humidity (0.03 in. Hg vapor pressure). The wall consists of painted plaster on gypsum lath on the inside over 2 × 4 in. studs, mineral wool fill between studs, 1 in. wood exterior sheathing, paper, and pine lap siding. Check for possible condensation.

To simplify the example, consider the paint, plaster, and lath as a single element having a permeance $M = 1.0$ perms and a thermal *conductance $C = 2.4$, and the exterior sheathing*, paper, siding, and paint as another single element for which $M = 2.0$ perms and $C = 0.50$. From Table 1 the value for the permeability of mineral wool fill may be found as $\bar{\mu} = 116$ perm-inches. The thermal conductivity for mineral wool, $k = 0.27$.

Solution: In this particular wall, insulated, and with moderate warm-side relative humidities, condensation is unlikely to occur until the sheathing is reached. To check directly for condensation on the warm side of the exterior sheathing (designated as plane X − X in Fig. 2 for convenient reference) proceed as follows:

Calculate according to the method of Chapter 9 the temperature at plane X − X. This is found to be 9 F. The saturation vapor pressure at this temperature is 0.06 in Hg. If condensation is imminent or occurring at X − X, the vapor pressure there will be 0.06 in. Hg. Calculate the permeance for the portion of the wall from the warm side to X − X, and the vapor flow rate to X − X as follows:

$$\text{Permeance of wall to X} - \text{X} = \frac{1}{\frac{1}{1.0} + \frac{3.625}{116}} = 0.97 \text{ perms.}$$

Vapor pressure drop to X − X = *0.37 − 0.06 = 0.31* in. *Hg.*

Vapor flow to X − X = 0.97 × 0.31 = 0.30 grains per (sq ft) (hr).

Calculate the vapor flow rate from X − X to outdoors as follows:

Permeance of wall from X − X to outdoors = 2.0 perms.

Vapor pressure drop from X − X to outdoors

= 0.06 − 0.03

= 0.03 in. Hg.

Vapor flow rate to outdoors = 2.0 × 0.03 = 0.06 grains per (sq ft) (hr).

It is apparent that continuity of vapor flow is not possible, since at the highest vapor pressure at X − X permitted by the *temperature, there is indicated a greater flow to plane* X − X than from it to outdoors. Condensation is indicated at a rate of 0.30 − 0.06 = 0.24 grains per (sq ft) (hr).

Whether this condensation rate will be serious must still be decided, since it might readily be absorbed by the sheathing during the condensation period without excessive wetting. When the temperature at X − X is below freezing, as in this case, the condensation will be in the form of frost which may accumulate until released over a short period upon a rise in outdoor temperature.

Condensation will be reduced or avoided if the permeance of the warm side of the wall can be reduced so that the flow to X − X is limited to 0.06 grains per (sq ft) (hr). Permeance required for this is $\frac{0.06}{0.37 - 0.06} = 0.19$ perms or less. A more resistant paint film on the plaster, reducing the paint-plaster-lath permeance to 0.19 perms would accomplish this.

When the critical plane for condensation is unknown, or for a more informative, graphical representation of the situation throughout the wall, temperatures and vapor pressures may be calculated and plotted as in Fig. 2. The vapor pressures throughout the wall, for continuity of flow, are calculated in a manner similar to the temperatures; the external vapor pressures are given, and the vapor pressure drops across each element are taken in proportion to resistance to vapor flow.

The curve for saturation vapor pressures at the various temperatures throughout the wall is also shown in Fig. 2 and is seen to fall below the curve for vapor pressures with con*tinuity of flow, toward the outer portions of the wall.* This indicates that with the given temperatures and vapor pressures, continuity of flow is not possible and that condensation will occur. Condensation on the sheathing is indicated as a definite possibility, and the new vapor-pressure curve can be constructed for this condition, as shown. This new curve does not rise above the saturation-vapor-pressure curve, thereby confirming that the critical plane for condensation was correctly assumed.

With the vapor pressures thus established, the relative humidities may be found, by reference to the saturation vapor pressures. The permeances originally assigned to the various elements may then be re-examined in the light of the service conditions of temperatures and relative humidities indicated, and the analysis repeated, if necessary, using more appropriate permeance values.

