 1.75 perm)
5.	Gypsum board +Type II barrier, permeance of 60 ng/(m^2.Pa.s) (≈ 1 perm)
6.	Gypsum board +Type I barrier, permeance of ng/(m^2.Pa.s) (≈ 0.25 perm)

Figure 2 Location of selected cities.

moisture content and the total moisture accumulations in the wall structures in the form of spatial and temporal contour plots were produced.

RESULTS AND DISCUSSION

The results from the two sets of simulations are reported below.

Constant Boundary Conditions

Initially, the entire wall construction was assumed to be dry and at 0°C. In Figures 3a through 3f, the spatial moisture content distributions are plotted for the first set of calculations using a constant interior temperature of 20°C and vapor pressure of 900 Pa (RH = 38.5%) and constant exterior conditions of −10°C and vapor pressures of 100 Pa (RH = 38.5%). The total time of exposure to these conditions was for 360 hours. The moisture content distributions clearly show the significant influence of the different vapor barrier cases. The results show a distinct moisture accumulation on either side of the interface between the exterior sheathing (wood chip board) and the glass fiber insulation. This effect is most prominent in case 1, where no vapor barrier is used. As the vapor barrier resistance increases, the moisture accumulation decreases considerably, as seen in Figures 3a and 3f. An appreciable height effect is also present in the results, which decreases as the vapor barrier resistance increases. This indicates that the two-dimensional vapor accumulation process occurring in the glass fiber insulation due to the convective effect is noticeable. In case 1, this effect is most pronounced at the top of the wall, which shows a much higher moisture content than the bottom.

The moisture content spatial distributions away from the chipboard-glassfiber insulation interface, particularly toward the interior side, show no appreciable moisture content accumulations. Figure 4 shows the integrated accumulation of moisture within the wall section as a function of time per one-meter section (hereafter referred to as unit depth) of the wall shown in Figure 1. The effect of vapor barrier permeance is displayed for time intervals of 30 hours. The consequences of not using a proper vapor barrier can be clearly seen. In Figure 5, the total vapor resistance ($m^2 \cdot Pa \cdot s/kg$), which includes the vapor barrier and the resistance of the gyspum board, is plotted against the total moisture accumulation. A simple equation was fitted to the data giving the expression

$$\text{Total Moisture (kg/m)} = 0.414 + 1.053/R \quad (1)$$

(where R is the total vapor resistance) to represent the total mositure accumulation per unit depth of the wall after 1,000

