DEPARTMENT OF ENGINEERING RESEARCH
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VAPOR BARRIERS

with Annotated Bibliography

by

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J. Louis York

TABLE OF CONTENTS

PART I - VAPOR BARRIERS

New interests and new ideas in building construction during recent years have resulted in increased comfort and a reasonable control over some of the evils in the design and operation of a house, but they have contributed materially to the problems of the architect and engineer by increasing moisture condensation in walls and ceilings. Elimination of drafts through the structure, increased control over interior atmospheres with its usual increase in relative humidities, and improved paints, building papers, and building materials have helped cause (and correct) condensation in structures in which it previously was unimportant or unnoticed.

Condensation itself is not a new problem, as may be seen from the early literature on ventilation, but the true explanation for its presence and control has been widely known only during the last decade. Work begun in 1937 at two different places, the Forest Products Laboratory under Teesdale and the University of Minnesota under Rowley, and first published (137, 108) in 1938 was sufficiently clear and correct to serve as the cornerstone of all future investigations. Both programs involved actual testing of model houses under conditions duplicating those existing for full-scale houses, the interior atmospheres being controlled at normal living conditions and the exterior conditions corresponding to normal winter climate in that region.

For structures in which condensation occurred, both groups noted the presence of one or more of the following features:

(1) Interior humidities were high relative to the exterior temperatures.

(2) The inner wall structure was rather permeable to transmission of water vapor.

(3) The outer wall structure was relatively impermeable to transmission of water vapor.

Further investigation by these and other workers showed condensation could be prevented by adoption of these recommendations:

(1) Reduce absolute humidities inside the building until the dew point throughout the wall is below the corresponding temperature.

(2) Render the inner wall structure impermeable and warm enough to be above the dew point of the interior atmosphere.

(3) Render the outer wall structure rather permeable to transmission of water vapor.

Specifically, these recommendations usually read:

(1) Keep interior relative humidities below 30 per cent if the outside temperature is down to 15 degrees Fahrenheit for any extended period, and below 20 per cent if the temperature is down to zero.

(2) Install vapor barriers in the warm side of new wall construction. Acceptable vapor barriers are usually asphalt impregnated and surface coated building papers, laminated papers, or laminated foil-kraft papers. Old construction can be corrected by proper painting of the inside surface or application of the vapor barrier beneath the wallpaper.

(3) Open the outer wall to permit circulation of air from the inner wall spaces to the outside. On new construction this can be done by using highly permeable sheathing materials such as slaters felt or rosin-sized paper. On old construction it may be done by actual creation of openings through the outer wall structure.

These recommendations are unchanged by the nature of the wall structure, since masonry or insulation redistribute the temperatures throughout the wall but are not in themselves a primary cause of condensation.

The determination of those permissible relative humidities within the structure subject to condensation is a problem capable of successful solution by theoretical means, and such results are available (5,6).

The usefulness of any specific material as a vapor barrier is provable only by actual usage, but is predictable from laboratory tests on the material itself. These tests are of many different types to give different aspects of the suitability of the materials. Tests of endurance, including tests for resistance to flame, bursting strength, tearing strength, tensile strength, are useful primarily as they assist in determining the resistance of the barrier to physical damage during installation and service.

The principal test, however, is of the barrier's ability to perform its specific function, prevention of condensation. This is measured by determining the rate of transmission of water vapor through the finished material. The tests for transmission rates are direct measures of the property desired in the barrier, and methods for this are extensively treated in the literature. Transmission rates for many typical materials are found in Table I, and the classification of the bibliography indicates the large number of references containing data.

Laboratory test procedures have developed according to the needs and desires of the individual laboratories, and therefore are subject to a multiplicity of test conditions and techniques. The wide deviation in conditions and units was clearly brought out by Carson (36) at the symposium on "water vapor permeability" (132) held by the Technical Association of the Pulp and Paper Industry in 1937.

