Condensation in Attics: Are Vapor Barriers Really the Answer?

G. S. Dutt

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Center for Energy and Environmental Studies
Princeton University
Princeton, N.J. 08544

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ABSTRACT

Calculations of water vapor flow through walls and ceilings are frequently based on the permeabilities of building material, and implicitly assume that most of the vapor transport takes place by diffusion. In order to determine the validity of this assumption, a model for vapor transfer between two spaces by diffusion and convection is first developed. Measurements in a number of houses reveal that, for normal construction practices in U.S. wood frame houses, the transfer of water vapor from living space to attic is almost entirely by air movement. "Kraft" paper "vapor barriers", frequently attached to batt insulation, do not effectively hinder air (or moisture) flow into attics. Even after numerous cracks and openings on the attic floor, below the insulation, were plugged, significant air flow from living space to attic remained, and evidence of condensation of water vapor within the attic was observed.

In new housing, a continuous sheet placed between the ceiling and the framing of the attic floor should effectively hinder air and moisture flow. In existing housing, where it may not be possible to install a continuous sheet under the attic insulation, adequate opening for ventilation with outside air should be provided to prevent moisture buildup and condensation.

I. Introduction

Water evaporates in the living space of houses. Some water vapor penetrates the walls and ceilings and may condense on cold surfaces. If a significant amount of condensation takes place on wooden structural elements, then the wood rots and serious damage to the house may ensue. When insulation is added into the wall cavities or the ceiling, then certain surfaces are cooled and the risk of condensation may be increased. Justifiable concern over the adverse side-effects of energy saving retrofits has led to guidelines for the installation of insulation. The most common requirement in the U.S. is that a "vapor barrier" be installed, where possible, prior to the addition of insulation. A vapor barrier is usually defined as any paint or material with a permeance or permeance coefficient of one perm* or less [i.e. <57 ng/N s].[1]

The effectiveness of a vapor barrier as defined above presupposes a model for water vapor penetration through walls and ceilings - that water vapor migrates primarily by diffusion through the boundary. This model is generally invalid in actual U.S. houses. On the basis of measurements in a number of townhouses at Twin Rivers, N.J., and other supporting evidence, we conclude that water vapor is transported from the living space to the attic primarily by air flow from living space to attic. Even when a one-perm "vapor barrier" is in place, significant amounts of vapor migrates into the attic. Our measurements of attic humidity indicate the extent to which condensation takes place in the attic. Our calculations further suggest that an air flow (rather

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*A perm is the same as $grain/h/ft^2/in_{Hg}$. Both units widely used in the U.S. and S.I. equivalents have been used throughout this paper, except for equations and some intermediate results. A set of conversion factors is presented in Appendix A.

than diffusion) dependent moisture transport also prevails for walls.

It should be stated at the outset that the principal result reported here -- that vapor flux by diffusion is usually negligible -- is not widely recognized leading to confusion about the effectiveness of "vapor barriers". The purpose of the present paper is to compare the moisture transport mechanisms in buildings, supported by experimental evidence, in order to correct this misunderstanding of the nature of vapor barriers. Evidence of condensation in attics equipped with traditional vapor barriers is presented. More effective ways of avoiding moisture buildup in attics are suggested.

II. Vapor Transport Through Walls and Ceilings

Water vapor is transported through a wall or other interface by porosity in the construction material as well as by air flow through cracks and other openings in the surface. Porosity may be considered to be a material property whereas the cracks and openings are determined by the manner in which the wall or ceiling is constructed. For example, moisture migration through a plywood sheet is due to its porosity, whereas the moisture migration associated with air flow between adjacent sheets of plywood or through an electrical outlet in the plywood sheet depends on how the sheets are put together. We will examine both processes for vapor transport and derive some general expressions for the two components in terms of the porosity, the air flow rate and the moisture content.

When a certain mass of air crosses a boundary between two spaces in a building, it is balanced by other air flows such that the mass of air in each space remains roughly the same. This follows from the fact that in buildings only small pressure differentials between various spaces occur and consequently no significant mass buildup in any space can take place. In fact, as shown in Appendix B, these pressure differentials are so small that migration of air takes place mainly through cracks and other openings and not by diffusion through the walls.