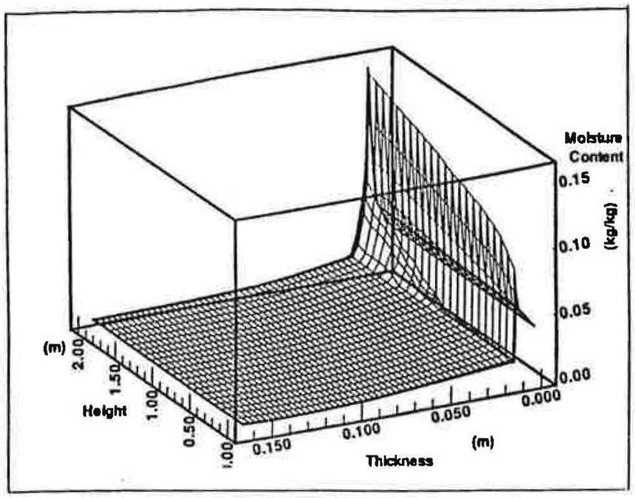

Figure 3.a No Retarder

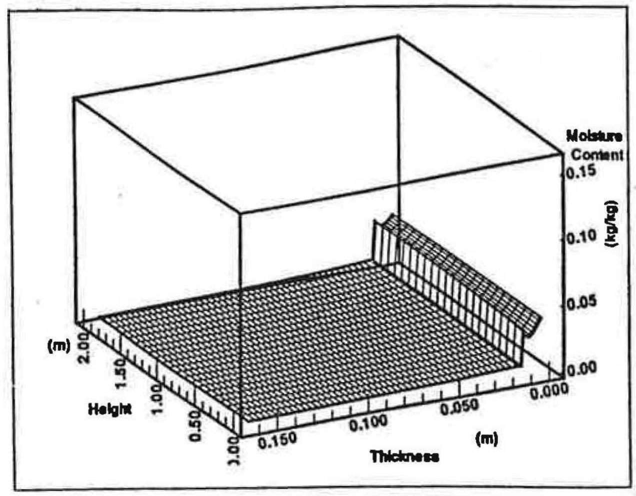

Figure 3.b Retarder with 400 $ng.m^{-2}.Pa^{-1}.s^{-1}$

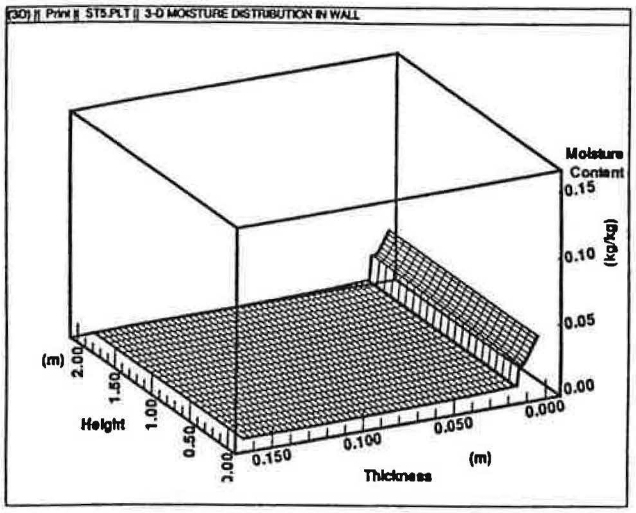

Figure 3.c Retarder with 200 $ng.m^{-2}.Pa^{-1}.s^{-1}$

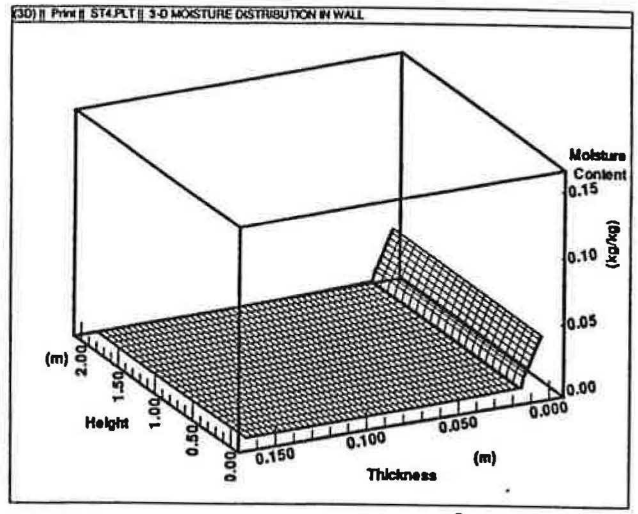

Figure 3.d Retarder with 100 $ng.m^{-2}.Pa^{-1}.s^{-1}$

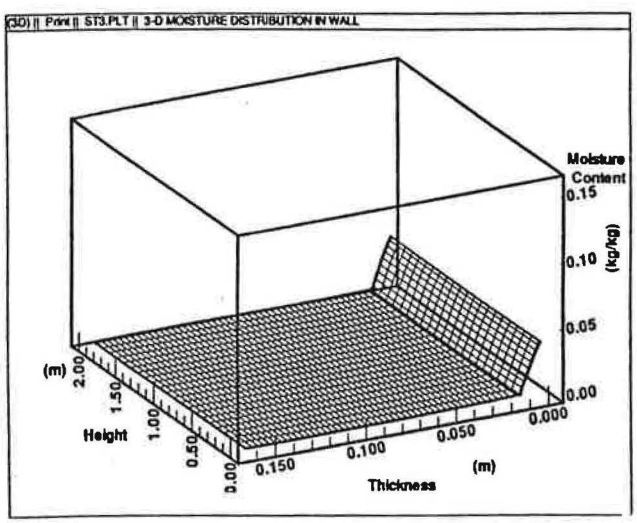

Figure 3.e Retarder with 60 $ng.m^{-2}.Pa^{-1}.s^{-1}$

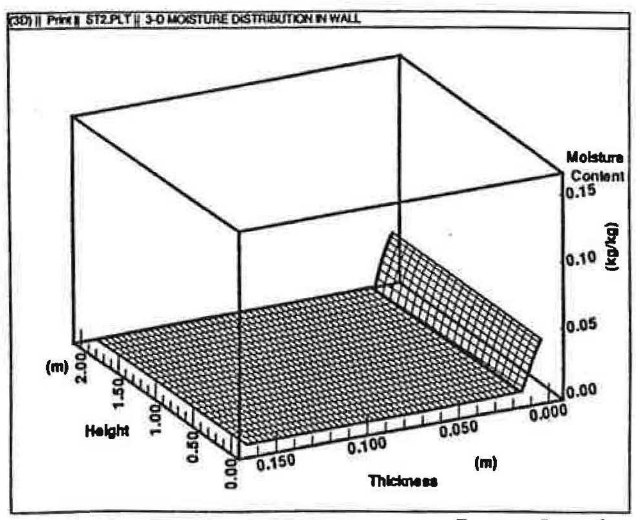

Figure 3.f Retarder with 15 $ng.m^{-2}.Pa^{-1}.s^{-1}$

Figure 3 *Effect of vapor retarder on the spatial moisture distributions for constant boundary conditions (0, 0 on thickness axis corresponds to exterior surface).*

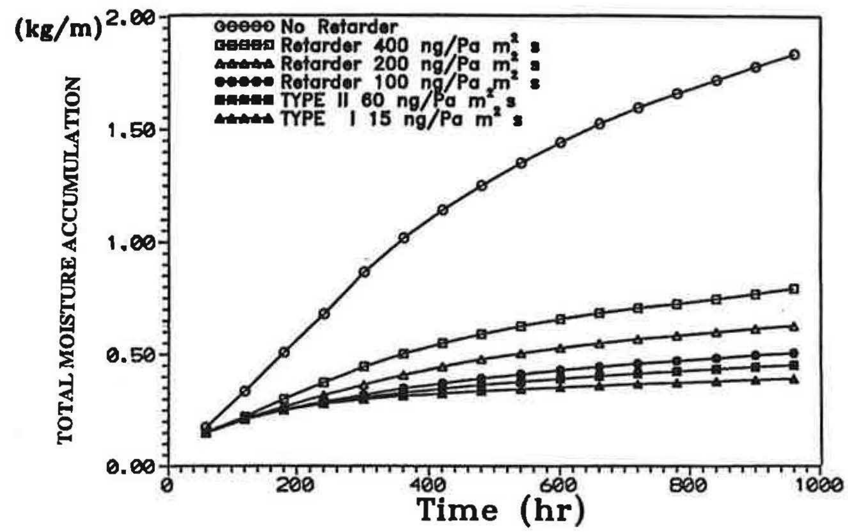

Figure 4 *Effect of vapor retarder on moisture accumulation in structure for constant boundary conditions.*

