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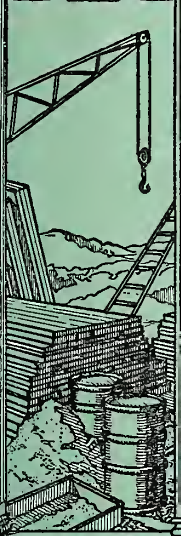


BUILDING MATERIALS AND STRUCTURES

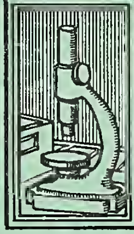
REPORT BMS63

Moisture Condensation in Building Walls

by

HAROLD W. WOOLLEY

NATIONAL BUREAU OF STANDARDS



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Moisture Condensation in Building Walls

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HAROLD W. WOOLLEY

ISSUED DECEMBER 14, 1940

The National Bureau of Standards is a fact-finding organization; it does not "approve" any particular material or method of construction. The technical findings in this series of reports are to be construed accordingly.

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Foreword

This paper was prepared as a result of numerous requests for information on moisture condensation in insulated walls, which will occur under certain conditions. It discusses these conditions in a general way and makes available to architects, builders, and others information concerning factors which control the humidity in walls.

Available data relative to certain types of wall have been collected so that estimates can be made concerning the probability of moisture condensation in walls of dwellings if the factors governing such condensation, including design, structural materials, construction details, and moisture conditions inside and outside of the building are known.

The Forest Products Laboratory has made extensive studies of this problem in relation to frame construction, and their reports, given in the list of references at the end of this paper, may be consulted for specific experimental data.

Lyman J. Briggs, *Director*.

Moisture Condensation in Building Walls

By Harold W. Woolley

CONTENTS

ABSTRACT

Moisture condensation in insulated walls will occur under certain conditions. This paper discusses these conditions in a general way and makes available to architects, builders, and others, information concerning factors which control humidity in walls. These factors are presented so as to make possible estimates of the probability of moisture condensation in walls of dwellings if the factors governing it such as design, structural materials, construction details, and moisture conditions inside and outside the building, are known.

I. INTRODUCTION

In recent years difficulties resulting from condensation of moisture, particularly within insulated walls of dwelling houses, have received considerable attention. When such condensation occurs to a sufficient degree, damage to the building structure or decorations may result. No definite statistics are available to indicate to what extent condensation is producing damaging results. However, a large number of cases of condensation have been reported, particularly in new houses in the colder parts of the country. Condensation problems are most frequent in houses of modern tight construction, with weather stripping, storm sash, insulation, and the newer types of heating systems that provide some means of humidification.

The principles involved in the condensation of moisture in building walls, though comparatively simple, are not understood by the average layman and not always by architects and builders. A general discussion of the principles of moisture condensation is therefore included in this paper, which may be helpful to both the buying public and the builder. The discussion is based not so much on definite tests made at the National Bureau of Standards as on well-established facts derived from various sources.

II. GENERAL PRINCIPLES INVOLVED IN CONDENSATION

Atmospheric air always contains moisture. Generally the moisture is not seen because it is in the form of an invisible vapor. It can easily be made visible as liquid water by cooling the air. Thus in the summer water condenses as dew on the outside of a pitcher of cold water. If the condensation occurs below the freezing point, it is expected to be in the form of frost. The freezing coils of a refrigerator acquire such a deposit continually. Condensation of moisture is so common an occurrence that the principles governing it should be known to everyone.

A definite volume of air held at a fixed temperature can contain permanently no more than a definite amount of water in the form of vapor. This limiting quantity of water per given volume is termed "moisture content at saturation." If the air contains a greater proportion of moisture than this at the particular temperature, the water will start condensing on the surfaces of the container or even on the dust particles in the air which then fall out in a fine mist. The ratio of the actual moisture content to the saturation moisture content for the particular temperature is termed "relative humidity." It is customarily expressed in percent.

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The concentration of water vapor may also be stated by giving its pressure. If water vapor is present, part of the atmospheric pressure is maintained by the water vapor and the remainder of the pressure by the other constituents of the atmosphere. At a particular temperature and at saturation the water vapor exerts a definite pressure. Data on pressure and density of saturated water vapor will be found in table 1. If the pressure of the water vapor at a particular temperature is less than the tabulated value the air is not saturated. The ratio of the actual pressure of the water vapor to the saturation pressure of water vapor for the particular temperature is also termed relative humidity. Its value when defined thus is essentially the same as that given previously. Throughout this paper, use is made of the last-named "relative humidity."

TABLE 1.—*Pressure and density of water vapor at saturation*

[Saturation vapor pressure for water, p, in pounds per square inch. Saturation vapor density for water, d, in grains [a] per cubic foot]

Temperature	p	d	Temperature	p	d
°*F*			°*F*		
−15	0.008230	0.2182	25	0.06405	1.558
−14	.009704	.2303	26	.06710	1.629
−13	.009201	.2430	27	.07034	1.704
−12	.009725	.2562	28	.07368	1.781
−11	.010276	.2702	29	.07717	1.862
−10	.010855	.2845	30	.08080	1.946
−9	.011464	.3001	31	.08458	2.033
−8	.012101	.3158	32	.08856	2.124
−7	.012775	.3327	33	.09230	2.203
−6	.013483	.3505	34	.09610	2.288
−5	.014226	.3692	35	.1000	2.376
−4	.015006	.3883	36	.1041	2.469
−3	.015825	.4086	37	.1083	2.563
−2	.016685	.4299	38	.1126	2.660
−1	.017586	.4521	39	.1171	2.760
0	.018533	.4750	40	.1217	2.863
1	.01953	.500	41	.1265	2.970
2	.02057	.525	42	.1315	3.081
3	.02166	.552	43	.1367	3.196
4	.02281	.580	44	.1420	3.315
5	.02401	.609	45	.1475	3.436
6	.02527	.640	46	.1532	3.562
7	.02658	.672	47	.1591	3.692
8	.02796	.705	48	.1652	3.826
9	.02941	.740	49	.1715	3.964
10	.03092	.776	50	.1780	4.106
11	.03251	.814	51	.1848	4.255
12	.03418	.854	52	.1918	4.407
13	.03590	.896	53	.1989	4.561
14	.03772	.939	54	.2063	4.722
15	.03961	.984	55	.2140	4.889
16	.04160	1.031	56	.2219	5.060
17	.04369	1.081	57	.2300	5.234
18	.04586	1.132	58	.2384	5.415
19	.04812	1.185	59	.2471	5.602
20	.05048	1.242	60	.2561	5.795
21	.05296	1.299	61	.2654	5.993
22	.05555	1.361	62	.2749	6.196
23	.05826	1.423	63	.2848	6.407
24	.06111	1.489	64	.2949	6.622

TABLE 1.—*Pressure and density of water vapor at saturation*—Continued

Temperature	p	d	Temperature	p	d
°*F*			°*F*		
65	0.3054	6.845	78	0.4744	10.38
66	.3162	7.074	79	.4903	10.71
67	.3273	7.308			
68	.3388	7.571	80	.5067	11.04
69	.3506	7.798	81	.5236	11.39
			82	.5409	11.75
70	.3628	8.055	83	.5588	12.11
71	.3754	8.319	84	.5772	12.49
72	.3883	8.588			
73	.4016	8.867	85	.5960	12.87
74	.4153	9.153	86	.6153	13.27
			87	.6352	13.67
75	.4295	9.448	88	.6555	14.08
76	.4440	9.749	89	.6765	14.51
77	.4590	10.06			

[a] 7,000 grains equals 1 pound.