Since the partial pressure of water vapor in air is usually very small, much larger relative variation of vapor pressure between different parts of a house are possible without significant air pressure differentials. These differentials in vapor pressure may make the process of diffusion of water vapor through walls a significant portion of the net transfer of vapor across an interface.

The rate at which vapor is transported across an interface by air flow is the product of the mass flow rate of air and the humidity ratio of the incoming air. The humidity ratio (W) is the mass of water per unit mass of dry air in a sample of moist air. The vapor flux associated with air flow from space 1 to space 2 is thus given by

$$w_a = V_{12}\rho_1 W_1 \tag{1}$$

where w_a is the rate of vapor flow (grains/h) [mg/s]

V_{12} is the volume flow rate of air from space 1 to 2 (ft^3/h) [mm^3/s]

ρ_1 is the density of air in space 1 (lb/ft^3) [kg/m^3]

and W_1 is the humidity ratio in space 1 $\frac{\text{grains water}}{\text{lb dry air}}$ [dimensionless]

The rate of migration of water vapor through a material of given porosity may be determined using Fick's Law:

$$w_p = - m \frac{dp_w}{dx}$$

where w_p is the vapor flux due to porosity (grains/h/ft^2) [μg/m^2/s]

$\frac{dp_w}{dx}$ is the gradient of vapor pressure (in$_{Hg}$/ft) [KN/m^3]

and m is the material permeability (grains ft/h/ft^2/in$_{Hg}$) [ng m/N s]

The units indicated are often adopted for moisture transport calculations. For a barrier of thickness ℓ and with a vapor pressure difference Δp_w, the rate of vapor flow is given by

$$w_p = \frac{m}{\ell} \cdot \Delta p_w \tag{2}$$

The quantity $M \equiv m/\ell$, which depends on the type of material and its thickness, represents the resistance to vapor flow across the barrier. M is called the permeance or the permeance coefficient and its unit of measurement is a perm, i.e. grains/hour/ft^2/in$_{Hg}$ [nanogram per Newton- second, or ng/N s]. Typical values of permeability and permeance are given in Ref. 2.

The steady state permeance, M, of a multilayer wall is given by $\frac{1}{M} = \sum_i \frac{1}{M_1}$ where M_i is the permeance of the ith layer.

The specific humidity or humidity ratio (W) is often a more convenient variable than the vapor pressure. A relation between the vapor pressure and the humidity ratio is derived here. Let ρ_w, ρ_a be the partial pressures of water vapor and air, and m_w, m_a be the masses of water vapor and air, respectively. The partial pressure of water vapor in air is usually small and the perfect gas relation is approximately valid:

$$p_w V = R_w m_w T$$

$$p_a V = R_a m_a T$$

where V, T are the volume and temperature of the mixture and R_w, R_a are the respective gas constants, related by

$$M_w R_w = M_a R_a$$

where M_w and M_a are the molecular weights of water vapor and air.

$$\frac{p_w}{p_a} = \frac{m_w}{m_a} \cdot \frac{M_a}{M_w} = \frac{28.8}{18} \frac{m_w}{m_a}$$

Noting that 1 lb is 7000 grains, the humidity ratio (W) in grains of water per lb of dry air is given by

$$W = \frac{m_w}{m_a} = \frac{18}{28.8} \times 7000 \frac{p_w}{p_a} .$$

$$= 4375 \frac{p_w}{p_a} ,$$

$$\text{or} \quad \frac{p_w}{p_a + p_w} = \frac{W}{4375+W}$$

Noting that the pressure of the moist air $p_a + p_w$ is in fact the atmospheric pressure, p,

$$p_w = \frac{Wp}{4375+W}$$

$$\simeq \frac{Wp}{4400} \qquad (3)$$

since W is typically around 25. Using the equation (2) and (3), the rate of vapor flow by diffusion through the wall is, therefore, given by

$$w_p = \frac{Mp}{4400} \quad \Delta W \tag{4}$$

where M is the wall permeance, p the atmospheric pressure and ΔW the difference in specific humidity across the wall.