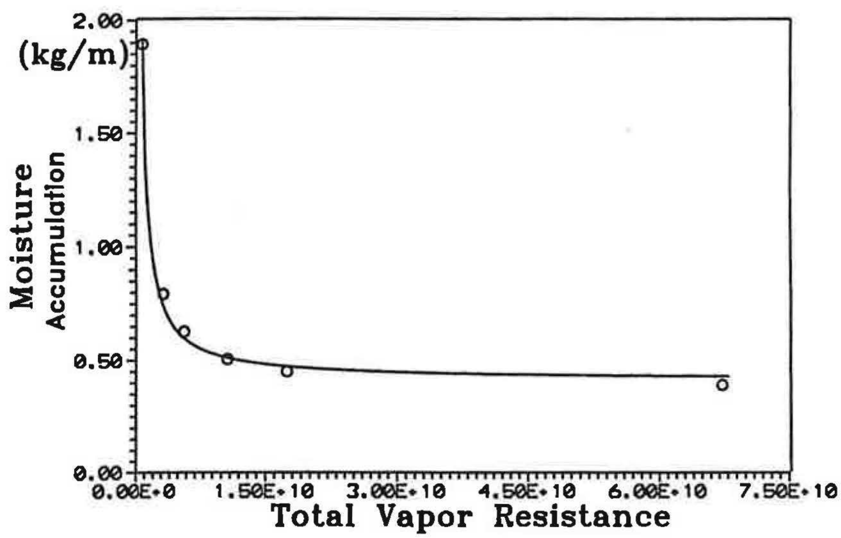

Figure 5 *Effect of total vapor resistances on the moisture accumulation for constant boundary conditions.*

hours' exposure to the constant boundary conditions. From Figure 5 one can conclude that the use of a total vapor resistance of $1.5E + 10$ ($m^2 \cdot Pa \cdot s/kg$), in the absence of solar or wind effects, would essentially provide as good a resistance to vapor flow as case 6, i.e., a total vapor resistance of $6.7E + 10$ ($m^2 \cdot Pa \cdot s/kg$), for the boundary conditions under investigation.

Real Weather Boundary Conditions

Vancouver The influence of real boundary conditions imposed on the exterior surface of the wall structure is investigated next. Initial conditions applied to the domain were the results from the previous constant boundary calculations at 360 hours. The hygrothermal performance of the wall structure with the six different vapor barriers for the city of Vancouver is shown first. The calculations start from the first day of January for a period of two years to arrive at results for the second year independent of the initial conditions chosen arbitrarily. Figures 6a through 6f depict the time-dependent behavior of the moisture content at the innermost layer of the sheathing (chipboard, close to the insulation). In each figure, a wetting and a drying period exists for each year. In all six cases, there is no