Ten variables of a physical nature are involved in the measurement of water-vapor transmission through membranes. They are the time of testing, area of the specimen, leakage at the edges, thickness of the specimen, partial pressure differential across the specimen, relative partial pressure at each face of the specimen, total pressure differential across the specimen, temperature, diffusion through intervening air spaces, and the von Schroeder effect of condensation of water on the specimen itself with a consequent change in rate of transmission. These physical and somewhat controllable variables are supplemented by the nature of transmission itself.

Water-vapor transmission proceeds in one or more of four different ways: (a) gaseous diffusion, (b) diffusion of water in solid solution, (c) movement of moisture along a concentration gradient determined by the difference in moisture content of the specimen at adjacent points through the membrane, and (d) adsorption of water vapor and migration of the adsorbed particles along internal surfaces.

The development of the various tests for transmission rates is brought out in Part II, "History of Measurement Methods." Salient features of the different test procedures are included in Part III, "Annotated Bibliography."

The current tests for transmission rates fall into two general groups, those carried out at atmospheric pressure and those conducted at special pressures on one or both sides of the specimen. The former are by far the most popular because of their simplicity and adaptability to routine operation, but the latter hold more promise for development of a reference test which will reproducibly measure standard values for water-vapor transmission.

The atmospheric-pressure tests are in two classes, those carried out at normal room temperature and those conducted at higher or lower temperatures and, usually, correspondingly higher or lower partial pressure differentials. The low-temperature tests are primarily for the examination of packaging materials for frozen foods, and are specialized and subject to package tests for final information.

The tests conducted at normal temperatures and at higher temperatures are most commonly used, and they are the subject of considerable disagreement within the industries concerned. Advocates of high-temperature tests stress the greater partial pressure differentials, the sharper distinction between samples of low transmission rates, and the better reproducibility of data. Normal-temperature advocates stress the simple and convenient operation, lack of complex apparatus required, and advantages of making all readings without removing the sample from the test atmosphere. Both types of tests will continue to be used, since they correspond to different conditions of service to which the materials may be subjected. Nevertheless, a single test procedure acceptable to all concerned would be of great benefit.

Table II is a presentation of results obtained in a series of tests for comparison of methods, sponsored by the United States Navy, using standard samples and the facilities of seventeen laboratories. The results are summarized in Table III, where it will be noted that the General Foods Moisture Vapor Transmission method (high temperature) has consistently better reproducibility of results than the other procedures. In general, this is substantiated by another series of comparison tests on standard samples run at the Institute of Paper Chemistry and the Bureau of Standards (118, 157).

These tests are valuable in two ways, one being the comparison of relative resistances to transmission for various materials, and the other being the eventual establishment of a limiting transmission rate for materials used in packaging and in vapor barrier applications.

Currently there is no accepted specification for limiting transmission rates for vapor barriers. The specification for blanket insulation (7) adopted by the American Society for Testing Materials discusses transmission but fixes no limitations. The Federal Public Housing Authority, in its specifications for house insulation (151, 152), fixes a limiting value of 1.23 grains per hour per square foot per inch of mercury partial pressure differential. The Housing Agency of Canada fixes (35) a maximum rate of 0.75 (in the same units). In 1938 Rogers (104) quoted a commercial recommendation of 1.35, in 1942 Teesdale (141) selected a value of 0.83, and in 1944 the organizational meeting of the Committee on Condensation Control (44) proposed a rate of 1.25. There is need for a uniform standard specification, accepted by all organizations.

Such a specification could be selected from the considerable mass of empirical data available for the usual materials of construction, but such data are still insufficient to permit the quantitative prediction of the probable transmission rate through an untested barrier. This cannot be done until the mechanism of moisture migration is thoroughly known.

As mentioned above, the mechanism of transmission is divided into four modes, based upon diffusion, solution, hygroscopicity, and adsorption. Actual transmission through any particular barrier occurs by one or more of these modes, the predominant ones depending upon the physical characteristics of the raw material and the peculiarities of formation of the membrane. For example, a duplex laminated paper made up of two sheets of heavy kraft paper bonded with a continuous layer of asphalt is an excellent barrier, but that same product with a loosely woven mesh of cellulosic material inserted in the asphalt for added strength will be a poor barrier. The cellulosic material destroys the continuity of the asphalt barrier, and being highly hygroscopic is an actual pathway for water-vapor transmission.

