ANNUAL CYCLE MOISTURE ANALYSIS

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ABSTRACT

The method currently used to screen construction types for possible condensation is the steady state ASHRAE dew point technique. This method estimates the outside conditions necessary to produce condensation within the wall but ignores the dynamics involved in daily and seasonal cycling of temperature and humidity. Other important characteristics of walls include the total amount of moisture accumulated during the winter and the length of time the moisture remains in the wall during the spring and summer months. This paper examines the effect of location and magnitude of the permeance of building materials, solar heating, daily and seasonal climatic variations, indoor relative humidity, and insulation level on the dynamic moisture behavior of a wall. Hourly calculations using weather data from the Minneapolis area are used to determine dynamic behavior for several wall types. Limitations of this method are discussed.

INTRODUCTION

During the winter season a substantial amount of water is released into the living space of a typical residential dwelling. A portion of this water will be removed via air exfiltration through the cracks around doors, windows, vents, etc., depending on the overall tightness of the house. The remainder of the water diffuses through the building envelope where, if conditions are unfavorable, condensation will occur. This condensation may cause damage to the house in the form of warping, paint failure, water spotting, and possible rotting and fungal growth. The potential for damage in wall cavities depends on several factors including the total amount of water which accumulates, the length of time water remains, the moisture capacity of the construction materials, and the temperature in the stud cavity.

The assessment of a particular wall construction in a location with certain climatic conditions cannot be properly made on the basis of design day calculations. In certain situations the design day calculation indicates that condensation occurs while a transient analysis would indicate that total moisture level would remain acceptable and would evaporate reasonably quickly. On the other hand, it is possible to conceive of construction types or climatic conditions for which design calculations indicate very little condensation occurring but water would remain in the cavity for extended periods. Recent developments in insulation products such as thermally efficient, low permeance, exterior sheathings have made traditional design practices, such as the 5:1 permeance ratio, more difficult to attain. Most investigations into the problem of condensation rely on steady state experimental and analytical techniques which cannot assess the effects of temperature and humidity cycling. The

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purpose of this paper is to propose a relatively simple method to examine the dynamic behavior of moisture accumulation in wall cavities. The important variables associated with condensation will be identified and the relative importance of each will be examined. Finally, the limitations of the method will be discussed.

BACKGROUND

At this point in time, the primary method of predicting condensation by design engineers is outlined in ASHRAE[1] and is based on work done by Glaser[2-3]. This method assumes that the primary mode of moisture transport is by one dimensional diffusion through the wall. By knowing the temperature profile through the wall, the saturation vapor pressure at each point can be calculated from psychrometric relations. The vapor pressure profile which would be established if no condensation occurred is found from the form of the diffusion equation

$$W = -\mu A \frac{dP}{dx} \tag{1}$$

where A is the area, m^2

P is the vapor pressure, kPa

W is the moisture flow rate, μg/s

x is the distance is the x direction, m

μ is the permeance, μg/(kPa s m)

The vapor pressure calculated from Equation 1 is compared to the saturation vapor pressure. Condensation occurs whenever the calculated vapor pressure is greater than the saturation vapor pressure. The vapor pressure modified by condensation is approximated by constructing piecewise linear segments from the warm side of the wall to a specified condensation point which is at saturated conditions and, in the same manner from this point to the cold side. By calculating the moisture flow into and away from the condensation point using the modified vapor pressure profile, an approximation to the condensation rate can be found.

This method does not account for some of the interactions between heat and mass transfer (i.e. the modification of the temperature profile due to phase change). It also ignores the other forms of moisture transport such as convection within the wall cavity and capillary movement in hygroscopic building materials. There have been attempts to combine vapor diffusion, liquid diffusion, and the interaction of mass transfer on heat transfer[4,6]. These treatments solve the combined heat and mass transfer equations using a finite difference scheme on a transient basis with simulated weather data input. The primary drawback with this technique is the complexity of the model. In order to apply the model for a particular wall type, detailed material properties must be available.