When a given mixture of air and water vapor is cooled without loss of moisture, a temperature is eventually reached where the air becomes saturated with water vapor and condensation can occur. The temperature then existing is called the dew point. At any given dew point, water vapor is always exerting a pressure corresponding thereto.

The air in the hollow spaces or pores in building walls always contains water vapor. Under certain conditions the temperature of portions of the wall may be below the dew point of the air in contact with them, and condensation will occur.

While at first it might appear that any water not in vapor form in the wall would be ordinary liquid water, the facts are not quite so simple. Many building materials are able to absorb water to a moderate extent without undergoing great changes. Wood will absorb water up to from 20 to 30 percent by weight at relative humidities near 100 percent. Beyond some such point further water absorbed is retained as free liquid water. Other similar materials differ in the moisture content at which further absorbed water is only mechanically held.

Water has several effects on building materials. As is very well known, some materials, such as wood, expand with increasing moisture content. If conditions of greatly varying humidity occur in different parts of the cross section of a single framing member there will be some tendency for the wood to warp. High humidity favors decay of wood. Some other materials are adversely affected by continued exposure to liquid water. Water promotes corrosion of metals, and even some mineral insulating materials show permanent change in the course of time when in contact with water. The insulating value of materials in general is greatly decreased by the presence of free water. Droplets of water tend to bridge gaps between separate solid portions of ordinary insulating materials and increase the transfer of heat. The distillation of moisture from place to place in the wall can also increase heat transfer since heat must be added to evaporate the moisture and then is released again in the colder region where the moisture may happen to condense. Normally this effect will be important mainly when the temperature indoors is increasing.

Moisture condensed in the walls may not remain in its first location. It is even possible for it to migrate and succeed in making the plaster and wallpaper damp and discolored. When that symptom appears in late winter or spring, and unless the trouble is caused by leaks, it is very probable that condensation in the wall is responsible. In such a case the following explanation should be to the point.

If different gases mix without stirring, the movement of the one gas into the other follows a simple law of diffusion. If one gas is of relatively low concentration, its rate of diffusion into the other is closely proportional to its pressure difference per unit distance. The law is found to hold fairly well for the diffusion of moisture, even through many solid materials. There are exceptions, but in this discussion they will be largely ignored. Data in regard to diffusion of water vapor through various materials will be found in table 2. In this has been used as a unit

Table 2.—*Permeability of various materials to water vapor*

Material	Thickness	Permeability to moisture (P)	Vapor resistance ($1/P$)
BABBITT [8] [a]			
	Inches	*Grains* / *sq ft hr (lb/sq in.)*	*sq ft hr (lb/sq in.)* / *Grains*
Fiberboard	0.492	60.6	0.0168
Fiberboard, 1 surface asphalt, rolled	.492	8.0	.125
Fiberboard, 1 surface asphalt, dipped	.63	17.3	.0578
BABBITT [8]—Continued			
Fiberboard, laminated, 2 samples cemented together with asphalt	.985	2.74	.365
Fiberboard, laminated, 6 layers with 5 layers of asphalt	.527	0.23	4.35
Fiberboard	1.06	37.0	0.0270
Fiberboard, same reduced in thickness	0.803	43.4	.0230
Do	.599	56.4	.0177
Do	.405	74.5	.0134
Do	.201	133.3	.0075
Wood, spruce	.563	3.48	.287
Do	.480	4.03	.248
Do	.405	3.94	.254
Do	.323	4.93	.203
Do	.232	7.24	.138
Do	.161	10.35	.097
Wood, pine	.80	1.88	.532
Do	.645	2.52	.397
Do	.496	3.45	.290
Do	.315	5.55	.180
Do	.169	9.65	.104
Wood (pine) A	.508	6.47	.155
Wood (pine) A, 1 coat of Al paint		3.42	.292
Wood (pine) A, 2 coats of Al paint		0.92	1.09
Wood (pine) A, 3 coats of Al paint		.71	1.41
Wood (pine) B	.508	6.68	0.150
Wood (pine) B, 1 coat of Al paint		3.85	.260
Wood (pine) B, 2 coats of Al paint		1.95	.512
Wood (pine) B, 3 coats of Al paint		1.53	.654
Kraft paper, 1 sheet	.00394	168.	.00595
Kraft paper, 2 sheets		107.	.00935
Kraft paper, 3 sheets		80.	.0125
Kraft paper, 4 sheets		63.6	.0157
Kraft paper, 5 sheets		53.5	.0187
Kraft paper, 5 sheets		65.3	.0153
Kraft paper, 5 sheets		61.6	.0162
Kraft paper, 7 sheets		45.5	.0220
Kraft paper, 7 sheets		38.3	.0261
Kraft paper, 8 sheets		38.3	.0261
Kraft paper, 8 sheets		33.1	.0302
Black vulcanized rubber, hardness 40	.0791	0.185	5.4
Plasticized rubber hydrochloride	.00158	.382	2.62
30-30-30 paper A	.0071	1.83	0.546
30-30-30 paper B	.0071	1.79	.558
Duplex Scutan 6-6, asphalt between 2 sheets of kraft	.0071	0.946	1.06
Scutan 0-14 (kraft infused with asphalt on 1 surface) A	.0071	8.6	0.116
Scutan 0-14 B	.0071	15.97	.0626
Scutan 14 (kraft infused with asphalt on surfaces) A	.0071	13.9	.0719
Scutan 14 B	.0071	15.8	.0633
Black building paper, black shiny paper infused with asphalt	.0173	0.376	2.66
Asphalt felt, 15-lb. felt building paper with soft dull appearance	.0319	13.5	0.0741
Pressed corkboard A	.905	4.75	.211
Pressed corkboard B	.985	5.42	.184
Plaster	1.34	27.1	.0369
Plasterboard, plaster between sheets of heavy paper	0.37	70.2	.0142
Masonite Presdwood, tempered	.13	9.76	.102
Masonite Presdwood	.13	21.7	.0461
Masonite Presdwood, 5 thicknesses		6.25	.16
Masonite Presdwood, 7 thicknesses		4.9	.204