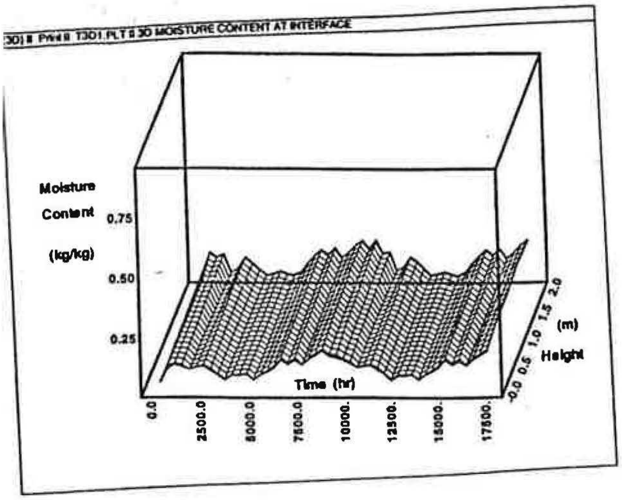

Figure 6.a No Retarder

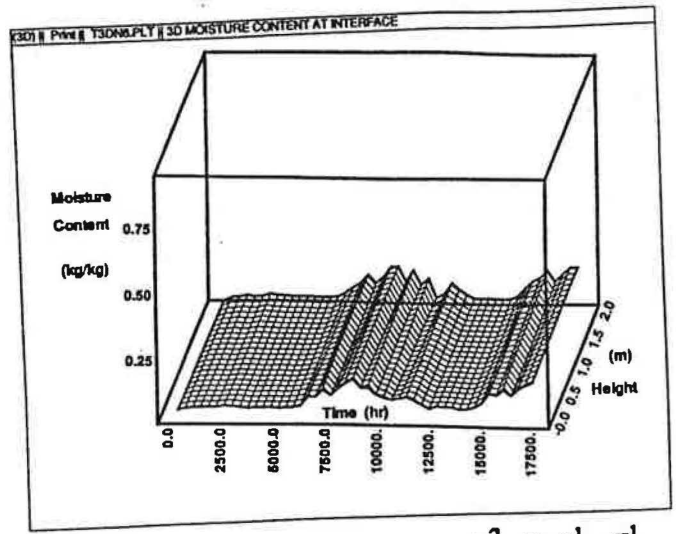

Figure 6.b Retarder with 400 $ng.m^{-2}.Pa^{-1}.s^{-1}$

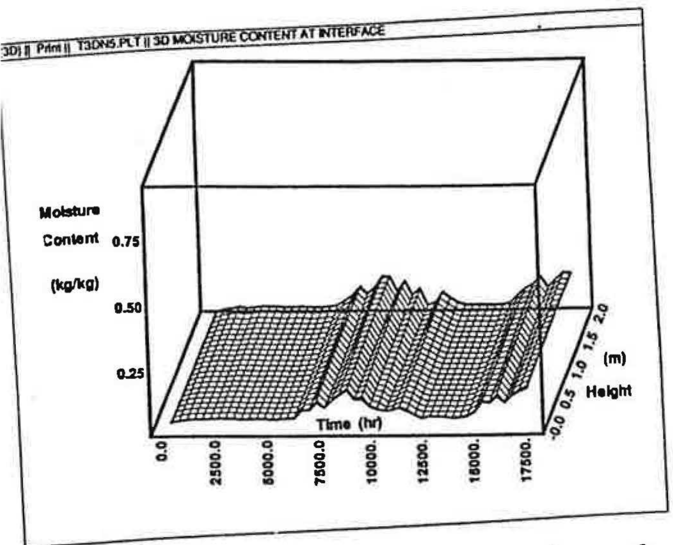

Figure 6.c Retarder with 200 $ng.m^{-2}.Pa^{-1}.s^{-1}$

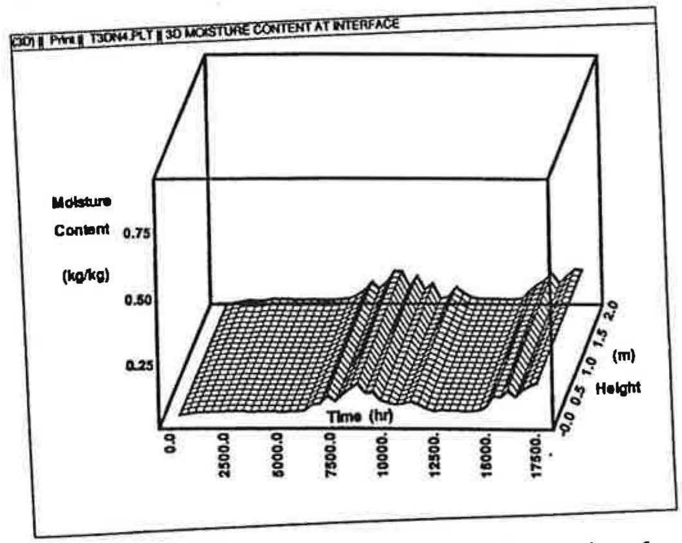

Figure 6.d Retarder with 100 $ng.m^{-2}.Pa^{-1}.s^{-1}$

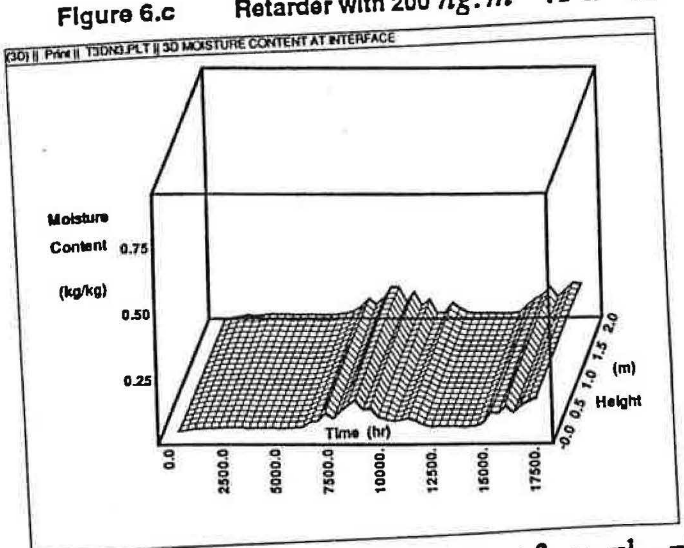

Figure 6.e Retarder with 60 $ng.m^{-2}.Pa^{-1}.s^{-1}$

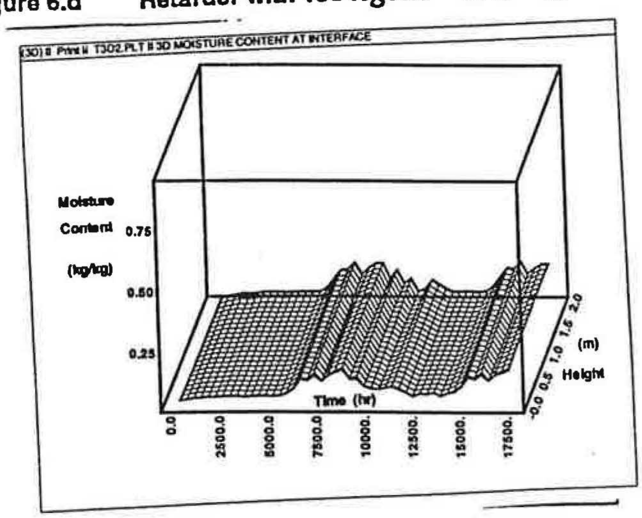

Figure 6.f Retarder with 15 $ng.m^{-2}.Pa^{-1}.s^{-1}$

Figure 6 *Effect of vapor retarder on temporal moisture distributions using Vancouver weather data (results are plotted out for the innermost layer of the sheathing).*

indication of cumulative effects, year after year, because the wall dries out during the summer. The low permeance of case 6 (Figure 6f) produces the only noticeable, albeit insignificant, difference when compared to the no-vapor barrier case 1 (Figure 6a). From the set of figures showing relatively low moisture content levels throughout the year with any of the six different vapor barriers (for the boundary conditions that neglected solar and wind effects), one may conclude that a vapor barrier in addition to the gypsum board may not be necessary at the interior side of the wall in Vancouver. Figure 7 depicts the moisture accumulation in the wall structure per unit depth. Here the wetting and drying seasons are clearly distinguished. Starting from January, which is already in the middle of the wetting period, the structure accumulates moisture and dries out during spring and summer. This cycle is resumed again for the following year at the beginning of winter.

Winnipeg Figures 8a through 8f show the wetting and drying of the innermost layer of the sheathing during a two-year period. These figures show a considerable amount of moisture uptake by the walls during the winter. This can be attributed to the extremely cold weather conditions found in Winnipeg. A pronounced two-dimensional effect appears again near the top of the wall. This two-dimensional effect is more evident during the winter. The choice of vapor barrier has a significant effect on the moisture accumulation in the structure. Completely different trends exist when comparing vapor barriers for case 1 and case 6. Figure 9 shows the moisture accumulation within the wall structure per unit depth. The results indicate a strong influence of the vapor barrier performance. It is this type of hygrothermal behavior that cannot be predicted if constant boundary conditions are used. According to Figure 8, for the city of Winnipeg, for the boundary conditions imposed in the simulations (no wind or solar effects), a vapor barrier of permeance equal to or lower than that defined by case 4 may prevent any local accumulation of moisture. The indication is that a type I vapor barrier may not be necessary for Winnipeg.