The mechanism of transmission by these modes is only sketchily known, and much more comprehensive information is necessary before satisfactory predictions can be made of the suitability of a new and untested material for use as a vapor barrier.

Table I

WATER-VAPOR TRANSMISSION RATES FOR VARIOUS BUILDING MATERIALS

Description of Material	WVTR grains/hour (sq. ft.)(in.Hg.)	Reference
Sheathing paper, #2 std. dry, 15#/400 sf.	170.4	14
Sheathing paper, heavy dry, 38#/400 sf.	134	14
Asphalt sat. rag felt, 10#	6.34	14
Asphalt sat. rag felt, 15#	3.02	14
Saturated asbestos felt, 20# (1 surf. coated)	0.134	14
Asph. sat. and coated sh. felt, 36# (both surf. ctd)	0.060	14
Asphalt sat. sheathing paper, 25#	4.15	14
Asp. sat. and ctd. kraft, 45# (glossy)	0.181	14
Duplex paper, 30-30-30	0.800	14
Duplex paper, 30-30-30	0.770	*
Med. wt. waxed paper	0.407	14
Vinylited paper	4.250	*
Vinylite sheet	2.795	*
Glassine	0.669	*
Writing paper	0.811	*
Moistureproof Cellophane	0.404	*
Al foil backed with Cellophane	0.0405	*
Plain foil, 0.0015 in.	0.0304	*
Beeswax dipped paper	0.1821	*
Scutan #6	0.850	*
Cincinnati Ind. X-Crepe	0.158	**
Ordinary Cellophane (store purchased)	24.9	**
U. S. Rubber, 10 oz. Army raincoat stock	4.48	**
Goodyear Pliofilm	0.492	**
Aluminum foil, 0.001 in. (crinkled)	0.171	**
Kitchen waxed paper, (store purchased)	6.96	**
Koroseal XP 2012 - 0.0020 in.	1.61	**
Armour and Co. waxed paper	0.794	**

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*Determined by wet-cup method, water in cup, 95% sulfuric acid is desiccant, 100 F, 80 mm. diam., 72 hours.

**Determined by dry-cup method, silica gel in cup, sat. sol. of potassium nitrate in atmosphere (90% r.h.), 100 F, 24 hours, 77 mm. diam.

(The data marked (*) and (**) are published through the courtesy of the Frigidaire Division, General Motors Corp.)

Table II

RESULTS OF ROUND ROBIN ON METHODS OF MOISTURE VAPOR TRANSMISSION

SPONSORED BY THE NAVAL AIRCRAFT FACTORY (160)

Laboratories	Temp. in °F.	High Humidity		Low Humidity		PPD in MM. of Hg.	Air Velocity over Sample	After Steady Rate?	Approx. Area in Sq. In.	Pliofilm (Grams per	Parchment 100 sq. in.	Glassine per 24 hrs.	Cellophane I at 4.8 mm. VPD)
		Relative Humidity	Obtained?	Relative Humidity	Obtained?								
1	73	50	Conditioned Air	2	Ca Cl_2 in cup	10.0	500 ft/min.	Yes	5	.26	.00	.11	.35
2	72	100	Water in Cup	65	Conditioned Air	7.0	500 ft/min.	Yes	5	.24	.01	11.8	.35
3	103	100	"	0	Conditioned Air	53.4	100 ft/min.	No	2	.35	.38	263.	.35
4	75	100	"	50	"	11.0	500 ft/min.	Yes	5	.19	.36	5.0	.34
5	73	100	"	20	"	17.3	500 ft/min.	Yes	5	.52	.32	2.54	.87
6	80	100	"	30	"	18.1	500 ft/min.	Yes	5	.51	.27	4.25	6.08
7													
8													
9	104	100	Water in Cup	0	Conditioned Air	54.9	Slight	Yes	10	.25	.24	.97	.45
10													
11	82	80	Conditioned Air	20	Saturated Salt Solution in Cup	16.6	Slight	Yes	3	.19	.16	.29	.44
12	100	95	Conditioned Air	9	Calcium Chloride $CaCl_2$ in Cup	41.8	"	No	21	.33	.32	.25	.22
13	100	95	"	9	"	41.8	"	"	21	.39	.39	.43	.26
14	100	95	"	9	"	41.8	"	"	21	.44	.35	.40	.26
15	100	95	"	9	"	41.8	"	"	21	.36	.34	.46	.45
16	100	95	"	9	"	41.8	"	"	21	.30	.30	.43	.30
17	100	95	"	9	"	41.8	"	"	21	.35	.33	.42	.35
18	68	93	"	20	Saturated Salt Solution in Cup	12.6	"	Yes	3	.25	.20	.69	.35
19													
20													
21	70	100	Water in Cup	10	Condition Air	16.6	"	No	5	.40	.26	5.93	.28
22	77	95	Conditioned Air	15	Saturated Salt Solution in Cup	18.8	"	Yes	10	.16	.14	.42	.26