TABLE 2.—*Permeability of various materials to water vapor*—Continued

Material	Thickness	Permeability to moisture (*P*)	Vapor resistance (1/*P*)
TEESDALE [11]			
	Inches	*Grains* / *sq ft hr (lb/sq in.)*	*sq ft hr (lb/sq in.)* / *Grains*
Foil-surfaced reflective insulation, double-faced	--------	0.172 to 0.263	5.82 to 3.8
Roll roofing—smooth, 40 to 65 lb/roll 108 sq ft	--------	.263 to .348	3.8 to 2.87
Asphalt impregnated and surface-coated sheathing paper, glossy, 50 lb and 35 lb/500 sq ft	--------	.433 to 1.57 .348 to 4.19	2.31 to 0.637 2.87 to .239
Duplex or laminated papers, 30-30-30	--------	2.80 to 5.24	0.357 to .191
Duplex or laminated papers, 30-60-30	--------	1.05 to 1.75	.952 to .572
Duplex papers, reinforced	--------	1.396 to 4.19	.716 to .239
Duplex paper, coated with metal oxides	--------	1.05 to 2.63	.952 to .381
Insulation backup paper, treated	--------	1.75 to 6.97	.572 to .144
Gypsum lath with Al-foil backing	--------	0.173 to 0.785	5.78 to 1.27
Plaster, wood lath	--------	22.4	0.0446
Plaster, 3 coats of lead and oil	--------	7.5 to 7.84	0.133 to .127
Plaster, 3 coats of flat wall paint	--------	8.72	.115
Plaster, 2 coats of Al paint	--------	2.35	.425
Plaster, fiberboard or gypsum lath	--------	40.2 to 41.9	.0249 to .0239
Slater's felt	--------	10.5 to 52.4	.0952 to .0191
Plywood, ¼-in., Douglas fir, soy bean glue, plain	--------	8.72 to 13.1	.115 to .0764
Plywood, 2 coats of asphalt paint	--------	0.87	1.15
Plywood, 2 coats of Al paint	--------	2.63	0.38
Plywood, ½ in., 5-ply Douglas fir	--------	5.43 to 5.59	.184 to .179
Plywood, ¼ in., 3-ply Douglas fir, artificial resin glue	--------	8.72 to 13.1	.115 to .0761
Plywood, ½ in., 5-ply Douglas fir, artificial resin glue	--------	5.59 to 6.85	.179 to .146
Insulating lath and sheathing, board type	--------	52.3 to 69.8	.0191 to .0143
Insulating sheathing, surface-coated	--------	6.17 to 8.88	
Compressed fiber board, 3/16 in	--------	10.3	.097
Insulating cork blocks, 1 in	--------	12.6	.0794
Blanket insulation between coated papers, ½ and 1 in	--------	3.90 to 4.07	.256 to .246
Mineral wool, unprotected, 4 in	--------	59.2	.0169
FOREST PRODUCTS LABORATORY			
Kraft paper	--------	112.	0.00893
Plastered wall, no paint, plasterboard lath	--------	41.7	.024
Plastered wall, no paint, wood lath	--------	22.2	.045
Slater's felt, best type	--------	10.1	.099
Duplex paper	--------	2.78	.36
Plastered wall, 2 coats of Al paint, wood lath	--------	2.43	.411
Asphalt-coated paper, 35 lb/500 sq ft roll	--------	2.08	.481
Asphalt-coated paper, 50 lb/500 sq ft roll	--------	1.04	.962
Metal-coated paper	--------	0.174	5.75
INTERNATIONAL CRITICAL TABLES			
Still air, 3 5/8 in	--------	70.9	0.0141
Still air, 1 in	--------	257	.00389
WRAY [3]			
1 coat of Al paint on wood, Bakelite resin varnish	--------	1.22	0.82
1 coat of Al paint on wood, glycerol phthalate varnish	--------	1.22	.82
2 coats of ordinary paint, linseed oil	--------	3.48	.287
1 coat of Al paint on wood, ester gum varnish	--------	2.26	.445

TABLE 2.—*Permeability of various materials to water vapor*—Continued

Material	Thickness	Permeability to moisture (*P*)	Vapor resistance (1/*P*)
HERRMANN [4]			
	Inches	*Grains* / *sq ft hr (lb/sq in.)*	*sq ft hr (lb/sq in.)* / *Grains*
Hydrocarbon wax	[b] 1	0.000052	1.9×10^4
Thiokol	[b] 1	.00014	7.1×10^3
Gutta percha	[b] 1	.00035	2.86×10^3
Hard rubber	[b] 1	.00035	2.86×10^3
Para gutta	[b] 1	.00042	2.38×10^3
Polystyrene	[b] 1	.00087	1.15×10^3
Asphalt sealing compound	[b] 1	.00087	1.15×10^3
Phenol fiber	[b] 1	.00148	676
Soft vulcanized rubber	[b] 1	.00157	637
Benzyl cellulose	[b] 1	.00226	442
Bakelite	[b] 1	.0035	286
Waterproof cellulose film	[b] 1	.062	16.1
Cellulose acetate	[b] 1	.12	8.3
MILLER [7]			
Plaster base and plaster, ¾ in	--------	30	0.033
Vapor barrier (Kimberly Clark Corp. data)	--------	1.65	.61
Fir sheathing, ¾ in	--------	6	.167
Waterproof paper	--------	100	.01
Pine lap siding	--------	10	.1
Paint film	--------	7	.14
Celotex, ¾ in	--------	25.5	.0392
Brick masonry, 4 in	--------	2.2	.454
MARTLEY [2]			
Wood, Scot pine, per inch	--------	21.4	0.0467
WRAY			
Wood, western yellow pine, ¼ in	--------	1.8	0.556

[a] Figures in brackets indicate the literature references at the end of this paper.
[b] Data recalculated on basis of 1-inch thickness.

of permeability to moisture the number of grains per hour passing through 1 sq ft of the actual thickness specified when the vapor pressures at the two surfaces differ by 1 lb/sq in. The reciprocal of this permeability has also been listed and has been called the vapor resistance. The number of grains of moisture passing through 1 sq ft in 1 hour with 1-lb/sq in. pressure difference=permeability=1/vapor resistance.