In a more detailed analysis, individual values might be assigned to the elements forming the outer portion of the wall which is here dealt with as a composite, homogeneous element.

The transmission of water vapor as outlined is based on the assumption of a diffusion process. The possibility of vapor being transferred as part of a moving air stream has thus far been ignored, except in *Example 1* in which it is implied that the air circulation on either side of the wall will be sufficient to eliminate surface-film resistances to vapor flow. Differences in total pressure of the air may result in a transfer of vapor with air, augmenting and at times over-riding the effects of the flow produced by vapor-pressure gradients alone. This can be particularly important in the transfer of vapor through cracks and pinholes or through air-permeable building constructions. Similar effects can be obtained with air-permeable materials themselves.[6]

This means of vapor transfer is similar to that of transfer of heat by air leakage in and through building constructions, and requires, for purposes of calculation, information on the nature and amount of the air leakage. It will seldom be important in constructions without air spaces and having parged or plastered surfaces. It may, however, be an important means of vapor transfer through constructions lacking in air tightness, and may contribute to condensation difficulties, since the mechanism of condensation is not dependent upon the way in which the vapor is transferred.

PERMEANCE AND TESTING

The simplest method of finding the permeance of a specimen is to seal it over the top of a cup containing desiccant or water, placing it in a controlled atmosphere, and weighing it periodically. The steady rate of weight gain or loss is normally the water vapor transfer. When the cup contains a desiccant the procedure is called the *dry-cup method* and when the cup contains water, the *wet-cup method*. Usually the surrounding atmosphere is held at 50 percent relative humidity, thus providing, in either method, substantially the same difference of vapor pressure, but the results obtained by the two methods for the same specimens are likely to be much different, the wet-cup method producing the higher values. The relationship between these values can best be understood by reference to Fig. 3, which shows a typical variation of spot permeability with relative humidity at one particular temperature (isothermal conditions) for a material such as wood. The vapor permeability is shown to vary only moderately at low humidities, but to increase at an increasing rate as higher humidities are reached. The dry-cup test of this material carried out with 0 percent relative humidity one side and 50 percent on the other, will experience throughout its thickness, because of the variation in relative humidity, a variation in spot permeability. The average permeability $\bar{\mu}$, is by definition (Equation 3), given by $\frac{\int_{p_1}^{p_2} \mu dp}{p_1 - p_2}$, and since at a fixed temperature there is a linear relationship between vapor pressure and relative humidity, this expression can be seen to correspond to the mean height of the area under the spot permeability curve, between the appropriate relative humidity limits. The average permeability as found for the dry-cup conditions should therefore have the value $\bar{\mu}_1$. Similarly for the wet-cup test between 50 percent and 100 percent relative humidity, the value should be $\bar{\mu}_2$. It is not uncommon for these values for wood and wood-fiber materials to be in the ratio of 1 to 3, or higher. (See Table 1.)

The average permeability $\bar{\mu}$ for any other relative humidities at a particular temperature is given by the mean height of the area under the curve of spot permeability for the material at that temperature, between the appropriate limits of relative humidity. Only average permeabilities (or permeances) are measurable directly in practical tests. However, if several average permeabilities at different relative humidities are known, and can be plotted as for the wet-cup and dry-cup tests shown in Fig. 3, it is possible to construct, by trial and error, a *spot permeability curve* which will satisfy the condition that the average height of the curve between the appropriate limits for each test must equal the value found in each test. Separate curves are required for each temperature so that a large number of permeance cup tests would be required to cover a range of conditions of both temperature and humidity.

Experience to date shows that the effect of temperature is quite moderate and, *for some purposes*, differences in temperature at which tests are run may be ignored. Corrections for temperature have been made with some success in the case of certain materials by the use of an equation based on activation energy[7] which states:

$$\mu = \mu_0 e^{-(E/RT)} \qquad (8)$$

where, in appropriate units,

μ_0 = permeability at $T = \infty$.

R = gas constant.