Table III

Summary of Test Results

Round Robin Sponsored by Naval Aircraft Factory (160)

Method	Number of tests by this method	Average for pliofilm	Average for parchment	Average for glassine	Average for cello-phane I	Individual results within ±10% of average for method	Individual results within ±20% of average for method	Individual results within ±25% of average for method
1. Dessicant in cup (except GFMVT)	1	.26	.00	.11	.35	-	-	-
2. Liquid water in cup	7	.35	.26	.42	1.23	15%	18%	22%
3. Saturated salt solution in cup	3	.20	.17	.47	.35	33%	58%	83%
4. GFMVT	6	.36	.34	.40	.31	54%	83%	88%

PART II - HISTORY OF MEASUREMENT METHODS

The earliest test made specifically for moisture vapor transmission of a membrane was developed by Gardner (45) in 1910. This was an open-mouthed glass bottle half-filled with sulfuric acid and covered over with a paint film sealed with Canada balsam. The bottles were placed in a location where the air was saturated with moisture and weighed every week. Three years later Muckenfuss (94) announced a much more complex form of the test. The apparatus had eight separate parts, a base with two concentric grooves and a circular depression in the center, a pair of matching rings which clamped the paint film between them and whose bottom edge fitted the inner groove in the base, a light wire ring to be placed on the specimen to carry a wire screen which supports a weighed dish containing desiccant, and a glass cover dish to fit over the entire assembly and match the outer groove in the base. Water is placed in the trough, the rings (with specimen), the wire screen, and desiccant dish set in place, and the cover placed over all. Mercury in the concentric grooves seals the compartments of the apparatus one from the other. The increase in weight of the desiccant dish gives a measure of the transmission rate in milligrams per 24 hours. Like Gardner's method, this was designed for the testing of paint, varnish, and lacquer films.

In 1925 Wilson and Lines (163) had taken the Gardner jar and added two brass flanges between which they clamped the specimens of leather which they tested. The jar held sulfuric acid and was placed in a desiccator containing water, thus giving approximately a 100 to 0 per cent differential in relative humidity.

Stillwell (124) and Martley (90) in Great Britain had adapted the same technique to testing of timber plugs up to five inches in length. In their case the water was sealed in the dish and the assembly placed in a closed jar containing sulfuric acid.

In a study of the weathering of paint films in 1928, Walker and Hickson (156) used a modified form of the method, painting their films onto No. 100 wire sieves and fastening the panels to petri dishes containing calcium chloride which were placed in an atmosphere of 30°C and 32 per cent relative humidity. Blanks were run for leakage, the seal being rubber bands. Eventually the system was discarded after enlarging the samples to 7.5 by 15 centimeter rectangles and fastening a drying tube to one side with rubber gaskets, with little improvement as to errors.

Gardner included the method in his laboratory manual (62), but using screw-cap jars with a three centimeter circular opening in the cap. The paint films, stripped from amalgamated tin plates, were tightly held by the cap, whose bottom edge was sealed with paraffin. This method was used with calcium chloride in the jar and an atmosphere of 32°C and 88 per cent relative humidity outside, with calcium chloride inside and water outside, and with water inside and sulfuric acid outside.