MODEL DESCRIPTION

The primary goal of the proposed model is to predict the moisture accumulation within wall cavities with a reasonable degree of accuracy while retaining the simplicity inherent in the Glaser model. To do this, we must extend the vapor diffusion model to account for evaporation and examine the magnitude of the mass convection caused by wind pressure.

When condensation occurs, the Glaser model, using Equation 1, predicts vapor pressure profiles of the form shown in Figure 1. Vapor pressure at the sheathing is set equal to the saturation vapor pressure and the condensation is assumed to occur there. For a wall insulated with a low density, non-hygroscopic, fibrous insulation, observation has shown that the small surface area in the insulation layer does not present a convenient location for condensation presumably because of the scarcity of nucleation sites. Most or all condensation has been observed to occur at the sheathing. If the sheathing material is a hygroscopic material, say wood fiber, this is also the most likely storage* location. When the outside temperature warms sufficiently so that condensation no longer occurs, the moisture which has accumulated in the sheathing will begin to vaporize forcing the vapor pressure to remain at the saturated level at that point. This will cause a vapor pressure gradient as in Figure 2 which allows water to escape from the cavity. In a manner completely analogous to the condensation calculation, flow rates out of the cavity may be calculated.

The effects of convection caused by wind pressures may be estimated by a slight variation on a method proposed by Burch, Treado, and Contrearas[7]. They measured the volumetric flow rate through a wall in an experimental investigation of condensation. Using the air conditions on both sides of the wall, they estimated the contribution of convection and added it to the diffusion component. Their situation was simpler than the present case because the flow rate was in one direction and they were able to measure it directly. In an actual house, the wind can come from any direction producing negative or positive pressures on the walls which cause flow into or out of the house. The form the equation takes depends on the direction of the flow and if condensation or evaporation is occurring. The equations describing the four possible situations are

$$\dot{W} = \dot{V}\,\rho\,(W_i = W_{o\,sat}) \tag{2}$$

for flow from inside to outside with condensation

$$\dot{W} = \dot{V}\,\rho\,(W_{sheath} - W_o) \tag{3}$$

for flow from outside to inside with condensation

$$\dot{W} = \dot{V}\,\rho\,(W_i - W_{sheath}) \tag{4}$$

for flow from inside to outside with evaporation

$$\dot{W} = \dot{V}\,\rho\,(W_o - W_{sheath}) \tag{5}$$

and for flow from outside to inside with evaporation, where

$\dot{V}$	is the volumetric flow rate, $m^3/(hr\text{-}m^2)$
$\dot{W}$	is the accumulation (dissipation) rate, $kg/(hr\cdot m^2)$
W_o	is ambient outside humidity ratio, kg water vapor/kg dry air
W_i	is ambient inside humidity ratio
W_{sheath}	is the humidity ratio of saturated air at the sheathing temperature
$W_{o\,sat}$	is the humidity ratio of saturated air at the outside temperature
ρ	is the density of the air, kg/m^3

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*Storage is used here to denote the net quantity of condensed water which remains at a particular location in the wall cavity, in this case the sheathing layer.

The flow rates of air through the wall were estimated by using data collected at our laboratory which relates mass flow rate to pressure difference. Data for blank walls was used (no windows, doors, or penetrations). To ensure that a "worst case" situation was considered, only data on unpainted walls without vapor barriers or air infiltration barriers were used. The pressure difference across the wall was estimated by using the theoretical wind pressure modified by the cosine of the angle between the normal to the wall and the wind direction.

Combining the convection terms with the diffusion, a total rate of moisture flow to or from a condensation zone may be calculated. These program elements can be combined with readily available ASHRAE psychrometric subroutines[8] and tabulated material properties to simulate a large variety of construction types and weather conditions. The effect of solar flux on moisture accumulation can be examined using the effective "sol-air" temperatures calculated by ASHRAE techniques[1]. Finally, the dynamic capability is provided by using National Oceanic and Atmospheric Adminstration (NOAA) weather tapes. Hourly mass balances over a period of one or more years can be made for walls with any orientation or tilt using sol-air or dry bulb temperature, relative humidity, wind speed, and wind direction. Moisture condenses, is stored, and evaporates at the sheathing layer.