Ottawa Figures 10a through 10f show the moisture content plots as a function of time for the six cases of vapor barriers. The results are similar to those in Figure 8, however, not as pronounced as those from the Winnipeg simulations. Higher moisture content levels are observed with case 1 and case 2 at the top of the wall structure. In Figure 11 the total moisture accumulation per unit depth of wall is shown. A hygrothermal behavior similar to that at Winnipeg is found for Ottawa, except that a vapor barrier of 200 ng/(m^2·Pa·s) (3.5 perm) permeance may totally prevent any localized moisture accumulation due to diffusion, in the absence of wind or solar effects.

CONCLUDING REMARKS

Vapor barriers have a significant effect on the hygrothermal performance of walls of residential buildings for

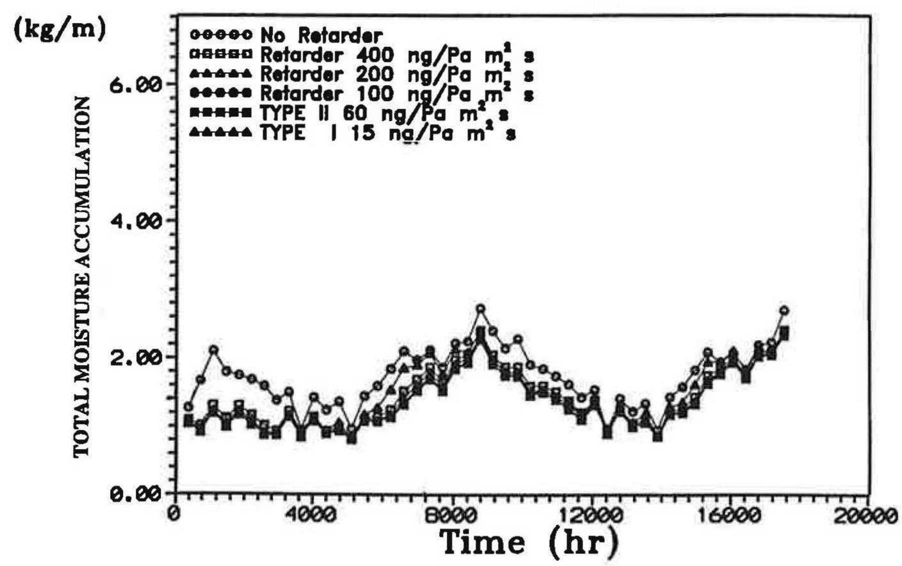

Figure 7 Effect of vapor retarder on the moisture accumulation as a function of time (Vancouver).