Gettens (63) and Gettens and Bigelow (64) used the same idea of a screwcap jar at first, but added a rubber gasket and an aluminum gasket, placing water in the jar and desiccating the atmosphere with calcium chloride. Later they cut the tops from the jars and cemented on an aluminum flange, placing the specimen between this and a brass disk without benefit of gaskets. Water was placed in the bottle and the outside atmosphere maintained at 32°C and 2-3 per cent relative humidity with silica gel. The paint films were dipped onto "Paperglas" as a reinforcing strip with negligible permeability.

Kittelberger (80) used thin wood disks as a base, placing water in the jars and holding them in an atmosphere of 120°F and 17-20 per cent relative humidity. Blanks were run on unpainted panels and the results expressed as a percentage of the loss through unpainted panels.

The glass jar was abandoned by Payne and Gardner (100) and the New York Paint and Varnish Production Club (97) for a metal cup with a metal flange and a metal disk which could be clamped together tightly enough to eliminate gaskets. Both placed water in the cup, but the former used an oven at 25°C and dried by calcium chloride, while the latter used an oven at 38°C and dried by phosphorus pentoxide. Payne (99) later used the same procedure as the New York Club but used Fiberglas as a support for his films instead of Patapar.

In 1929 Hyden (77) described the method used on Cellophane. The sample is sealed over a glass dish containing water by using beeswax, then kept in an oven at 100°F and zero humidity, the air being circulated over concentrated sulfuric acid. Six years later Charch and Scroggie (39) were using the same method in a thorough investigation of the effect of the variables in the method now called the "cup" method.

Birdseye (25) used a glass crystallizing dish, sealing the specimen upside down, inverting and breaking the seal enough to allow the entrance of a pipet through which water is introduced to the dish, then resealing. The dish is stored in an oven at 38°C with air dried by calcium chloride or sulfuric acid.

In work at the Bell Telephone Laboratories, Herrmann (73) and Taylor, Herrmann, and Kemp (128) used an improved form of the same device, making changes so as to handle rigid or semirigid substances, those exhibiting cold flow, and those with very low diffusivities. A little later Deeg and Frosch (47) went back to a cup like the Payne cup, with water inside and dry air at 25°C outside. Their results show strikingly that the permeability varies with the relative humidity as well as the partial pressure differential.

In 1930 Abrams and Chilson (3) started investigations on papers by studying the many variables in the operation. They began to use water in a shallow dish, sealing the specimen with beeswax, and submitting it to an atmosphere of 70°F and 50 per cent relative humidity. Using either water or a desiccant in the dish, having the same partial pressure differential in either case, this method was carried on and refined by Abrams (1), Tressler and Evers (145), Abrams and Brabender (2), Carson (38), Rabak (102), and Brabender (27, 28, 29) until in 1941 it became a standard procedure for measuring the water-vapor permeability of paper - still leaving an alternate of water or a desiccant in the dish (129).

In 1944 the water alternate was dropped from the standard because of difficulty with condensation on the underside of the paper. In 1942, however, this standard was adopted by the American Society for Testing Materials as a standard test for the water vapor permeability of plastic sheets (8), and it still contains both alternates. The Technical Association of the Pulp and Paper Industry added a standard in 1944 for creasing of the papers before testing (131) to better simulate actual conditions of service.

Some time previously, however, a test was developed at General Foods by Southwick and Rhoads, usually known as the GFMVT method. This test (10, 127, 154) operates with shallow dishes filled with calcium chloride and sealed tightly with wax around the edges of the specimen, the assembly being placed in a cabinet maintained at 100°F and 90-95 per cent relative humidity. The test is accelerated and gives relative values for packaging materials that indicate how they will survive under severe service. This test was later established as a standard of the Technical Association of the Pulp and Paper Industry (130), and is now specified as the official test in Army-Navy and Ordnance specifications (146, 147).