SAMPLE RUNS

To illustrate capabilities of the proposed model, a series of runs were made using weather tapes from Minneapolis. The year 1956 was selected because as noted in Table 1 and Figure 3, it was fairly typical based on heating degree days, cooling degree days, and average monthly temperature. To illustrate the different types of walls, several variables are identified as having a significant effect on moisture accumulation. The first is the ratio of outside to inside permeance of the building materials. The usual practice in building design is a 5 to 1 ratio. The second variable is the overall permeance of the wall. This effective permeance magnitude governs the total vapor flow rate through the wall. The third variable is the insulation level in the cavity. The insulation level will determine the saturation vapor pressure and affect the condensation/evaporation rate. The fourth variable is the interior vapor pressure. This variable is controlled by humidifiers in the house or by reducing air infiltration. The inside to outside vapor pressure difference is the driving potential for vapor diffusion. The last variable considered here is the effect of solar flux. The south wall of a house will experience significantly higher outside temperatures than the north wall during the day. The higher temperatures will reduce the accumulation rates during periods of condensation and increase dissipation rates during periods of evaporations.

The effects of these variables are clearly shown in Figures 4 through 8. Figure 4 shows a large effect of the perm ratio of the building materials. The usual practice of a perm ratio of 5 to 1 appears to be sufficient even for a climate with almost 8000 degree days. Any interruption of the barrier which may alter this ratio will significantly change the behavior of the wall. Figure 5 shows the effect of perm magnitude on the annual cycle behavior. The figure shows that even with an unfavorable perm ratio, if the overall permeance of the wall is kept low, relatively small amounts of moisture will accumulate. Figure 6 shows the effect of added insulation on moisture accumulation. Changing the insulation level from no insulation to R-13 has relatively little effect on moisture. Figure 7 shows that the interior vapor pressure maintained in a house has a large influence. Humidification or sealing the house against air infiltration could aggravate condensation in this manner. Finally, the contribution of solar flux is shown in Figure 8. South facing walls appear to accumulate less moisture and retain that water for a shorter time period than north facing walls due to solar heating.

DISCUSSION

The predictions made by this model strongly depend on the validity of certain simplifications and assumptions. Calculations are made from a steady state model and integrated using hourly time steps. The major simplification of this model is that transport in the liquid phase is ignored. For the case of a stud wall composed of drywall, non-hygroscopic insulation, wood fiber sheathing and wood siding, this should be fairly accurate. During periods of condensation, the water will condense at the sheathing layer despite the location of the intersection of the saturation vapor pressure with the continuous vapor pressure. Very little water will condense in the insulation because of the small nucleation area and low moisture capacity. Once water collects in the sheathing, experience has shown that it will not be transported in the liquid phase through the insulation. Some liquid may be transferred to the wood siding but the relatively slow liquid diffusion through wood will not introduce large errors in the calculations. These calculations are not intended to represent situations where hygroscopic insulation materials (e.g. cellulose) are used.

Another simplification is the calculation of temperature profiles without including the effects of phase change or heat capacity. This device is commonly used in these types of calculations. Sandberg[5] and Jury[9] have examined the effect of all forms of moisture transport on the temperature distribution using finite difference methods and found only a small effect. The effect of heat capacity was small because only light wall construction was considered and hourly averages for the outside conditions were used. Thus the approach adopted here appears to be appropriate.

The effect of convection on moisture transport has been estimated only for wind induced situations and, even then, simplified estimates were made. The objective of considering wind induced convection was to estimate its magnitude in relation to diffusion. The Minneapolis airport weather data used here produced an upper bound of the estimate of convection because airports are relatively unobstructed in comparison to residential situations so the measured wind speeds should be larger. Despite this, condensation or evaporation due to convection never became significant. This might change in the presence of penetrations in the wall or construction defects. Based on a case where the west wall with 2.3 m^2 C/W (R-13), 1:5 perm ratio, 0.17 g/Pa s m^2 permeance magnitude, and 50% interior RH, little difference was detected when wind convection was included and excluded. Maximum deviation between the two cases was less than 1%.