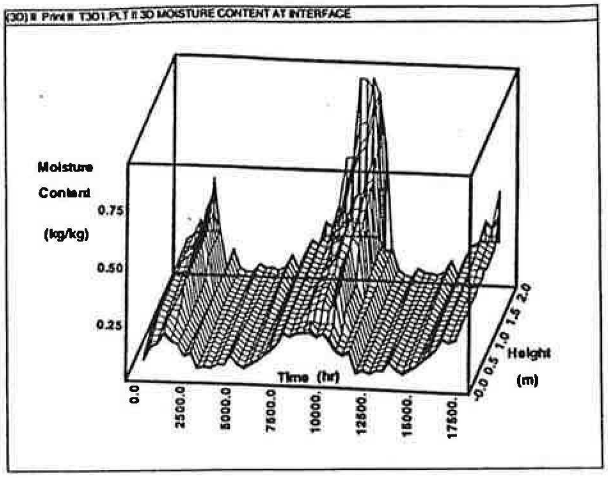

Figure 8.a No Retarder

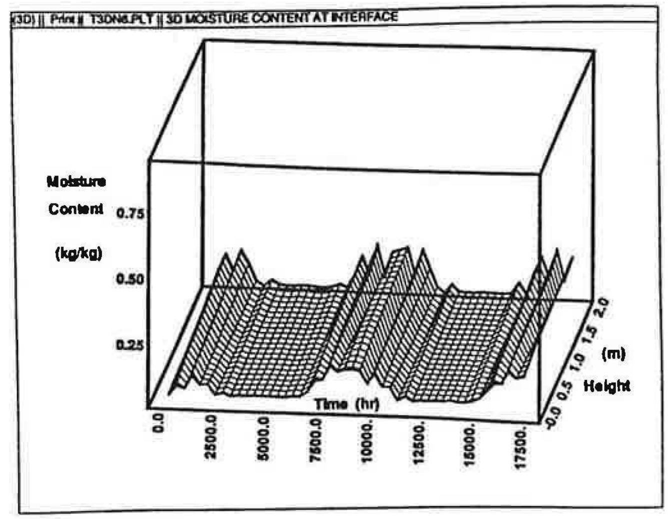

Figure 8.b Retarder with 400 $ng.m^{-2}.Pa^{-1}.s^{-1}$

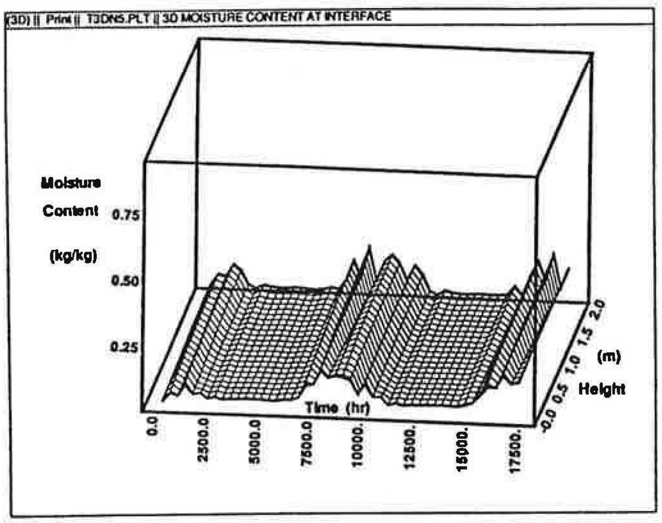

Figure 8.c Retarder with 200 $ng.m^{-2}.Pa^{-1}.s^{-1}$

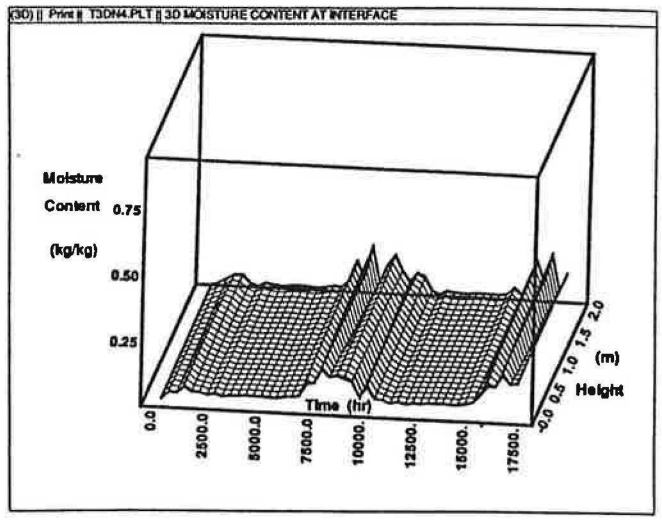

Figure 8.d Retarder with 100 $ng.m^{-2}.Pa^{-1}.s^{-1}$

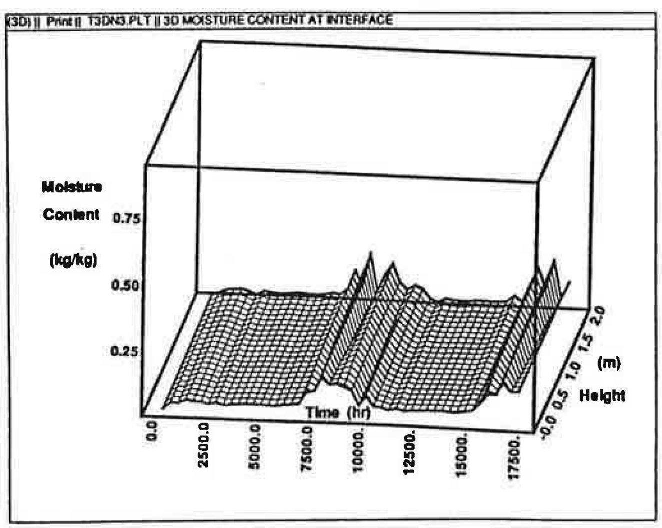

Figure 8.e Retarder with 60 $ng.m^{-2}.Pa^{-1}.s^{-1}$

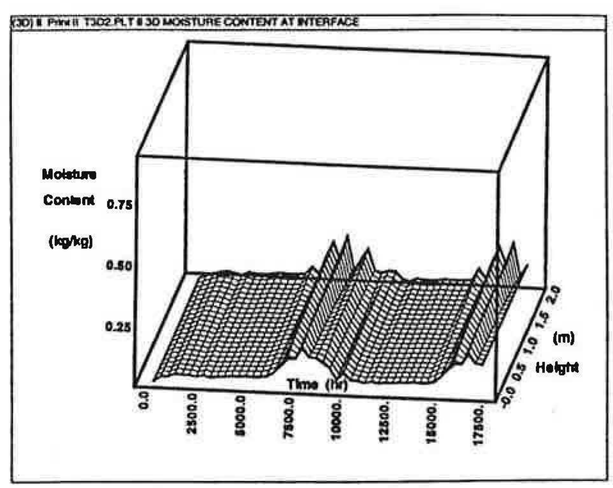

Figure 8.f Retarder with 15 $ng.m^{-2}.Pa^{-1}.s^{-1}$

Figure 8 *Effect of vapor retarder on temporal moisture distributions using Winnipeg weather data (results are plotted out for the innermost layer of the sheathing).*

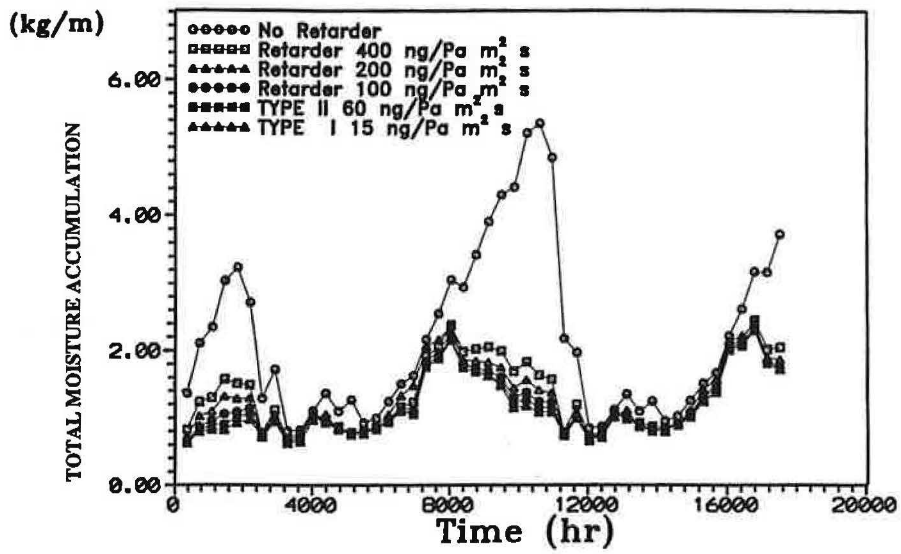

Figure 9 *Effect of vapor retarder on the moisture accumulation as a function of time (Winnipeg).*

colder climates. The study, which looked at vapor diffusion only, has found that the use of a polyethylene vapor barrier (type I or type II) may not be needed in some climatic conditions; thus a potential for construction cost reductions may be realized in some cases by avoiding the installation of such barriers if the installed system does not have functions other than that of a vapor barrier. Instead, a coating of a paint with the required vapor resistance may prevent any harmful moisture accumulation due to diffusion.