The total rate of vapor flow between space 1 and 2 is the sum of the components associated with diffusion and air flow:

$$\begin{aligned} w &= A\, w_p + w_a \\ &= \frac{AMp}{4400} \quad \Delta W + V_{12} \rho_1 W_1 \end{aligned} \tag{5}$$

where A is the surface area of the interface. The following numerical example helps to put the above equation in perspective.

The problem of water vapor transport from living space to attic is illustrated here with a couple of numerical examples, based on actual measurements, handbook values and estimates.

Numerical example 1

Consider the flow of water vapor from the house (region 1) into the attic (region 2) of a typical Twin Rivers townhouse. Batts of fiberglas insulation backed by a kraft paper vapor barrier lie on the gypsum board floor of the attic between the joists. This type of insulation and vapor barrier combination is common in U.S. housing. The permeance of the components of the interface are shown below:[2]

Table 1

	M(grains/ft^2 h in$_{Hg}$)	[ng/N s]
Interior paint	50	2860
Gypsum board	50	2860
Insulation (vapor barrier)	1	57
Insulation (fiberglas)	50	2860

The overall M equals 0.94 perm, essentially the permeance of the vapor barrier. The characteristics of the attics in our example are as follows:

Floor area	$= 726\ ft^2\ [67.5 m^2]$
Atmospheric pressure	$= 29.9$ inches of Hg
	$= 2117\ lbf/ft^2$
Density of air	$= 0.074\ lb/ft^3$
Humidity ratio in living space	$= W_1$
	$= 35\ \frac{\text{grains of water}}{\text{lb of dry air}}$ *
Humidity ratio in attic	$= W_2$
	$= 22.4\ \frac{\text{grains of water}}{\text{lb of dry air}}$ *

The total rate of vapor flow from house to attic is then given by equation 5:

$$W = \frac{0.94 \times 29.9 \times 12.6 \times 726}{4400} \quad \frac{\text{grains of water}}{\text{h}} \quad \text{(diffusion)}$$

$$+ V_{12} \times .074 \times 22.4 \quad \frac{\text{grains of water}}{\text{ft}^3 \text{ of air}} \quad \text{(air flow)}$$

$$w = 58.4 \text{ grains/h} + 1.66\ V_{12} \quad \frac{\text{grains of water}}{\text{ft}^3 \text{ of air}} \tag{6}$$

The two components of vapor flux expressed by the two terms on the right hand side of the equation are equal if

$$V_{12} = 35.2\ ft^3/h$$

If V_{12} is much larger than 35 ft^3/h [1.0 m^3/h] then most of the moisture transport is by air movement. Estimates of the flow rate V_{12} from living space to attic in a Twin Rivers townhouse were made using sulphur hexaflouride as a

*These values are based on measurements in one townhouse at 7 AM on March 8, 1977.

tracer gas. As part of another experiment in this attic, the insulation had been rolled back and cracks in the attic floor/upstairs ceiling sealed prior to this test. The flow rate measured was in the range 200-800 ft^3/h.[3] [5.6 - 22.6 m^3/h]. Since these values are much larger than 35 ft^3/h, we conclude that the flow of moisture from living space to attic by diffusion through the ceiling is much smaller than the transport by air movement. In other houses where the attic floor cracks had not been carefully sealed, the air flow component of moisture transport would be even larger. A simple calculation shows that, if no vapor barrier were present then, for the above example, migration of vapor by diffusion would be about 1040 grains/hour and would equal the migration by air movement for V_{12} = 625 ft^3/h [17.7 m^3/h]. Thus even without a vapor barrier and a house-to-attic air flow as low as that obtained for the 'sealed' ceiling at Twin Rivers, the migration by diffusion and by air movement would be comparable. This does <u>not</u> imply that vapor barriers should not be used, because they presumably reduce air flow from living space to attic as well.