The method used to calculate evaporation rates uses saturated air conditions at the sheathing. For very large values of moisture content, this condition will probably be accurate. When the moisture content approaches equilibrium values, the air conditions will fall below saturation and the model will over-predict evaporation rates. A more accurate condition would have the air follow the sorption lines for that material. However, it was felt that this would increase the complexity of the model without sufficiently increasing accuracy.

CONCLUSION AND SUMMARY

A relatively simple model was proposed to predict annual moisture cycling behavior of wall cavities in response to weather conditions. This model uses measured hourly weather data and thermophysical building material properties as input and predicts moisture levels as a function of time. In this way various wall configurations can be compared in terms of maximum moisture levels and the length of time moisture remains in the wall for any climatic condition. Several of the variables affecting moisture accumulation were identified and the relative importance of each examined. The limitations and restrictions of this model were also discussed. An experimental program to verify the model using laboratory facilities and an outdoor facility which subjects building components to actual weather conditions is currently underway.

ACKNOWLEDGMENTS

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TABLE 1

Weather Statistics, Minneapolis, 1956

	1956	Average
Average Temperature	7°C	7°C
Maximum Temperature	37°C	-
Minimum Temperature	-23°C	-
Cooling Degree Days	700	585
Heating Degree Days	7985	8159

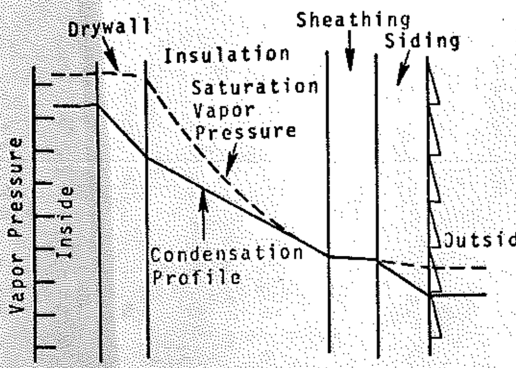

FIGURE 1 CONDENSATION VAPOR PRESSURE PROFILE

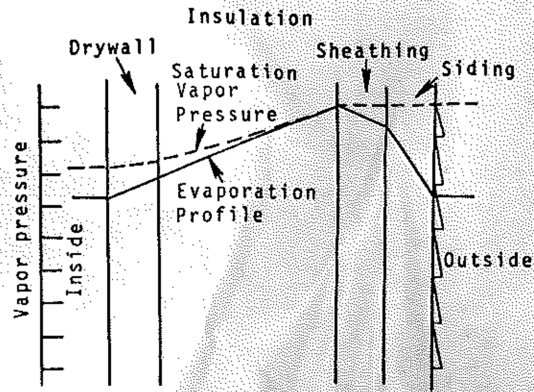

FIGURE 2 EVAPORATION VAPOR PRESSURE PROFILE

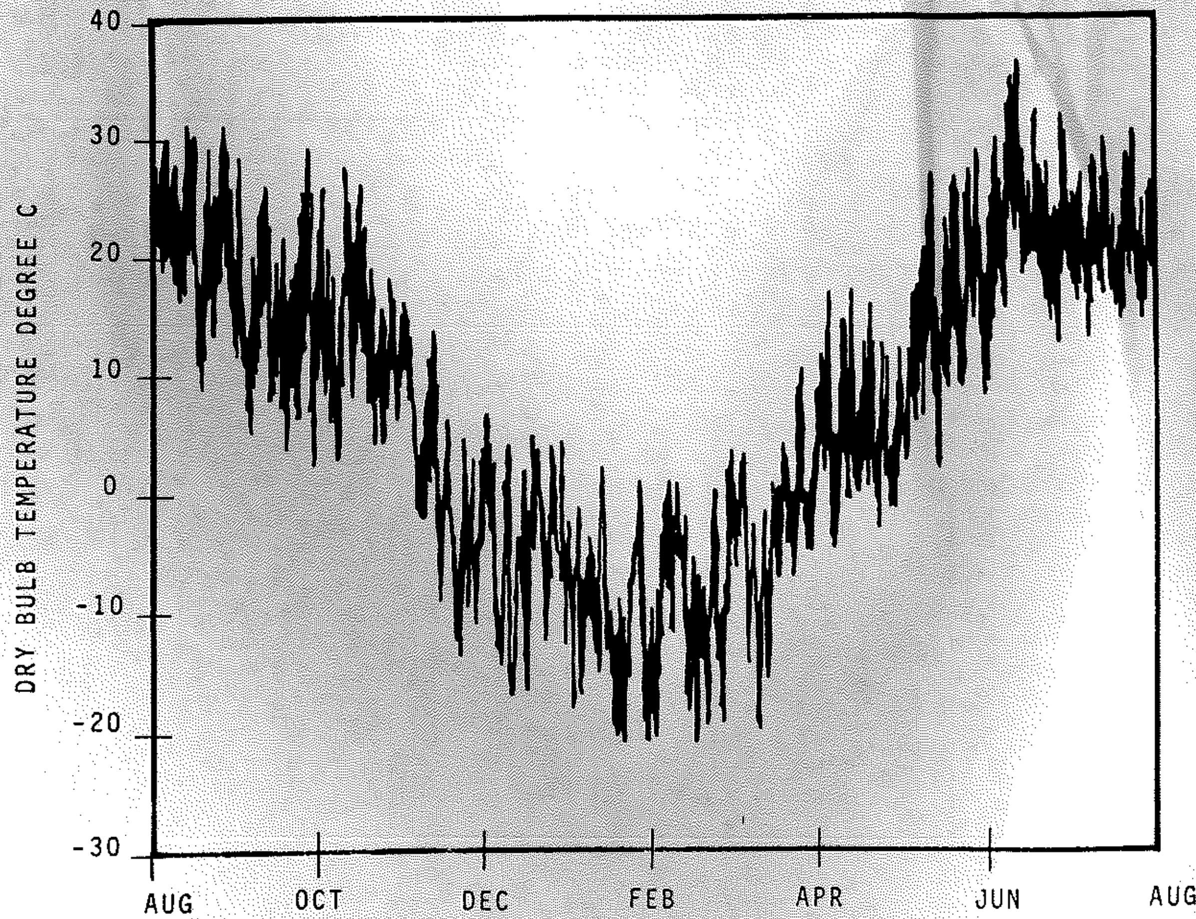

FIGURE 3 DRY BULB TEMPERATURE, MINNEAPOLIS, 1956

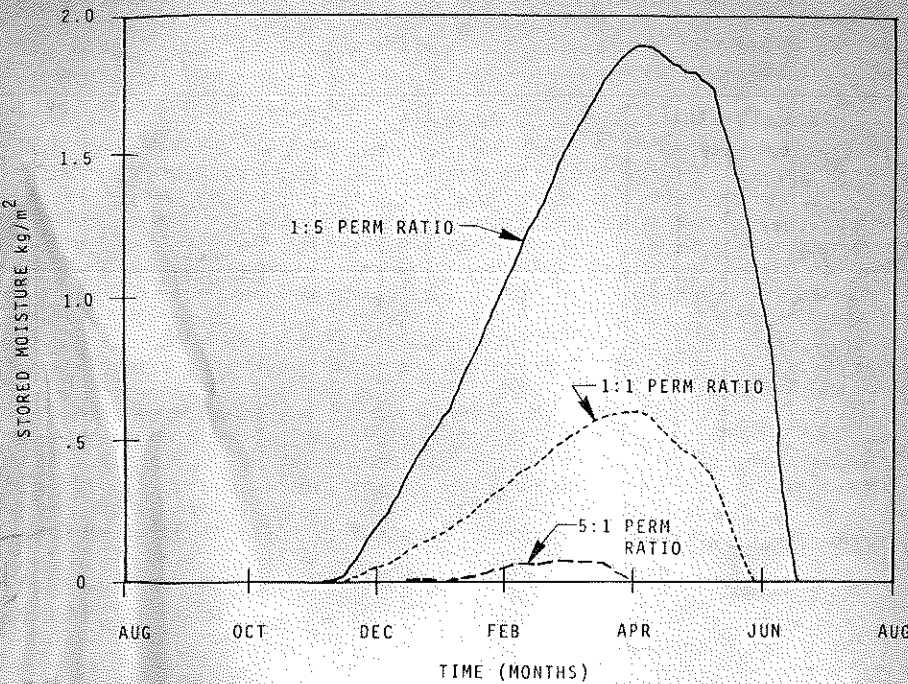

FIGURE 4 EFFECT OF PERM RATIO ON MOISTURE STORAGE NORTH EXPOSURE, 50% INTERIOR RH, 22C INTERIOR TEMPERATURE 2.3m^2 C/W INSULATION LEVEL, 1.7 $\mu g/Pa\ s\ m^2$ PERMEANCE MAGNITUDE

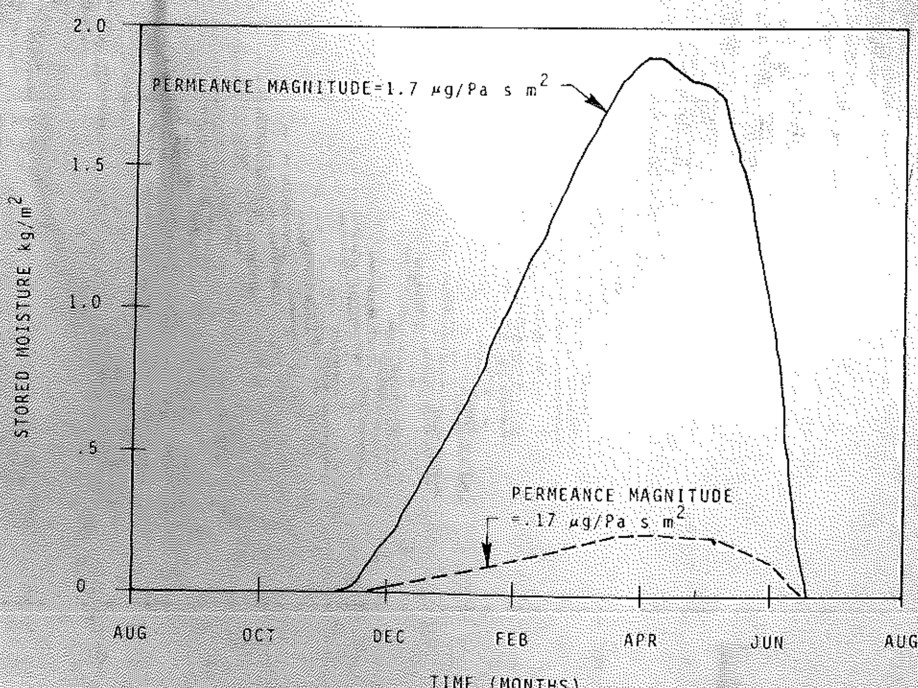

FIGURE 5 EFFECT OF PERMEANCE MAGNITUDE ON MOISTURE STORAGE NORTH EXPOSURE, 50 INTERIOR RH, 22 C INTERIOR TEMPERATURE 2.3 m^2 C/W INSULATION LEVEL, 1:5 PERM RATIO