The constant boundary results provide important information, but guidelines should not be generated solely based on them, especially if the calculations are based on one-dimensional steady-state methods. Future work may be undertaken to develop simpler methods that include the transient effects for determining the requirements for the design of vapor barriers applicable to a specific location. For example, the use of relations similar to Equation 1 as a design tool may be further investigated.

Although vapor barriers may be able to significantly reduce the amount of moisture accumulation within the wall structure, additional consideration should be given to the effects of air infiltration/exfiltration due to the combined stack and wind pressure, wind-driven rain, and variations in geographic location and vapor barrier location. The biological and chemical effects of localized moisture on various components of the wall assembly also need to be considered. These will allow one to develop concise and realistic guidelines for the application of vapor barriers.

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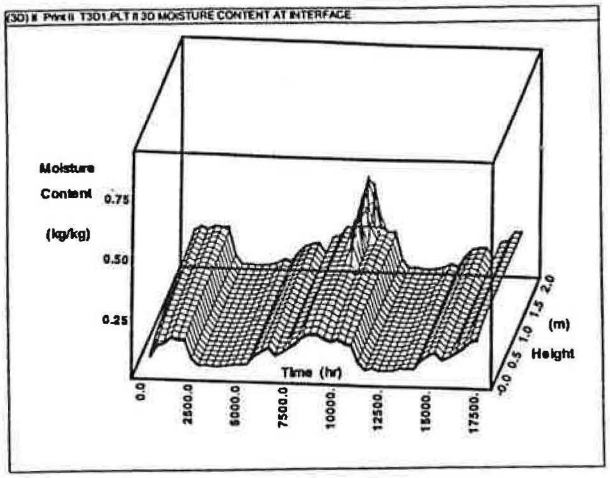