If winter air is brought into a house from the outdoors and is heated without addition of moisture, the resulting warm air will contain the same proportion of moisture as before, and therefore the pressure of the contained water vapor will be the same, but the relative humidity will be lower than that of the air outside. This is true because the warm air [1] can contain more moisture than it could when cold. If the diffu-

[1] Strictly, the space contains the moisture.

sion of the water vapor through the walls is proportional to the vapor-pressure difference between inside and outside, there will be no net passage of moisture, since this difference is zero. In such a case there would be no tendency for air in any part of the wall to have a relative humidity greater than the value outdoors. In fact all parts would be subject to lower relative humidities, since the air would be warmer than the air out of doors.

Actually, in an occupied house moisture is always being added to the air, so that the vapor pressure is higher inside the house than outside. The water vapor penetrates the plaster or other interior finish and passes on through the rest of the wall to the outside. Accordingly, the vapor pressure within the walls will be higher than that outside, although less than that within the interior of the house. The manner in which the vapor pressure falls off from the high value inside the house to the low value outside the house, together with the temperature distribution across the wall, determines the relative humidity at all points within the wall.

In an ordinary frame wall condensation is more likely to occur on the inner surface of the sheathing than elsewhere, except when sheathing papers highly resistant to water vapor are employed, in which case condensation may first appear on the sheathing paper. In other types of hollow walls condensation tends to occur in corresponding regions.

Differences in vapor pressure through different parts of the wall from inside to outside distribute themselves in proportion to the vapor resistance of the respective parts. That is, the fraction of the total vapor-pressure drop from inside to outside occurring between the air in-

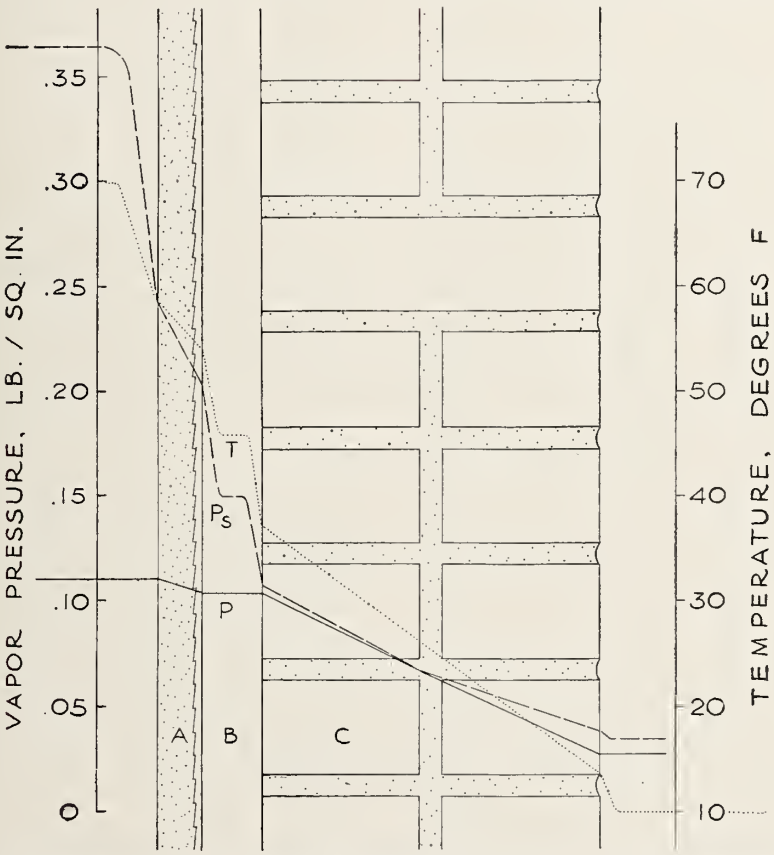

FIGURE 1.—*Nature of the temperature, corresponding saturation vapor pressure, and actual vapor pressure distributions in an uninsulated brick wall.*

Wall composed of *A*, plaster on metal lath; *B*, air space between furring strips; and *C*, brick, exposed to 70° F and 30-percent relative humidity indoors and 10° F and 80-percent relative humidity outdoors.

doors and some chosen point within the wall is the same as that fraction of the total vapor resistance of the wall occurring between the air indoors and the chosen point.

In this it is analogous to heat flow, in which differences in temperature through different parts of the wall from inside to outside are proportional to the thermal resistance of these parts. In other words, the fraction of the total temperature drop from inside to outside included between the indoor air and the chosen point is the same as that fraction of the total resistance to heat flow included between the indoor air and the same chosen point.

From these facts one can calculate the vapor pressure and temperature at any point in the wall and estimate whether the calculated vapor pressure is safely below saturation vapor pressure for the calculated temperature. As an explanation of this the following examples are given.

1. A brick wall composed of metal lath and plaster, air space between furring strips, common and face brick is exposed to 70° F and 30-percent relative humidity indoors and 10° F and 80-percent relative humidity outdoors. A section of this wall is pictured in figure 1 with curves showing the nature of vapor-pressure and temperature distributions within the wall. To determine whether condensation will occur on the inner surface of the brick, data on vapor resistance and thermal resistance of the various parts of the wall are examined.[2]

The following vapor resistances are taken, starting with the indoor side of the wall:

Air to surface of plaster	not over 0.001
Metal lath and plaster (data for wood lath and plaster)	.045
Air space	not over .014
Brick (doubling the figure for 4-in. masonry)	.9
Surface of face brick to outside air	Negligible.

The sum of the first three is 0.060, and the total for the entire wall is 0.960. The vapor-resistance fraction is therefore equal to 0.060/.960, or about 0.0625. This means that about one-sixteenth of the vapor resistance of the wall is comprised between the air of the room and the inner surface of the brick.

[2] Units of vapor resistance and thermal resistance have been omitted in much of the discussion following. The units are hr sq ft (lb/sq in.)/grain, and hr sq ft deg F/btu.

One may similarly examine the data on thermal resistance, or insulating value, for the separate parts of the wall, as given in table 3. The following are taken as thermal resistances:

Table 3.—*Thermal resistance of various materials*

Materials	Thermal resistance
	hr sq ft deg F / Btu
Yellow pine or fir, 25/32 in. thick	0.98
Yellow pine lap siding	.78
Wood lath and plaster	.40
Metal lath and plaster	.23
Mineral wool, per in	3.70
Stucco	0.08
Brick, common 4-in	.80
Brick, face 4-in	.44
Fiberboard, per in	3.0
Plasterboard ½-in	0.35
Surface film, still air	.61
Surface film, 15 mph	.17
Surface film, rough stucco, 15 mph	.11
Air space more than ¾ in. across not lined with reflector	.91

Air to surface of plaster	0.61
Metal lath and plaster	.23
1⅝-in. air space	.91
Common brick	.80
Face brick	.44
Surface of face brick to outside air	.17

The sum of the first three thermal resistances is 1.75, and the total thermal resistance of the wall is 3.16. The thermal-resistance fraction is therefore equal to 1.75/3.16, or 0.554. This means that about 55 percent of the thermal resistance of the wall is comprised between the air of the room and the inner surface of the brick.