<u>Numerical example 2</u>

In the course of the winter '77-'78, about 15 single family detached houses were studied in order to determine the extent of attic heat transfer that bypasses the ceiling insulation.[4,5] In these houses, of various ages and design, an average bypass heat transfer rate between living space and attic was equivalent to a "U-value", U_B, of about 0.3 $Btu/ft^2/h/°F$ [1.7 $W/m^2/°C$]. It was inferred that a part (say, α) of the bypass heat transfer from living space to attic was by air flow. The air flow rate, V_{12}, necessary to provide this heat transfer is given by:

$$V_{12} = \frac{\alpha U_B}{\rho C_p} A$$

where ρ, C_p are the density and specific heat for (moist) air in the living space, and A is the ceiling area. Since the value of $\rho C_p = 0.018$ Btu/ft^3/°F, we have

$$V_{12} = 16.7\ \alpha A \text{ ft/h } [= 5.09\alpha A \text{ m/h}]$$

The total vapor flow rate from living space into the attic is given by Eq. (5). Using the same permeance values and typical values of W_1 and W_2 as used in Example 1, the vapor flux from living space to attic is given by:

$$w = A \quad \underbrace{\frac{0.94 \times 29.9 \times 12.6}{4400}}_{\text{diffusion}} \quad + \quad \underbrace{16.7\ \alpha \times 0.074 \times 224}_{\text{air flow}} \quad \text{grain of water/h}$$

$$= A \left[0.09 + 27.6\ \alpha \right] \text{ grain of water/h} \qquad (7)$$

The vapor transport by air flow exceeds the transfer by diffusion if

$$27.6\alpha > 0.09$$

$$\text{or} \qquad \alpha > 3.26 \times 10^{-3}$$

Our experiments suggest that α is typically between 0.5 and 1 so that moisture transport to the attic by air movement far exceeds that by diffusion.

These two examples show that vapor transport from living space to attic in insulated attics is largely by air flow. This is true even when the insulation on attic floor is backed by a "kraft paper" vapor barrier. Indeed, air flow continues to dominate even when cracks below the insulation are "sealed". These data suggest that a continuous barrier which hinders air flow would be a better barrier to the moisture flux into the attic than a traditional vapor barrier. This would be true even if the porosity of the continuous barrier to water vapor flow was somewhat higher than that of kraft paper.

Measurements in other houses suggest that only a small fraction (~ 30%) of the air infiltration passes directly through doors and windows.[6] A significant portion takes more circuitous routes through wall cavities. It is therefore reasonable to suppose that in wood frame buildings, the moisture transport through walls is also dominated by air flow.

III. Condensation in Attics

One way of determining if condensation takes place during cold periods (say nighttime) is by looking for evaporation during subsequent warm periods. This is particularly easy to detect in attics which get heated by the sun during the day. Fig. 1 shows the specific humidity (mass of water vapor/mass of dry air) in a Twin Rivers attic and living space based on recorded relative humidity and temperatures. The corresponding specific humidity outside was obtained from dry and wet bulb temperature data recorded at Trenton, N.J. (about 15 miles away) by the U.S. National Weather Service.

During the course of the day, March 8, 1977, the specific humidity in the living space remained roughly constant while that outside fell a little. If no moisture evaporated or condensed in the attic and the air flow in and out of the attic, from the living space, and outside remained constant, then the specific humidity in the attic would have remained at a fixed proportion in relation to the specific humidity in the living space and outside:*

$$\text{i.e.} \quad W_A = k_H W_H + k_O W_O$$

However, the attic specific humidity did not remain in constant proportion during the day, instead rising to a peak around midday and then falling. Changes in attic ventilation rate, brought about by changes in wind speed cannot account for the specific humidity pattern in the attic. The wind speed increased from 7 AM till midday (Fig. 2) and would have brought W_A closer to W_O (see Appendix C). Again this did not occur.

