large decrease in relative humidity. This explains, in part, the greatly reduced relative humidities experienced in houses in extreme cold weather, when cold outdoor air enters the house and is heated.

WATER IN BUILDING MATERIALS

The surfaces of most common materials have an affinity for water molecules. Molecular forces of attraction will hold water molecules to the surface, but decrease very rapidly with increase in distance of molecular proportions. The film thickness and therefore the amount of water held in equilibrium with the surrounding atmosphere is roughly proportional to relative humidity. Surface films of water molecules, at low humidities, may be only one molecule thick; at moderate humidities poly-molecular films may be established, while at humidities very close to 100 percent, the films become so thick, relatively, that small pores may become filled and larger capillaries may be partially filled. At saturation conditions all voids in the material may be completely filled.

Some materials such as silica gel, alumina and most natural fibrous materials present very large effective surfaces to the water molecules, so that the amount of water held on the effective surface in these materials may be relatively large, even at moderate humidities. These are said to be hygroscopic. Other materials, such as most metals, not penetrated by the water molecules, present relatively small surfaces and so may take only minute quantities of water, except when wetted directly by liquid.

Substances having a great affinity for water, and their use as dehumidifying agents, are described in Chapter 17. Data on the moisture contents of various common materials in equilibrium with the atmosphere at various relative humidities are given in Table 2 of Chapter 24 of the 1964 GUIDE AND DATA BOOK, and equilibrium moisture content is further discussed in Chapter 22 of this volume.

Significant dimensional changes take place in many materials used in buildings, with change in moisture content. The best known are those which take place in wood, of the order of 0.1, 2, and 4 percent in the longitudinal, radial and tangential directions, respectively, on a change from air dry at 12 to 15 percent moisture content to oven dry conditions. Most wood-fiber products, including papers, will exhibit moisture expansion consistent with the basic wood properties to a degree dependent on the fiber orientation and arrangement. Data on wood are available in publications on wood technology. Almost all plant and animal fibers experience appreciable moisture changes with changing relative humidity and undergo substantial dimensional changes of the same order as those in wood. Less generally recognized are the dimensional changes that can occur in masonry materials as a result of changes in moisture content.

Water is either an essential or a contributory factor in almost all cases of breakdown of building materials resulting from chemical changes such as the rusting of steel, physical changes such as the spalling of masonry by frost action, or biological processes such as the rotting of wood. The control of water in building constructions may be necessary to ensure adequate service from the materials involved.

Condensation of water vapor, although not the only means by which wetting may be brought about, is nevertheless a most insidious one, particularly in respect to freeze-thaw breakdown, since from its nature it is most likely to occur at points of low temperature at which they may later be risk of freezing while the material remains in a saturated condition.

Moisture in building materials may have a marked effect upon the transmission of heat through them. It has been commonly assumed that moisture when present in a material will remain more or less stationary and will increase the conductivity largely by adding to the path available for heat flow. On this basis, the effect of moisture on heat flow can be accounted for quite simply by the use of suitable coefficients of conductivity in the usual heat-flow equations. The data presented in Chapter 24 on moist soils are of this type.

Evidence to date indicates, however, that in porous materials partially saturated with water there is likely to be a migration of moisture to the cold side under the influence of the temperature gradient. This can occur by a process of evaporation, vapor flow, and condensation within the material, a substantial amount of heat being transferred as latent heat of the vapor, particularly in the case of open fibrous materials. The transmission of heat through moist materials becomes complex whenever conditions are such as to produce any appreciable migration of the moisture, and, consequently, calculations by the usual heat-flow theory alone, are an approximation.

The usual approach to the calculation of moisture migration has been to consider the flow as hydraulic, under the influence of hydrostatic forces when the materials are saturated, and as a vapor flow produced by vapor pressure differences in unsaturated materials. These simple concepts might be adequate were it not for the fact that there are interactions between water molecules and the material through which they are passing, as already mentioned. Further complications may be introduced by the presence of salts and electrical potentials.

It is now recognized that the migration of moisture under conditions of partial saturation in a material having an affinity for water actually occurs as a kind of series-parallel flow of vapor and liquid, with the liquid phase having more and more influence as the moisture content, or the degree of saturation, increases. The two kinds of flow cannot be separated since they are closely coupled everywhere along the flow path by evaporation and condensation. Enough is already known to indicate that the isothermal or constant temperature case of vapor flow under a vapor-pressure gradient is much more manageable than the cases in which there are both temperature and vapor-pressure gradients. Cases of combined heat and moisture flow are now known to be extremely complicated and it is quite clear that when both are occurring, neither one can be adequately dealt with independently of the other. No adequate way of handling the general case theoretically has yet been found, despite efforts being made in many laboratories. The bibliography at the end of this chapter includes some of the more important papers on this subject.