These fractions will now be applied. For the water vapor there is indoors a vapor pressure of 30 percent of 0.3628 lb/sq in., or 0.109 lb/sq in. Outdoors there is a vapor pressure of 80 percent of 0.03092 lb/sq in., or 0.02474 lb/sq in. The drop in vapor pressure through the wall is 0.109 lb/sq in. minus 0.025 lb/sq in., or 0.084 lb/sq in. Multiplying this drop by the vapor-resistance fraction 0.0625, one obtains 0.00525 lb/sq in. to be subtracted from the 0.109 lb/sq in. indoors. The result, 0.104 lb/sq in., is the vapor pressure adjacent to the inner surface of the brick—corresponding to a "dew-point" temperature of 36° F.

The same procedure may be continued in regard to temperature. The temperature indoors is 70° F. The temperature outdoors is 10° F. The drop in temperature through the wall is then 60°. Multiplying this drop by the thermal-resistance fraction, 0.554, one gets 33.24° as the drop in temperature between the air of the room and the inner surface of the brick. Subtracting the 33.24° from 70°, the indoor temperature, one obtains 36.76° as the temperature of the inner surface of the brick—which is higher than the above-noted "dew-point" temperature.

This temperature and the vapor pressure for the same point are compared with the figures given in table 1 for saturation pressures. One finds for the temperature calculated a saturation pressure of 0.107 lb/sq in. Since the actual vapor pressure as calculated (0.104 lb/sq in.) is less than this, it is not indicated that condensation will occur on the inner surface of the brick in this particular wall for the particular conditions of temperature and relative humidity quoted.

2. As a second example the same wall is considered, except that for the air space will be substituted a fill of insulating material adding negligible vapor resistance. The following values of vapor resistances and thermal resistances are based on tables 2 and 3:

	Vapor resistance	*Thermal resistance*
Air to surface of plaster	0.001	0.61
Lath and plaster	.045	.23
Insulation (1⅝-in. mineral wool)	.014	6.01
Brick	.9	1.24
Surface to air	0	0.17

The vapor-resistance fraction is as before, 0.0625, and the thermal-resistance fraction is 6.85/8.26, or 0.83. The use of these, with the total vapor pressure and temperature drops calculated before, gives for the inner surface of the brick a temperature of 20.2° F, and, as before, a vapor pressure of water of 0.104 lb/sq. in. and a corresponding "dew-point" temperature of 36° F. Table 1 indicates that for the temperature 20.2° F a vapor pressure of only 0.05098 lb/sq in. can occur without condensation. It is thus seen that under these conditions of temperature and humidity water will be condensing against the inner surface of the brick—the temperature being below the above-noted "dew-point" value.

Similar calculations may easily be made for any wall, if data are available for its constituent parts. As table 2 shows, data are not abundant on all construction materials. For types of wall construction which have been considered, the results are somewhat similar to those just obtained for the brick wall. In practically all hollow walls, the possibility of condensation on the cold side of the hollow space is the critical point, since condensation is generally more likely to occur there than in neighboring regions. A summary of calculations for different walls for several indoor humidities and outdoor temperatures is given in table 4.

In interpreting the results given here, it is necessary to recall the warning that since the data were obviously very uncertain the results are also very uncertain.

If the figures are to be used in building design, an ample factor of safety should be included, although the figures seem likely to be in error in such a direction that a factor of safety is already present. An important reason for this is that in all this discussion the air leakage into the wall from the outside has been disregarded. Its effect is to reduce the tendency for condensation, but by an amount which naturally cannot be estimated without definite data as to the amount of air leakage occurring.

Most of table 4 should be clear from the discussion already given. To clarify the method for calculating the last three columns, the following example gives a calculation of the vapor resistance which must be added to the warm side of the wall to just barely prevent condensation. The case considered is that of the brick wall with 1⅝ in. of insulation and exposed to 30° F and 80-percent relative humidity outside and 70° F and 40-percent relative humidity indoors. It is assumed that the vapor resistance of lath and plaster and insulation in the wall is 0.06 hr sq ft (lb/sq in.)/grain and the vapor resistance of the remaining outer part of the wall is 0.9 hr sq ft (lb/sq in.)/grain. The temperature at the inner surface of the brick, according to the previous explanation is found to be 70° F−0.83 (70° F−30° F)=70° F−0.83 (40° F)=70° F−33.2° F=36.8° F.

TABLE 4.—*Illustrative calculations concerning vapor barriers*

Wall type	Thermal resistance [a]		Thermal-resistance fraction (to chosen point: Cold side of insulation, or hollow space, if present	Vapor resistance [b]		Vapor-resistance fraction (to chosen point)	Necessary increase in inner vapor resistance [b] to prevent condensation at the chosen point		
	Inner part	Total		Inner part	Total		30° F. 80% outside; 70° F. 40% inside	10° F. 80% outside; 70° F. 30% inside	−10° F. 80% outside; 70° F. 20% inside
Frame wall:									
Uninsulated	1.92	3.85	0.50	0.06	0.460	0.13	0	0	0
3⅝ in. of insulation	14.41	16.34	.88	.06	.460	.13	.47	1.28	2.24
1 in. of insulation in middle of space	6.53	8.46	.77	.06	.460	.13	.14	0.48	0.83
2 in. of insulation in middle of space	10.23	12.16	.84	.06	.460	.13	.32	.90	1.54
Frame and stucco:									
Uninsulated	1.92	3.09	.62	.06	.305	.197	0	0	0.06
3⅝ in. of insulation	14.41	15.58	.93	.06	.305	.197	.43	1.24	2.30
1 in. of insulation	6.53	7.70	.85	.06	.305	.197	.19	0.58	1.01
2 in. of insulation	10.23	11.40	.90	.06	.305	.197	.32	.92	1.65
Brick veneer:									
Uninsulated	1.92	3.87	.50	.06	.71	.0845	0	0	0
3⅝ in. of insulation	14.41	16.36	.88	.06	.71	.0845	.80	2.11	3.67
1 in. of insulation	6.53	8.48	.77	.06	.71	.0845	.27	0.82	1.38
2 in. of insulation	10.23	12.18	.84	.06	.71	.0845	.56	1.49	2.54
Brick, solid 8 in., furred, metal lath, and plaster:									
Uninsulated	1.75	3.16	.554	.06	.96	.0625	0	0	0.05
1⅝ in. of insulation	6.85	8.26	.83	.06	.96	.0625	.73	1.92	3.24

[a] hr sq ft deg F/Btu.
[b] hr sq ft (lb/in.^{2})/grain.