An alternative explanation is suggested by the similarity between the solar radiation and W_A for that day (Figures 1 and 2): The sun heats the roof and moisture is expelled into the attic air. At first glance this moisture may be either the result of the plywood in the roof giving off its <u>absorbed</u> moisture or of water vapor <u>condensed</u> on the roof under-side being re-evaporated. The former process -- air drying of wood -- is normally associated with a time constant of several days (partly because the water is distributed throughout the material), whereas evaporation is a surface phenomena and takes place much more rapidly.[7] The rapid increase in W_A can then

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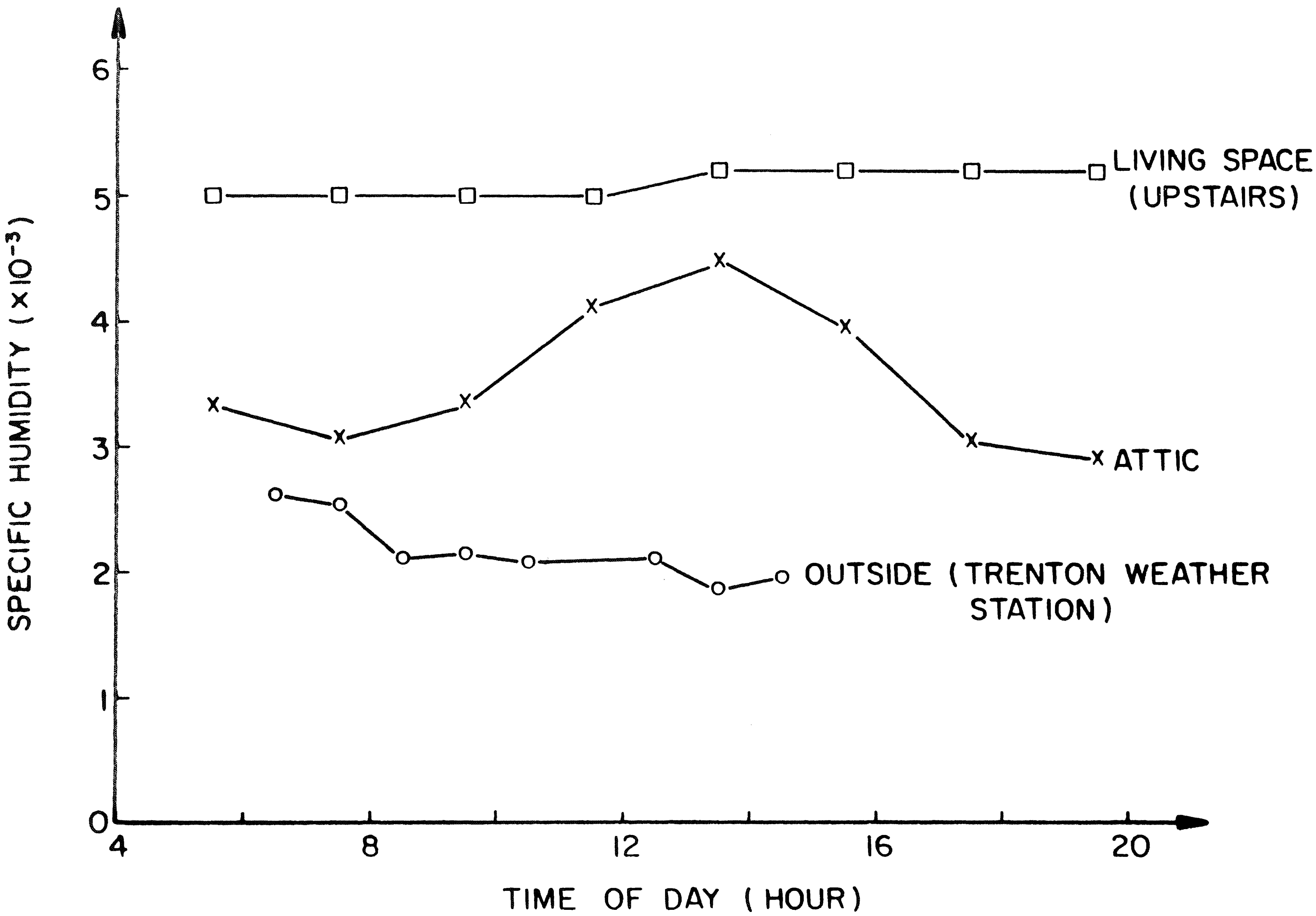
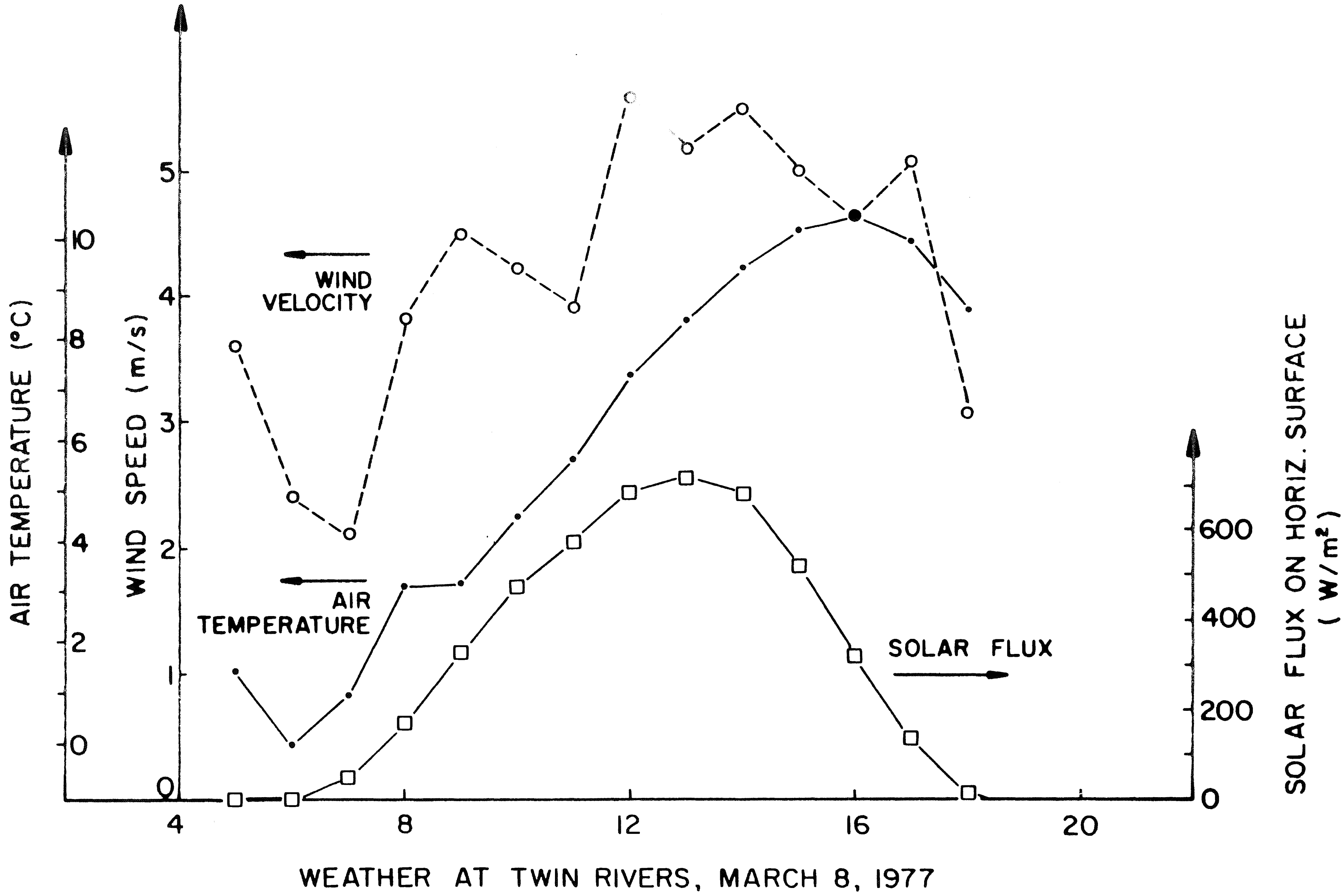
*For a derivation of this equation and the interpretation of k_H and k_O see Appendix C.