One of the standard methods for testing moisture vapor transmission of paints is to actually use them as paints, since producing a film on a different material often changes its character so as to nullify any results. A procedure of investigating paints by painting standard wood panels and exposing them to conditions of constant temperature and humidity. (Browne) (32) used a humidity of 97 per cent and painted the panel completely, which tends to give a changing partial pressure differential and thus a changing rate. Wray and Van Vorst (165) painted the wood on both sides and then sealed the panel over a jar of activated alumina to maintain a steady driving force. Edwards and Wray (57) and also Wray and Van Vorst (166) used a shallow dish carrying activated alumina and exposed to variable humidities at constant temperature and variable temperatures at a constant moisture content in the air.

It was an obvious step to eliminate some of the difficulties of the cup methods by arranging the film or membrane as a septum between two chambers through which the air streams are directed at a controlled velocity, temperature, and humidity. Edwards (54) and Edwards and Pickering (56) used a shallow chamber on each side in their testing of rubber for its permeability to gases, with dry air passing through on one side of the film and dry, pure gas through the other side at a slight increase in pressure so as to maintain the driving force in a definite direction and help retard counterdiffusion, and the leaving air with its pick-up of gas passing through a drying tube to a Rayleigh interferometer with which the composition was accurately measured, followed by saturation with water and passage through a wet meter to measure the air flow.

Thomas and Reboulet (143) arranged their specimen so that dry air is on one side, under no circulating influence, and saturated air on the other side at an elevation in pressure of 0.2 inch of water. The installation is maintained at 30°C and the transmission is measured as an increase in weight for the drying tube on the dry side of the specimen. Lishmund and Siddle (83) devised an assembly resembling a pipe union, with the union tightening up two flanges between which the specimen is clamped and exposed to circulating moist air in one chamber and circulating dry air in the other.

An installation similar in principle to that of Teesdale (140) or of Rowley (110) is that of Hechler, McLaughlin, and Queer (70). The specimen of wall or building material is installed in a set-up reminiscent of a guarded hot-box, but the moisture transmission is measured as well as the heat transmission. The high temperatures are around 100°F and the low temperatures are around 10°F. The effect of moisture on the thermal conductivity of the insulation can be measured directly here.

It has never been established whether water vapor alone but at the conditions existing in the mixture will act as if it were in that mixture. It was natural, therefore, that some tests would arise using pure water vapor at the low pressures actually found in moist air. Schumacher and Ferguson (115) devised an apparatus which holds the specimen in a recess between two flanges which are tightened by a pipe-union type arrangement improved by the addition of ball bearings to lessen the danger of twisting and distorting the film. The apparatus can be evacuated and a capsule of water broken on one side, the flow through the membrane being measured by a sensitive manometer or by the extension of a calibrated quartz spring holding a small basket of phosphorus pentoxide, as developed by McBain and Bakr (85) or Barrett and Birnie (21). The edge seal is made by pouring mercury into a special well made into the instrument. Schumacher and Ferguson (116) checked the comparative accuracy of the two methods of measuring the flow during a comprehensive investigation of water diffusion through rubber.

Trillat and Matricon (144) used a similar arrangement, but they used an ionization gauge to determine the moisture content of the air flowing through the membrane and a McLeod gauge to measure the total air flowing.

A Quartermaster Department project at Brooklyn Polytechnic Institute is using an instrument operating on exactly the same principle as that of Schumacher and Ferguson, but the equipment of Doty, Aiken, and Mark (49) is constructed so that the water is introduced gradually in the quantity desired instead of by breaking a capsule. The instrument is primarily useful because it is capable of extreme temperature ranges in its measurements. It also checks the other methods, especially the TAPPI cup method, rather well on absolute values of the permeability. It is the first test which attempts to distinguish between transmission by diffusion, by absorption, and by capillary action.

Boor and Dixon (26) developed the permeameter based on the variation of thermal conductivity of air with humidity content. The specimen is clamped over a shallow cell containing water and air of known humidity is forced across the face and through a thermal conductivity cell where its resistance is compared with that of standard air, thus determining the relative humidity. The unit is versatile, but highly resistant papers give results within the limits of error of the instrument.