The vapor pressure at this inner brick surface must not be higher than the saturation vapor pressure for 36.8° F, as given by table 1, namely 0.1075 lb/sq in. The vapor pressure on the outside of the wall is found to be 0.80 times 0.0808 lb/sq in., or 0.06464 lb/sq in. The vapor pressure indoors is 0.40 times 0.3628, or 0.1451 lb/sq in. The drop in vapor pressure across the outer part of the wall is 0.1075 lb/sq in. minus 0.0646 lb/sq in., or 0.0429 lb/sq in.

The drop in vapor pressure across the inner side of the wall is 0.1451 lb/sq in. minus 0.1075 lb/sq in, or 0.0376 lb/sq in. Since the vapor resistance of the various parts are proportional to the corresponding vapor pressure drops, the vapor resistance on the inner side needs to be 0.0376/0.0429 times as great as the vapor resistance of the outer side. This gives 0.0376/-0.0429 times 0.9 hr sq ft (lb/sq in.)/grain=0.79 hr sq ft (lb/sq in.)/grain as the inner vapor resistance desired. Since this wall was supposed to have an inner vapor resistance of 0.060 hr sq ft (lb/sq in.)/grain originally, it is necessary to add a barrier having as vapor resistance the difference of these, or 0.73 hr sq ft (lb/sq in.)/grain. One might now search table 2 for possible barriers having vapor resistances of this magnitude or greater and having negligible thermal resistance.

The graphs in figures 2, 3, and 4 may be convenient for rapid judgment as to the adequacy of a given moisture barrier for a given wall. The outdoor relative humidity is here assumed to be 80 percent and the indoor temperature 70° F for each case. These are considered more or less typical of winter conditions occurring in many parts of the country with snow throughout the winter. If thermal-resistance fractions and vapor-resistance fractions are laid out along their corresponding axes, the point thus located by intersection of the horizontal and vertical lines indicates the indoor relative humidity at which trouble might occur under the conditions quoted for the separate charts, namely for outdoor temperatures of 30°, 10°, and −10° F, respectively.

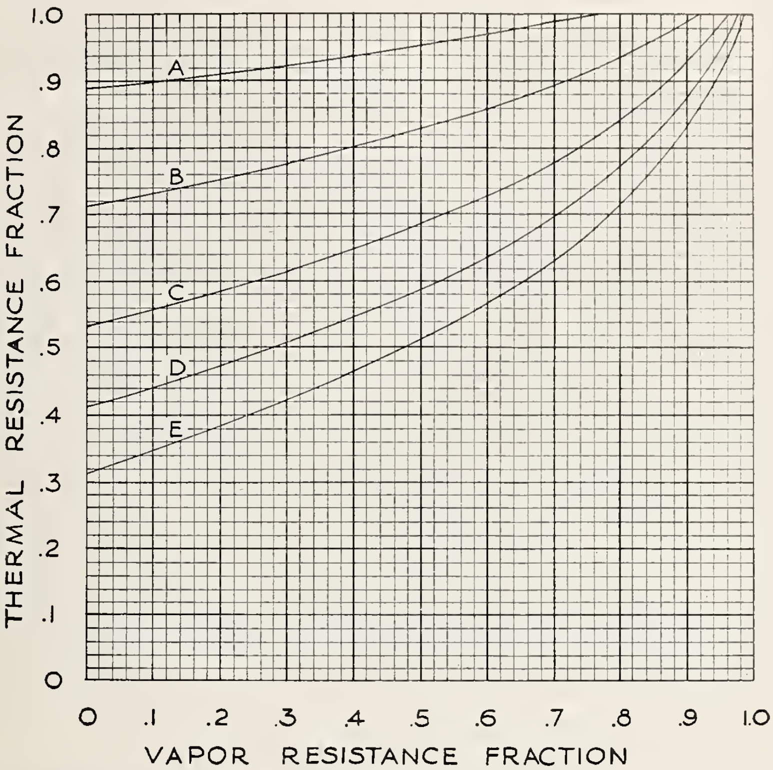

FIGURE 2.—*Indoor relative humidity able to cause condensation at a given point in a wall, as determined by the thermal-resistance fraction and the vapor-resistance fraction.*

(Fraction of thermal resistance on warm side of the point and fraction of vapor resistance on warm side of the point in question.)

Curves *A*, 30%; *B*, 40%; *C*, 50%; *D*, 60%; and *E*, 70% indoor relative humidity.

Conditions: 30° F outdoors; 70° F indoors; and 80-percent relative humidity outdoors.

For example, any combination of thermal-resistance fraction and vapor-resistance fraction represented by a point on or below the 40-percent line represents a type of wall in which condensation will not occur unless the indoor humidity exceeds 40 percent. The region below the 40-percent line therefore represents combinations of thermal and vapor resistances in which relative humidities up to 40 percent are safe. The region above the line represents combinations in which humidities as high as 40 percent should be avoided.

Thus one may consider the case of a wall the thermal-resistance fraction of which is 0.50 and the vapor-resistance fraction 0.13. Figure 2 shows that a relative humidity of about 54 percent or more indoors could lead to condensation when the outdoor temperature is 30° F. Figure 3 indicates about 38 percent for a temperature of 10° F, and figure 4 indicates about 26 percent for an outdoor temperature of −10° F. These results would doubtless be considerably altered if the ventilation of the wall by air leakage could be allowed for.

Figures 2, 3, and 4 can be used for determining the moisture-condensation conditions at a selected spot in insulated walls of many types, through which heat is transferred by conduction or its equivalent, provided the heat-transfer resistance and the vapor-transfer resistance fractions are known. It cannot be directly utilized in connection with walls having appreciable ventilating spaces.

When studying any thermal-conduction type of wall, full consideration must be given to the actual space distribution within the wall of both the thermal and the vapor-transfer resistances. Critical points are to be looked for where there is space concentration of vapor-transfer resistance on the cold side of any space concentration of thermal resistance.