HUMIDITY IN A TWIN RIVERS TOWNHOUSE, MARCH 8, 1977

FIGURE 1



AIR TEMPERATURE (°C)
0
2
4
6
8
10
WIND SPEED (m/s)
0
1
2
3
4
5
WIND VELOCITY
AIR TEMPERATURE
SOLAR FLUX
SOLAR FLUX ON HORIZ. SURFACE (W/m²)
0
200
400
600
4
8
12
16
20
WEATHER AT TWIN RIVERS, MARCH 8, 1977

FIGURE 2

only be explained by evaporation of water vapor from attic surfaces. The subsequent decline in W_A takes place when the rate of evaporation is exceeded by the rate at which humid air is flushed out of the attic by ventilation with outside air.

Other humidity data in the same house shows that the specific humidity did not always go up during sunny days. This is consistent with the hypothesis that evaporation can only be seen if condensed water was available in the attic. Thus, evaporation is an indication of prior condensation.

Are condensation-evaporation cycles of a few days' duration damaging to the structure of the house? It seems unlikely, since such cycles probably would persist in most attics because of changes in outside weather conditions alone.

The situation in walls is different, however, especially for walls shaded from the sun. Here condensation may continue to build up throughout the winter and result in structural damage.

IV. Conclusions and Recommendations

Moisture transport into the attic is largely by air flow and not by diffusion through the ceiling. This air flow is not significantly hindered by the vapor barrier backing of batt insulating materials. An effective vapor barrier should aim to block air flow. Since significant air flow takes place through cracks and openings, an ideal vapor barrier is a continuous sheet, e.g. a polyethylene film or aluminum foil. A resistance to porosity, indicated by a low "perm" rating, is also desirable.

If it is not possible to install an effective vapor barrier, e.g. in a house being retrofitted with additional attic insulation, moisture flow should be inhibited by blocking openings that connect to living areas. The accompanying reduction in air flow has a large energy savings potential as well.[4,5] However, substantial air flow through the attic floor may persist. Therefore, in spaces such as attics and crawl spaces where condensation is likely to occur (and cause damage), ventilation openings to the outside must be left open. This will permit the moisture that does find its way into such spaces to be flushed out.

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Appendix A: Conversion Factors

Quantity	American units	S.I.
Mass	1 grain	64.94 mg
Permeability	$1 \dfrac{\text{grain ft}}{\text{h ft}^2 \text{ in}_{Hg}}$	$17.43 \dfrac{\text{ng m}}{\text{N s}}$
Permeance or permeance coefficient	$1 \text{ Perm} = 1 \dfrac{\text{grain}}{\text{h ft}^2 \text{ in}_{Hg}}$	$57.19 \dfrac{\text{ng}}{\text{N s}}$
Vapor flux	$1 \dfrac{\text{grain}}{\text{h ft}^2}$	$193.7 \dfrac{\mu\text{g}}{\text{m}^2 \text{s}}$
Vapor pressure gradient	$1 \dfrac{\text{in}_{Hg}}{\text{ft}}$	11.11 KN/m^3

Appendix B: The Effect of Material Porosity on Air Infiltration

The exchange of house air with the outside represents a significant energy loss in both the heating and the cooling season. In general, this air exchange is caused by air flow through cracks in the building envelope as well as by porosity through the material walls of the structure. The porosity component is examined here and shown to be negligible even for the most porous construction materials in general use.

The analysis is based on the premise that since molecules of oxygen and nitrogen (principal constituents of air) are somewhat larger than that of water, the porosity of a material with respect to air must be smaller than the porosity with respect to the transport of water vapor. Here porosity is defined as the <u>number of molecules</u> passing through unit area of the wall per unit pressure difference imposed across it. (By contrast, permeability refers to the <u>mass</u> transported through unit area per unit pressure difference across the wall.) The average molecular weight of air is 28.8 compared to 18 for water vapor, so that for the same porosity, the permeability for air will be 28.8/18 times as much for water.

Consider a typical wall structure without any special barriers to restrict humidity transport across it. The side walls of the Twin Rivers house is a good example. This wall is made of 1/2" Gypsum board with a water emulsion interior paint. ASHRAE values of permeance of each is around 50 perms so that the permeance of the wall is 25 perms.*

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*A perm is the same as grains/(h ft^2 in_{Hg})

According to the premise of our analysis the permeability of the wall with respect to air movement is at most 25 x 28.8/18 perms, or 40 perms, or 8 x 10^{-5} lb/lbf/h [2.29 mg/Ns].