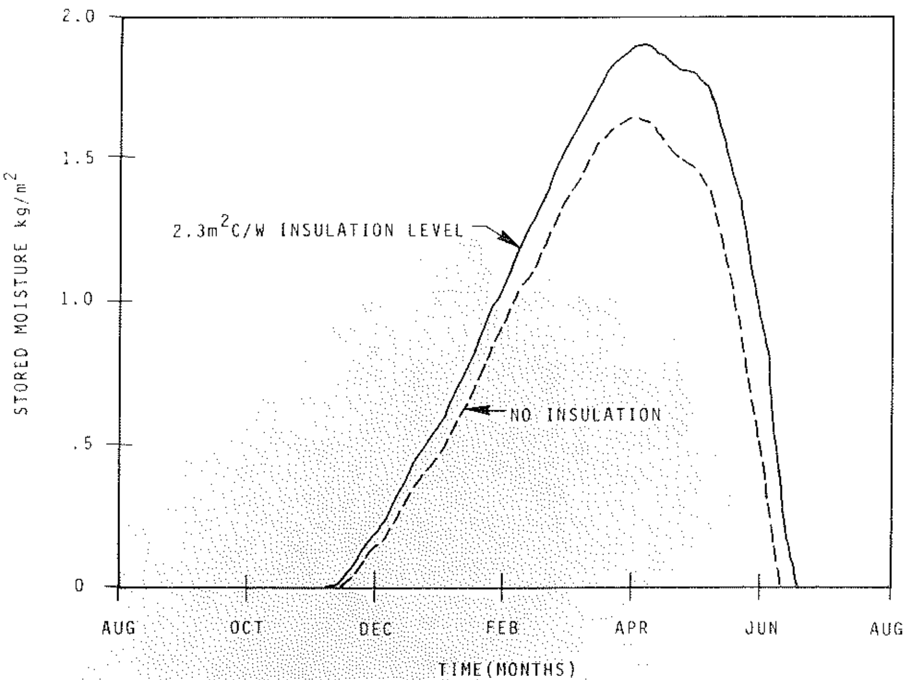

FIGURE 6 EFFECT OF INSULATION LEVEL ON MOISTURE STORAGE
NORTH EXPOSURE, 50 INTERIOR RH, 22 C INTERIOR TEMPERATURE
1.7 μg/Pa s m^2 PERMEANCE MAGNITUDE, 1:5 PERMEANCE RATIO

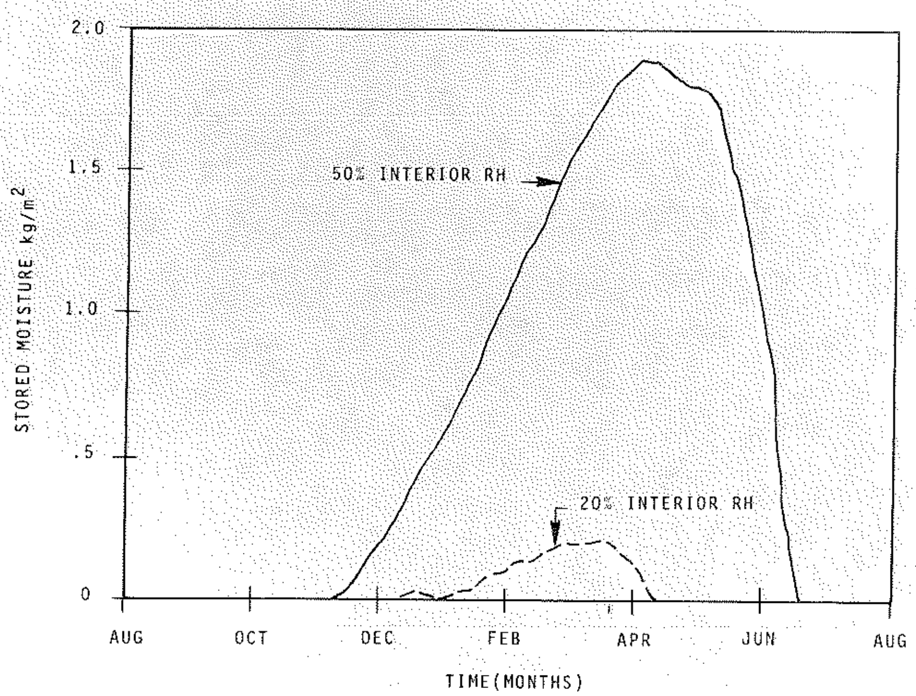

FIGURE 7 EFFECT OF INTERIOR RELATIVE HUMIDITY ON MOISTURE STORAGE
NORTH EXPOSURE, 22C INTERIOR TEMPERATURE,
1.7 μg/Pa s m^2 PERMEANCE MAGNITUDE, 1:5 PERMEANCE RATIO