A relatively simple equation for the calculation of water-vapor flow based upon the concept of vapor pressure alone as the driving force, has been in use for a number of years. It can be applied without great difficulty to cases where uniform temperatures or only small temperature gradients exist, and to cases of low or moderate relative humidity. It has also been shown to be useful in other cases, provided that the proper values representative of the conditions to which it is being applied can be found for the flow coefficient to be used in the calculations. The complications inherent in the combined mechanisms of heat and moisture flow are not adequately covered by the variables used in the equation, but appear in the determination of suitable values of the flow coefficient, which, however, may vary greatly for any one material, depending on the conditions of flow.

VAPOR TRANSMISSION THROUGH MATERIALS

The equation presently used in calculating water-vapor transmission through materials is based on a form of Fick's Law, and is as follows:

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			d	
Cellular glass	0.0*		d	
Corkboard	2.1–2.6*	75–0	d	5
Corkboard	9.5*	100–45	w	12
Structural Insulating Board (vegetable, uncoated)	20–50*	40–x	t	10
Mineral Wool (unprotected)	116*	100–30	w	9
INTERIOR FINISH				
Plaster on wood lath	11	100–30	w	9
Plaster on metal lath—$\frac{3}{4}$ in.	15	40–x	t	10
Plaster on plain gypsum lath (with studs)	20	40–85	t	4
Gypsum wall board—plain—$\frac{3}{8}$ in.	50	50–20	v	16
Insulating wall board (uncoated)—$\frac{1}{2}$ in.	50–90	40–x	t	10
Hardboard, $\frac{1}{8}$ in.	11			20
Hardboard, tempered, $\frac{1}{8}$ in.	5			20
**PAINT—2 coats				
Asphaltic paint on plywood	0.4	100–30	w	9
Aluminum in varnish on wood	0.3–0.5	95–0	d	13
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	10
Various *Primers* + 1 coat flat paint on plaster	1.6–3.	40–x	t	10
Flat paint (alone) on insulating wall board	4	40–x	t	10
Water emulsion on insulating wall board	30.–85.	40–x	t	10
**PAINT—Exterior, 3 coats				
White *lead & oil* prepared paint on wood siding	0.3–1.0	50–0	d	16
White lead-zinc oxide & linseed oil on wood	0.9	95–0	d	13
WOOD				
Sugar Pine	0.4–5.4*	various	tv.	4
Plywood (Exterior type 3 ply D.F.), $\frac{1}{4}$ in.	0.72	50–	4.	14
Plywood (Interior type 3 ply D.F.), $\frac{1}{4}$ in.	1.86	50–	4	14
MASONRY				
Concrete (1:2:4 mix)	3.2*	100–45	w	12
Concrete (8 in. cored block wall, limestone aggt.)	2.4	79–68	t	4
Brick wall—with mortar—4 in.	0.8	50–x	t	11
Tile wall—with mortar—4 in.	0.12	50–x	t	11
FILMS				
Aluminum foil, 1 mil	0.0	100–0	d	22
Aluminum foil, 0.35 mil	0.05	100–0	d	22
Polyethylene, 2 mil	0.16	50–0	d	19
Polyethylene, 4 mil	0.08	50–0	d	19
Polyester, 1 mil	0.70	50–0	d	21
Cellulose acetate, 10 mil	0.46	50–0	d	21

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

* These boldface values are permeability *M* 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. 10 also includes *Bulletins* 22 and 25 of the Engineering Experiment Station, University of Minnesota. No. 16 includes values from unpublished tests at the Pennsylvania State University, Engineering Experiment Department.

$$w = -\mu \frac{dp}{dx} \qquad (1)$$

where

w = weight of vapor transmitted through a unit area in unit time.

p = vapor pressure.

x = distance along the flow path.

and hence:

$\frac{dp}{dx}$ = vapor pressure gradient.

μ = permeability.

The close parallel with Fourier's equation for heat flow will be noted. The actual transmission of vapor through a material is extremely complex, so that the coefficient, μ, is not a simple one but is actually a function of relative humidity and temperature, and may vary along the flow path through the material in question.[3]

Integrating Equation 1 from $x = 0$ to $x = l$ and from p_1 to p_2, and rearranging, the following is obtained:

$$w = \frac{\int_{p_1}^{p_2} \mu dp}{p_1 - p_2} \times \frac{(p_1 - p_2)}{l} \qquad (2)$$

Let

$$\frac{\int_{p_1}^{p_2} \mu dp}{p_1 - p_2} = \bar{\mu} \qquad (3)$$

Then,

$$w = \bar{\mu} \frac{p_1 - p_2}{l} \qquad (4)$$

where

l = length of flow path (or thickness of material).

If Equation 1 had been integrated, assuming the coefficient