The motive force for air movement is a pressure difference across the wall. A typical pressure difference between the inside and outside of a house is

$$\Delta p = 1/2 \; \rho \; v^2$$

where v is the wind velocity and ρ its density.

Consider a typical wind speed of 10 ft/s [3.05 m/s]. The mass flow rate of air through a wall of area 1120 ft^2 [104 m^2] is:

$$M_{OH} = 8 \times 10^{-5} \frac{\text{lb}}{\text{lbf h}} \times 1/2 \; \rho \; 10^2 \frac{\text{ft}^2}{\text{s}^2} \times 1120 \text{ ft}^2$$

and the volume flow rate is:

$$V_{OH} = \frac{M_{OH}}{\rho}$$

$$= 0.139 \text{ ft}^3/\text{h} \; [3.94 \times 10^{-3} \text{ m}^3/\text{h}]$$

A typical air change rate for even a tight house is about 0.5 house volumes per hour or 6500 ft^3/h [184 m^3/h] for a house of volume 13000 ft^3.

Thus the contribution of air diffusion through even a very porous wall is a small portion of the total air flow across the wall.

Appendix C.: Specific Humidity in Attics

The rates at which water vapor enters and leaves the attic determine the moisure levels in the attic. Hence the moisture level in the attic is determined by air flow in and out of the attic.

The vapor buildup rate in the attic air is the difference between the rate of vapor influx and efflux. Designating the house (living space), attic and outside by the suffices H, A, and O, we have from Eq. (10)

$$\frac{dW_A}{dt} = V_{HA}\rho_H W_H + V_{OA}\rho_O W_O - V_{AH}\rho_A W_A - V_{AO}\rho_A W_A \tag{11}$$

where, V_{HA} is the volume flow rate of air from house to attic, etc., as before.

From continuity, we also have:

$$V_{HA}\ \rho_H + V_{OA}\ \rho_O - V_{AH}\rho_A - V_{AO}\ \rho_A = 0 \tag{12}$$

We are mainly concerned with long term moisture buildup in the attic, and not on instantaneous peaks. Therefore, we may average the humidity balance equation (11) over long time intervals such that the time varying term is negligible:

$$\frac{dW_A}{dt} \simeq 0$$

In that case, Eq. (11) becomes:

$$V_{HA}\rho_H W_H + V_{OA}\rho_O W_O - V_{AH}\rho_A W_A - V_{AO}\rho_A W_A = 0 \tag{13}$$

The density of air is inversely proportional to its absolute temperature if the pressure remains constant. Therefore, Eq. (12) and (13) may be re-written as:

$$\frac{V_{HA}}{T_H} + \frac{V_{OA}}{T_O} - \frac{V_{AH}}{T_A} - \frac{V_{AO}}{T_A} = 0 \tag{14}$$

and

$$\frac{V_{HA}W_H}{T_H} + \frac{V_{OA}W_O}{T_O} - \frac{V_{AH}W_A}{T_A} - \frac{V_{AO}W_A}{T_A} = 0 \tag{15}$$

where the temperatures T_H, T_A, T_O are expressed in absolute degrees.

$\frac{V_{AH}}{T_A}$ and $\frac{V_{AO}}{T_A}$ may be eliminated between Eq. (14) and (15) to yield

$$\frac{V_{HA}W_H}{T_H} + \frac{V_{OA}W_O}{T_O} - W_A \left[\frac{V_{HA}}{T_H} + \frac{V_{OA}}{T_O}\right] = 0$$

or

$$W_A = \left[\frac{V_{HA}/T_H}{\frac{V_{HA}}{T_H} + \frac{V_{OA}}{T_O}}\right] W_H + \left[\frac{V_{OA}/T_O}{\frac{V_{HA}}{T_H} + \frac{V_{OA}}{T_O}}\right] W_O \tag{16}$$

If the volume flow rates and temperatures are constant then the attic specific humidity remains in fixed proportion to the specific humidity in the living space and outside:

$$W_A = k_H W_H + k_o W_o \tag{17}$$

Since the ventilation of the attic with outside air, V_{OA} increases with the wind speed, an increase in wind speed brings W_A closer to W_o, i.e. the attic is flushed out more effectively with outside air.