E = activation energy.

e = Naperian base of logarithms = 2.718.

T = absolute temperature.

Applications of this equation may be limited to materials such as resins, rubbers, and polymers in which the water molecules enter and move through the molecular structure by a process known as activated diffusion. It may serve also as a useful approximation in other cases.

By use of Equation 8, spot permeability curves for a variety of temperatures can be constructed from a curve for one temperature, provided only that two tests at different temperatures can be run, from which E, the activation energy, can be evaluated. In this way it becomes possible to describe the permeability of a material with reasonable completeness from

Table 1 .... Permeance and Permeability of Materials to Water Vapor

Material	Permeance Perm	% RH_1-RH_2	Method†	Ref.‡
Air (still)	120*	92–73	b	4
Insulation				
Cellular glass	0.0*		d	
Corkboard	2.1–2.6*	75–0	d	5
Corkboard	9.5*	100–45	w	11
Structural Insulating Board (vegetable, uncoated)	20–50*	40–x	t	9
Mineral Wool (unprotected)	116*	100–30	w	8
Interior Finish				
Plaster on wood lath	11	100–30	w	8
Plaster on metal lath—¾ in.	15	40–x	t	9
Plaster on plain gypsum lath (with studs)	20	40–85	t	4
Gypsum wall board—plain—⅜ in.	50	50–20	v	15
Insulating wall board (uncoated)—½ in.	50–90	40–x	t	9
**Paint—2 coats				
Asphaltic paint on plywood	0.4	100–30	w	8
Aluminum in varnish on wood	0.3–0.5	95–0	d	12
Enamels, brushed on smooth plaster	0.5–1.5	92–0	b	4
Primers or *Sealers* on insulating wall board	0.9–2.1	40–x	t	9
Various *Primers* + 1 coat flat paint on plaster	1.6–3.	40–x	t	9
Flat paint (alone) on insulating wall board	4	40–x	t	9
Water Emulsion on insulating wall board	30.–85.	40–x	t	9
**Paint—Exterior, 3 coats				
White *lead & oil* prepared paint on wood siding	0.3–1.0	50–0	d	15
White lead-zinc oxide & linseed oil on wood	0.9	95–0	d	12

Material	Permeance Perm	% RH_1-RH_2	Method†	Ref.‡
Wood				
Sugar Pine	0.4–5.4*	various	tv	4
Plywood (Exterior type 3 ply D.F.), ¼ in.	0.72	50–	4	13
Plywood (Interior type 3 ply D.F.), ¼ in.	1.86	50–	4	13
Masonry				
Concrete (1:2:4 Mix)	3.2*	100–45	w	11
Concrete (8 in. cored block wall, limestone agrgt.)	2.4	79–68	t	4
Brick wall—with mortar—4 in.	0.8	50–x	t	10
Tile wall—with mortar—4 in.	0.12	50–x	t	10

	lb per 500 sq ft	Permeance-Perms dry cup	Permeance-Perms wet cup	
**Building Papers and Felts				
Duplex sheet, asphalt laminae, *aluminum foil* one side	43	0.002	0.176	14
Saturated and *coated* felt heavy roll roofing	326	0.05	0.24	14
Kraft and *asphalt laminae*, Reinforced 30-120-30	34	0.3	1.8	14
Insulation back up, asphalt-sat., one side glossy	31	0.4	0.6–4.2	14
Asphalt-saturated and coated sheathing paper	43	0.3	0.6	14
Asphalt-saturated sheathing paper	22	3.3	20.2	14
15-pound asphalt felt	70	1.0	5.6	14
15-pound tar felt	70	4.0	18.2	14
Single sheet Kraft, double infused	16	30.8	41.9	14

* These boldface values are permeability in perm-inches.
** Description is a guide only, and does not insure permeance.
† Methods: d—dry cup; w—wet cup; t—two temperatures; b—special cell; v—air velocity both sides; 4—average of four methods.
‡ References. No. 9 also includes *Bulletins* 22 and 25 of the Engineering Experiment Station, University of Minnesota. No. 15 includes data to be published by the Engineering Experiment Station, Pennsylvania State College.