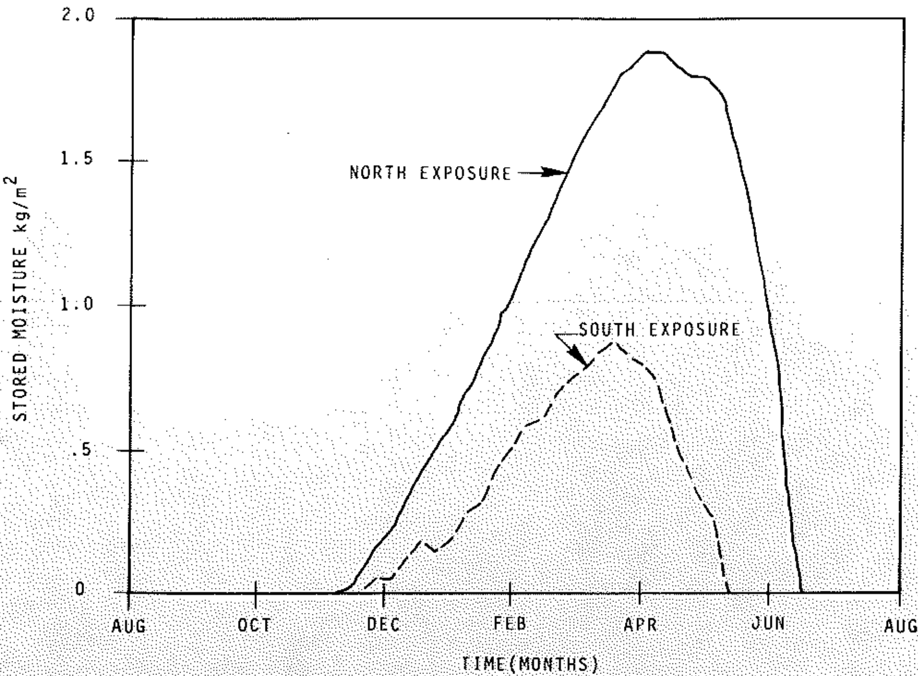

FIGURE 8 EFFECT OF WALL ORIENTATION ON MOISTURE STORAGE
50% INTERIOR RH, 2.3 m^2C/W INSULATION LEVEL, 22C INTERIOR TEMPERATURE
1.7 $\mu g/Pa\ s\ m^2$ PERMEANCE MAGNITUDE, 1:5 PERM RATIO

SESSION IX QUESTION AND/OR COMMENT

Knab, Jenkins, Methey

a. David T. Harrje, Princeton University

Q: Since the polyurethane 1 inch and 2 inch results were so different, did you do a micro analysis with regard to possible variations in all structure?

A: We have not performed a micro analysis of cell structure, but hope to do so in the near future.

As stated in the paper, we suspect that the 1 and 2 inch boards were cut from different batches because of the density difference (Table 1, 1 inch: 1.59 pcf; 2 inch: 1.86 pcf). Visual differences were also observed with the 2 inch boards appearing less uniform in texture than the 1 inch boards (Table 1: coefficient of variation of density for the 2 inch boards was 9.4% as compared to 4.9% for the 1 inch boards).

Homma

a. David Grimsrud, LBL

Q1: What depth was the flow channel, and how large was the flow velocity

A1: In the experimental model, the depth of the air passage was 28 mm. In the computer simulation this parameter was treated as a variable, and was changed between 10 and 100 mm. The air velocity varies according to the arrangement of the air passage and also to the radiative heat on the siding. The computer simulation predicted the average air velocity to be 0.23 m/3 at noon for an air space of 30 mm depth and opening ratio 50%, which is shown in Table 4 of the text. An example of air felocity distribution is also shown in Figure 6. The peak air velocity was over 0.3 m/s.

Q2: Is it possible that a transition to turbulent flow occurs?

A2: In our computer simulation, which was based on laminar flow theory, Reynold's number exceeded the critical value of 1000, when the depth of the air space was large and heat irradiation high. Experimentally the entrance shape to the air space was not smooth, thus it was possible that eddies were generated at flow rates below the critical Reynold's number.

Q3: Will your model be able to treat such a transition?

A3: The present simulation program cannot treat air flow in the turbulent regions; however, suitable modifications are presently being considered. The transition region presents somewhat greater difficulties, and unfortunately, it would probably occur very often in a real situation. This region will only be simulation after sufficient experimental data has been obtained.