Without regard in any respect to the actual space distribution of the thermal and vapor-transfer resistances, if the space distribution of

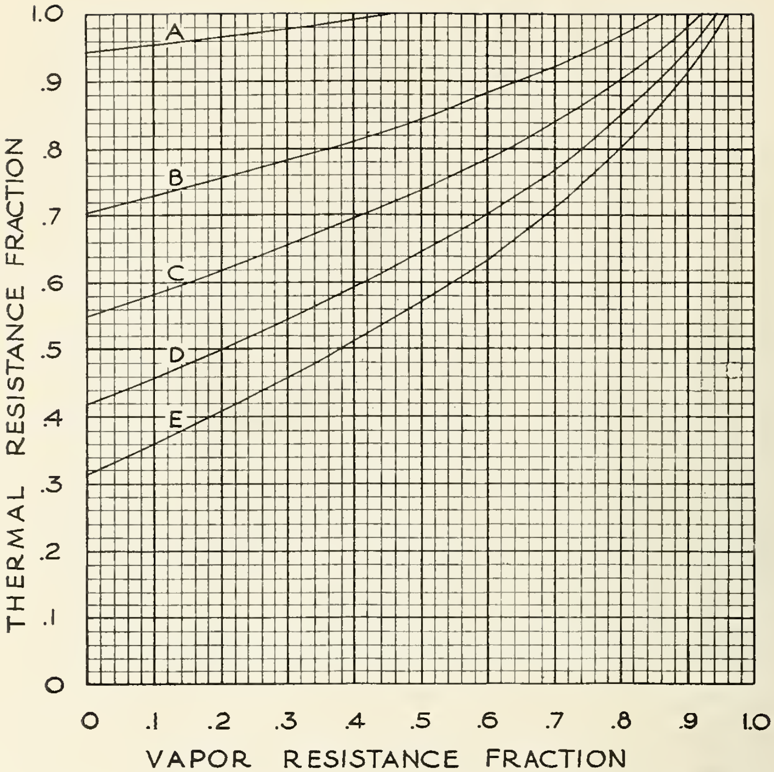

FIGURE 3.—*Indoor relative humidity able to cause condensation at a given point in a wall, as determined by the thermal-resistance fraction and the vapor-resistance fraction.*

(Fraction of thermal reisistance on warm side of the point and fraction of vapor resistance on warm side of the point in question.)
Curves *A*, 10%; *B*, 20%; *C*, 30%, *D*, 40%; and *E*, 50% indoor relative humidity.
Conditions: *10° F outdoors;* 70° F indoors; and 80-percent relative humidity outdoors.

the thermal resistance is the same as (or approximately the same as) the space distribution of the vapor-transfer resistance, the wall acts exactly (or approximately) as though it were composed of homogeneous insulating material. In certain cases the walls may well be treated as though made up of separate layers of homogeneous insulating materials. When this condition is reached (or approximated) one cannot determine by mere superficial examination just where and when condensation may take place—the below-dew-point temperatures may be reached within the mass of the material, although not at either edge.

Consider, for example, the case where the wall may properly be regarded as a single uniform thick sheet having at its warm surface air of one temperature and relative humidity and at the cold surface air of another temperature and relative humidity. There is in all parts of the wall the same rate of passage of moisture if no condensation is occurring and a steady state has been established. The vapor-pressure drop is then uniformly distributed across the material in the same manner as is the temperature drop. This may be illustrated by figure 5 in which the temperature is indicated at uniform intervals along a horizontal axis. This may be considered the direction across the layer of material having uniform spacing of insulation of uniform thermal resistance or at least uniform sections of the total thermal resistance of the material. The two surfaces of the material are then located on this scale by their corresponding temperatures. Plotted vertically are the saturation pressures for water vapor corresponding to all temperatures along the horizontal axis. If the actual vapor pressures at the two surfaces are now plotted for their positions as indicated on the temperature scale, for example *A* and *B*, the vapor pressure at any point between will be indicated by the distance vertically upward to the straight line between them. As examples, three cases have

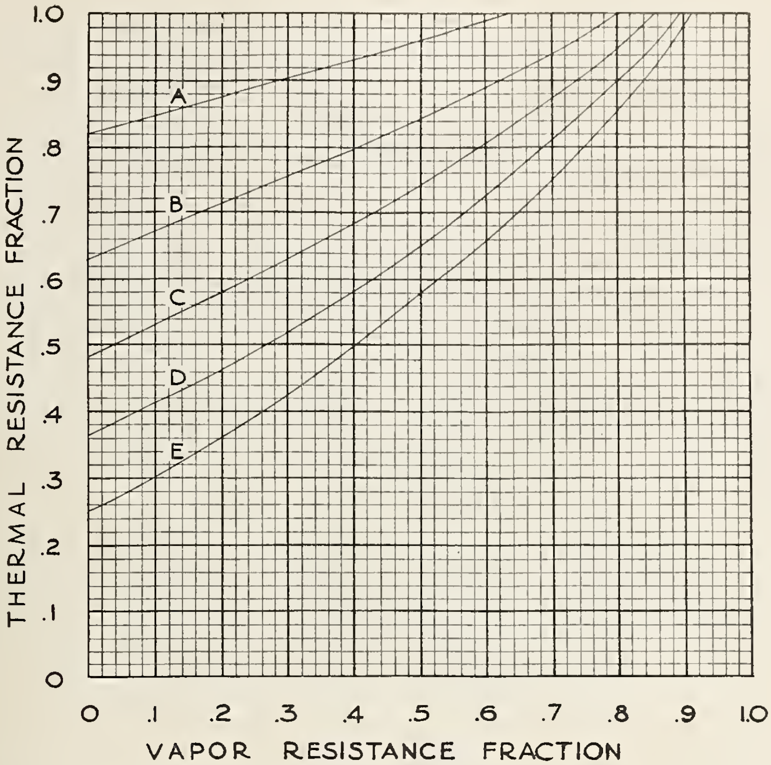

FIGURE 4.—*Indoor relative humidity able to cause condensation at a given point in a wall, as determined by the thermal-resistance fraction and the vapor-resistance fraction.*

(Fraction of thermal resistance on warm side of the point and fraction of vapor resistance on warm side of the point in question.)
Curves *A*, 50%; *B*, 10%; *C*, 20%; *D*, 30%; and *E*, 40% indoor relative humidity.
Conditions: −10° F *outdoors;* 70° F indoors; and 80-percent relative humidity outdoors.

been shown, originating from having different vapor pressures at the point *A* corresponding to 25-, 50-, and 80-percent relative humidities.

In each case the vapor pressure at the point *C* with temperature 40° F is indicated on the vapor-pressure scale by the line upward from *C* to the appropriate slanting line. Thus the slanting line through *D* illustrates a case with 50-percent relative humidity at *A* in which the vapor pressure at *C* is below the saturation value, although the apparent tangency with the saturation pressure curve near 20° F indicates that condensation is in danger of occurring in a very limited region of the part at 20° F. The slanting line through *D′* lies above the saturation curve for much of the wall and in particular for the point *C*, indicating that for a relative humidity of 80 percent at *A* condensation is to be expected throughout a considerable portion of the wall. The third slanting line, passing through *D″*, lies entirely below the saturation-pressure curve and indicates that condensation will occur at no point in the slab when the relative humidity at *A* is 25 percent. These calculations, which are approximately correct, may be useful in indicating possibilities of condensation within the material of a wall with similar spatial distribution of the heat and vapor-transfer resistances, where seemingly there is no specific critical condensation point.