PART III - ANNOTATED BIBLIOGRAPHY

CLASSIFICATION

References from field of packaging, with data:
1, 2, 3, 25, 26, 27, 28, 30, 39, 49, 50, 59, 68, 77, 82, 102, 114, 117, 118, 123, 142, 145, 157, 159, 160.

References from field of packaging, without data:
10, 29, 31, 36, 37, 38, 48, 52, 58, 60, 67, 79, 84, 87, 98, 120, 121, 122, 127, 129, 130, 131, 132, 133, 134, 135, 143, 144, 146, 147, 148, 153, 154, 161.

References from field of building materials, with data:
6, 9, 13, 14, 15, 19, 70, 71, 90, 108, 109, 110, 111, 112, 124, 139, 140, 141, 158,162.

References from the field of building materials, without data:
5, 7, 11, 12, 16, 17, 22, 23, 24, 33, 34, 35, 40, 41, 42, 44, 46, 51, 52, 53, 61, 66, 69, 75, 76, 78, 86, 88, 91, 93, 96, 101, 103, 104, 106, 107, 113, 125, 126, 136, 137, 138, 149, 150, 151, 152, 155, 164.

References from the fields of paint and plastics, with data:
8, 32, 47, 49, 54, 56, 57, 63, 64, 73, 80, 81, 83, 94, 95, 100, 105, 128, 142, 156, 165, 166.

References from the fields of paint and plastics, without data:
45, 55, 62, 92, 97, 99, 115, 116, 120.

References from the field of leatherworking:
4, 72, 74, 163.

References from the field of textiles:
18, 65.

General references, no specific field:
20, 21, 85, 89, 119.

Reference on agricultural coatings:
43.

ANNOTATED BIBLIOGRAPHY

1. Abrams, Modern Packaging, 5: No. 5: 51-53; No. 6: 88-92, 98; (1932).
Testing methods are discussed for paper packaging materials, including the Penescope for water transmission, the Vapometer for water-vapor transmission, and package tests for water-vapor transmission. Details of the tests are given, and data are presented for a variety of materials ranging from moisture-proof cellophane to vegetable parchment.

2. Abrams and Brabender, Tech. Assn. Papers, 19: 121-130; (1936).
-- Paper Trade Journal, 102: TS204-213; (1936).
Factors affecting the determination of water-vapor transmission are discussed. The effect of water-vapor partial-pressure differential across the paper, the distance between the water surface and the test specimen, the time required for steady-state conditions to be established, the overall dimensions of specimen and test device, and edge leakage are discussed and a new vapometer is described.

3. Abrams and Chilson, Tech. Assn. Papers, 14: 379-384; (1931).
-- Paper Trade Journal, 91: No. 18: 175-180; (1930).
-- Paper Ind., 12: No. 6: 1047; (1930).
-- Paper Mill, 53: No. 38: 24-28; (1930).
Data are presented and discussed on water-vapor transmission through papers, usually cellulose acetate, with studies of effects of different variables. Data are given for varying amounts of water in device, varying velocity of air, varying time of exposure, varying temperature, varying air humidity, used vs. unused paper, and the effect of vacuum. All tests were of the wet-cup type. A standard test is proposed, using 50 cc. of water in aluminum cup having test area of 7.07 sq. in., exposed for a minimum of 6 hours to air at 70 F, 50% rel. hum. and 600 feet per minute.

4. Am. Leather Chem. Assn., J. Am. Leather Chem. Assn., 37: 370-371; (1942).
A method for measuring the water-vapor transmission of leather is proposed, weights ranging from 1.25 to 11 ounce vegetable-tanned leathers. A 2.75-inch diameter sample is sealed with 50-50 beeswax-rosin between two brass rings, the assembly sealed to a tannin dish partially filled with activated alumina and stored in an atmosphere of 95 F and 90% rel. hum., and weighings made until a straight line relation is obtained.

5. Am. Soc. Heating and Vent. Engr., "Heating, Ventilating, Air Conditioning Guide," 21: (1943), Am. Soc. Heat. Vent. Engr., New York.
Section on "Condensation in Buildings" gives brief discussion of causes of surface and interstitial condensation, and also brief statement in general terms of remedy - the use of vapor barriers on warm side of insulation and vents on the cold side.