Figure 10.a No Retarder

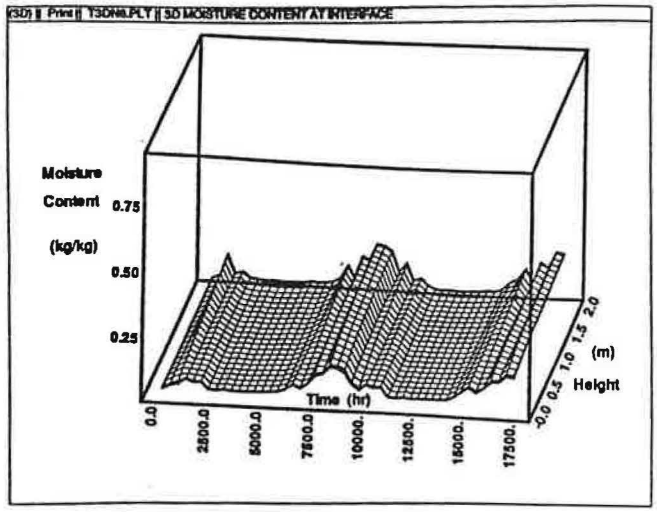

Figure 10.b Retarder with 400 $ng.m^{-2}.Pa^{-1}.s^{-1}$

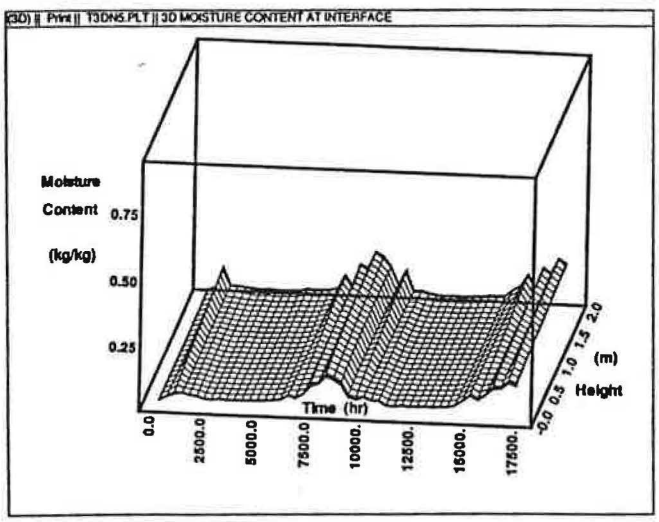

Figure 10.c Retarder with 200 $ng.m^{-2}.Pa^{-1}.s^{-1}$

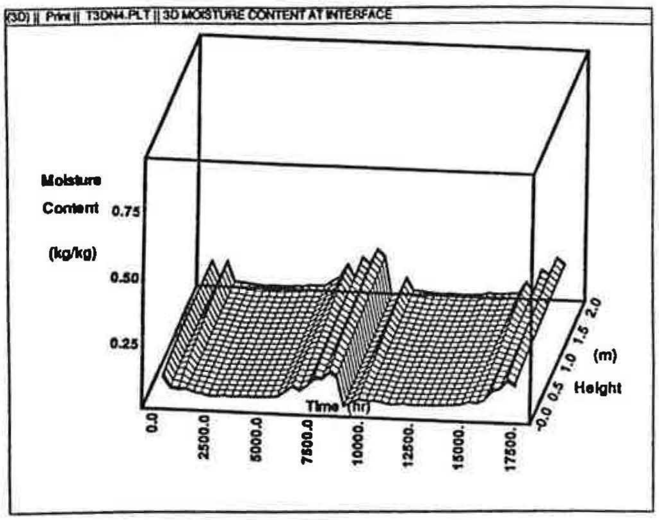

Figure 10.d Retarder with 100 $ng.m^{-2}.Pa^{-1}.s^{-1}$

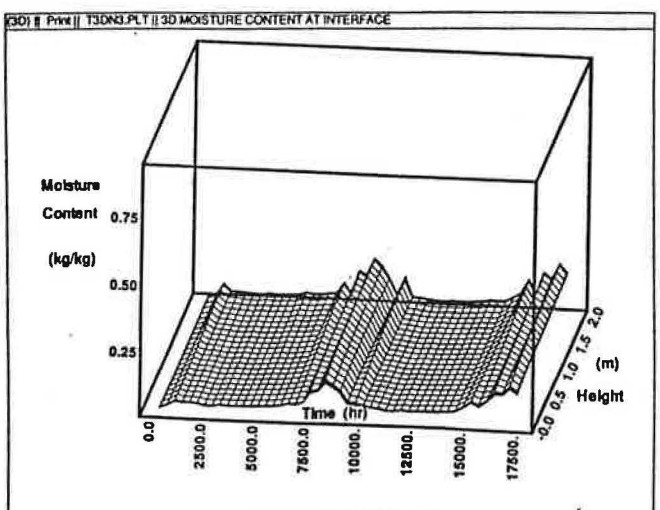

Figure 10.e Retarder with 60 $ng.m^{-2}.Pa^{-1}.s^{-1}$

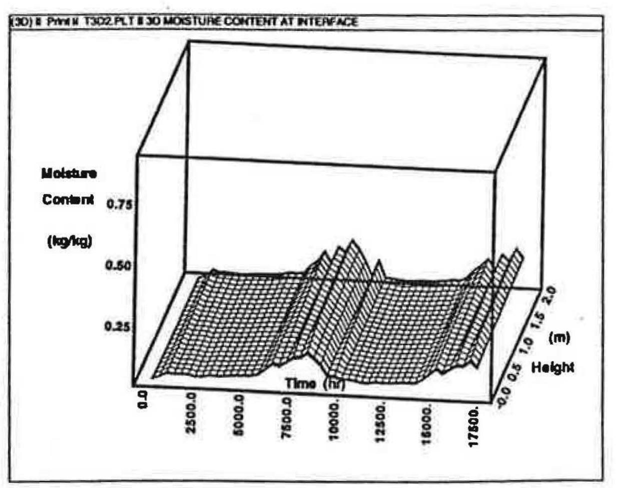

Figure 10.f Retarder with 15 $ng.m^{-2}.Pa^{-1}.s^{-1}$

Figure 10 *Effect of vapor retarder on temporal moisture distributions using real Ottawa weather data (results are plotted out for the innermost layer of the sheathing).*

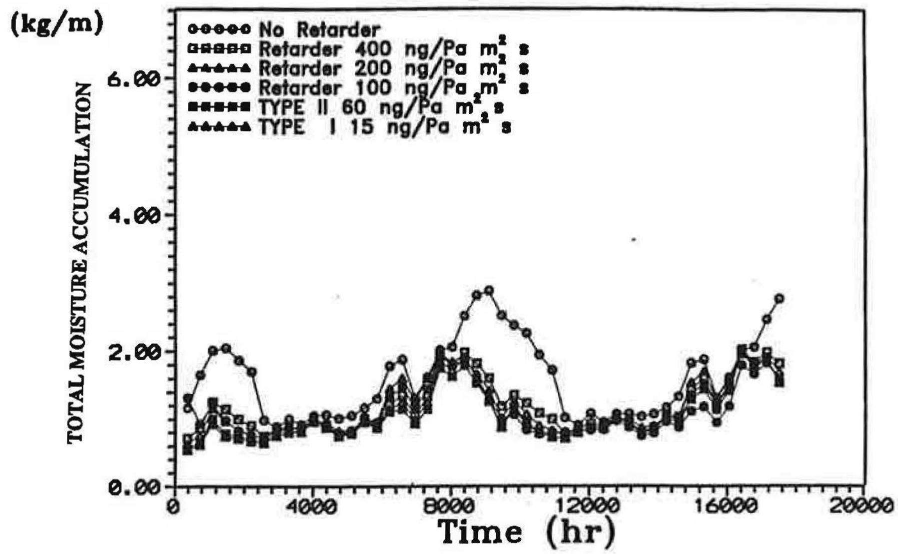

Figure 11 Effect of vapor retarder on the moisture accumulation as a function of time (Ottawa).

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DISCUSSION

Ken Gill, Senior Vice-President, H.D.R. Inc., Dallas, TX: Reconcile the practice in Scandinavian countries, which require negative building pressure to prevent moisture buildup problems in walls, with North American building codes, which *require* buildings to be slightly positive.

Should codes require negative pressure in the north and positive pressurization in southern, humid areas?

Also, should studies field-test housing to determine *actual* infiltration *and* account for voids in vapor barriers such as electrical outlets/wall switches/window and door penetrations?

A.N. Karagiozis: This particular investigation of vapor retarder performances in cold climates that neglected air effects suggests that in all cases when a type I vapor retarder is used, moisture problems are not encountered in the wall. In an earlier investigation from our laboratory, the influence of exfiltration on the hygrothermal performance of residential walls was reported (Ojanen, T., and M.K. Kumaran. 1992. *ASHRAE/DOE/BTECC Thermal Performance of Exterior Envelopes of Buildings*, pp. 491-500). Negatively pressurized buildings in colder climates infiltrate cold and dry air and avoid moisture condensation within the wall. However, other problems may arise with this practice associated with the indoor air quality, gas appliances, radon and soil gas infiltration, etc.

Research in the area of moisture transport would certainly benefit from more field tests on housing to determine the actual air infiltration and leakage regions.

Jeff Christian, Oak Ridge National Laboratory, Oak Ridge, TN: Can this model handle stack and wind pressure differences across the wall? Was the pressure difference on?

Karagiozis: The model can handle pressure differences due to wind and stack effects. This paper focused on the performance of vapor retarders with no applied external pressure differences. Natural convection in the porous insulation was modeled to account for stack effect.