III. MEANS OF PREVENTING CONDENSATION

The methods by which condensation of moisture in insulated walls may be avoided are becoming fairly well known. A little consideration of the principles already explained here shows that possible remedies will include:

1. Lowering the indoor relative humidity, either by lowering the rate at which water vapor is added to the air in the house or by increasing the ventilation of the house interior to the outdoors.

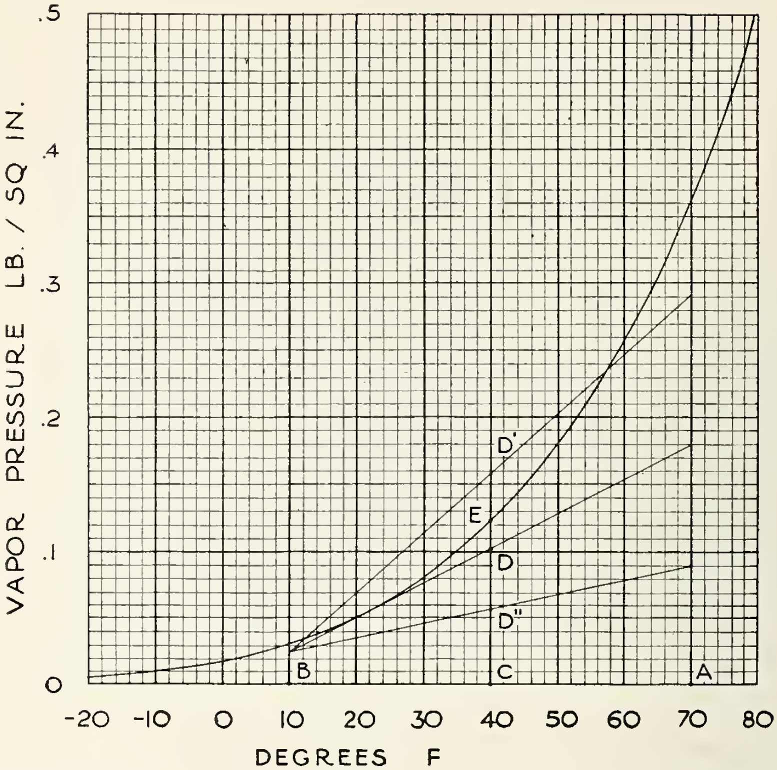

FIGURE 5.—*Method of predicting vapor pressure conditions in a wall composed of a single slab of permeable material.* 80-percent outside humidity (at *B*); *D'*, line for 80-percent humidity inside (at *A*); *D*, line for 50-percent humidity inside (at *A*); *D''*, line for 25-percent humidity inside (at *A*); straight lines, actual vapor pressures; and curve, saturation vapor pressures.

2. Increasing the vapor resistance on the warm side of the insulation.

3. Lowering the vapor resistance on the cold side of the insulation by venting to the outside air or by using less vapor-resistant outer wall materials without diminishing protection against driving rains.

These will be considered in order.

1. The indoor relative humidity is likely to be kept at sufficiently moderate values to avoid condensation on windows most of the time. When use is made of single-glazed windows, the mean relative humidity is then likely to be so low that trouble from condensation within walls will not occur. However, when use is made of double-glazed windows, or storm windows, there may be condensation within the wall without condensation on the glass, either inside or outside.

2. The addition of a vapor barrier on the warm side of the wall insulation is an effective procedure. High humidities frequently occur temporarily, even in houses which would scarcely be described as humidified. If the inside relative humidity is kept high the vapor barrier is of value because it furnishes the only remaining way of effectively reducing the rate at which moisture enters the wall. Naturally, if a vapor barrier prevents part of the loss of moisture through the walls, it will also reduce the rate at which moisture must be supplied to maintain any chosen relative humidity. Any water evaporated is, of course, removed largely by normal ventilation.

3. The provision for adequate ventilation from the interior of the wall to the outdoors or the use of sheathing paper with smaller vapor resistance can be helpful. Unless the ventilation to outdoors is abundant, there is a tendency for the beneficial effect of ventilation of the wall to be limited to the vicinity of the openings to the outside. The air space between the insulation and sheathing should be so proportioned as to permit air circulation and thus allow water vapor to seek natural outlets. It is, of course, obvious that the wall must be left capable of

shedding the rains, or even more water may enter from the outside than would have accumulated by condensation from the inside.

The calculation of the resistance necessary in a vapor barrier in order to prevent condensation in a particular wall has already been discussed, and some results are given in table 4. It will be noted that for conditions which do not seem unusually severe the resistance which must be added is such that the vapor resistance on the warm side of the insulation becomes several times as great as that on the cold side. The metal foils and some of the asphalt papers are effective vapor barriers.

Some of the flexible blanket and rigid board types of insulating materials are now provided with self-contained vapor barriers. When used on the warm side of the insulation a barrier is advantageous; on the cold side it is disadvantageous. When a moisture-repelling protective sheet is used on the cold side, it is essential to have a sheet of considerably greater—usually several times greater—vapor resistance on the warm side.

The blanket type of insulation can be installed near the center of certain types of wall space so as to leave a continuous air space for ventilation on the cold side. For old houses, in which it is difficult to install barrier sheets next to the insulation, the use of two coats of aluminum paint on the inside wall surface has been recommended by some investigators.

In insulated attics the situation is quite different. For insulation on the attic floor, ventilation with attic window louvres may take care of many cases so as to avoid condensation of moisture on the under side of the roof, but in some cases vapor barriers are needed in addition to ventilation. If the insulation is placed close to the roof, it becomes much more difficult to ventilate the space between, and recourse to effective vapor barriers becomes especially necessary. An additional factor is that some modern roofs, such as the metal and built-up types, are made of materials with very high vapor resistance. For these it becomes much harder to get a vapor barrier on the warm side with vapor resistance several times as great as that of the roof. In such cases attempts to provide both adequate ventilation and vapor barriers would appear necessary.

Further discussions of the problem of condensation in insulated walls will be found in a number of the publications referred to at the end of the paper.

IV. CONCLUSIONS

The available data on the moisture permeability of various building materials and the more modern types of structures are too meager and discordant to permit any more than a very rough estimate of the conditions under which condensation will take place in insulated walls. It is possible, however, in the case of many types of wall to calculate for any given condition of humidity and temperature the ratio between the moisture permeabilities of the interior and exterior portions of the wall which is necessary to prevent condensation. For exterior and interior conditions of temperature and humidity which do not seem impossibly severe, it is necessary in a well-insulated wall to have the vapor resistance of the warm side of the wall several times as great as that on the cold side in order to prevent the possibility of condensation. The extent to which air leakage into a wall from the outside is significantly advantageous is unknown, but any such leakage will decrease the tendency for condensation.

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