6. Am. Soc. Refrig. Engr., "Refrigerating Data Book," 5th ed.; (1943). Am. Soc. Refrig. Engr., New York.
Basically correct discussion of the mechanism of water-vapor transmission and remedies is given, with table of transmissions of materials included from McDermott (86).

7. Am. Soc. Testing Mat. Comm. C-16, Emer. Spec. ES-14, "1942 Book of Standards," Part II: 1038-1039; (1942). Am. Soc. Testing Mat., Philadelphia.
Specifications for blanket or batt insulation in flexible or semirigid form do not include limitations or procedures for testing for water-vapor transmission, although need is recognized.

8. Am. Soc. Testing Mat. Comm. D-20, Tent. Std. D697-42T, "1942 Book of Standards," Part III: 1280-1283; (1942). Am. Soc. Testing Mat., Philadelphia.

Standard test procedure for measuring water-vapor transmission of plastic sheets is identical with TAPPI Standard T448m. The specimen is sealed with 50-50 beeswax-rosin to a dish containing either magnesium perchlorate or water, stored in an atmosphere of 77 F and 50% rel. hum. at 500 feet per minute, and weighed until steady-state equilibrium is attained.

9. Anonymous, Heating and Ventilating, 39: No. 9: 43-47; (1942).
-- Heating and Ventilating, 40: No. 3: Ref. Data 241-242; (1943).
-- Heating and Ventilating, 40: No. 4: Ref. Data 243-244; (1943).

A comprehensive list of building materials and their rates of water-vapor transmission is presented, the data being from the work of Babbitt (14), Barre (19), and Rowley, Algren, and Lund (110).

10. Anonymous, Modern Packaging, 16: No. 3: 78, 82, 100; (1942).

An illustrated description of the General Foods Moisture-Vapor Transmission cabinet is given. The cabinet consists of two cylindrical shells mounted concentrically with insulation between and a wire rack inside to carry 24 test dishes, which are stored at 90-95% rel. hum. and 100 F, the air being blown across a pan of water in the bottom of the unit. The 5-5/8-inch diameter specimen is sealed over calcium chloride in a shallow dish and weight increases measured.

11. Arnold, New York Agri. Exp. Sta., Ithaca, Bull. 724: (1939).

A discussion of refrigerated spaces on farms includes a discussion of moisture migration through the walls. Based upon average conditions around Ithaca, a vapor barrier is recommended on the outside wall, contrary to normal arrangements.

12. Babbitt, Heating, Piping and Air Cond., 10: 751-755; (1938).

Discussion is presented of work of Rowley and Teesdale, and methods of measurement of water-vapor transmission through pure barrier.

13. Babbitt, Can. J. Research, A 17: 15-32; (1939).

The theory of diffusion through building materials is discussed and data presented. The theory is based on Fick's Law. The data come from tests by the dry-cup method using calcium chloride and air at 91 F and 75% rel. hum., the specimens being various fibreboards, woods, laminated kraft paper, building paper, asphalt felt, plaster, corkboard, rock wool, and Presdwood. A carefully accurate analysis of the use of a vapor barrier is given, with interior placing and exterior venting.

14. Babbitt, Can. J. Research, A 18: 90-97; (1940).

Data are presented as to the water-vapor transmission of various building papers, tested at 90 F with calcium chloride in the cup and air of 75% rel. hum. outside. Specimens are grouped as sheathing papers, asphalt saturated rag felts, asphalt saturated asbestos felts, asphalt saturated and coated sheathing felts, asphalt saturated sheathing papers, asphalt saturated and coated kraft papers, asphalt coated kraft papers, tar saturated rag felts, duplex papers, waxed papers, heavy roofing papers, and infused papers. The maximum permissible transmission rate is suggested as 0.76 grains per square foot per hour per inch (Hg) partial pressure differential.

15. Babbitt, Can. J. Research, A 18: 105-121; (1940).

The effect of hygroscopicity of the materials is discussed and some data and tests described to illustrate various features of this effect, in this paper the only relative humidities being below 75%. It is suggested that two types of transmission occur, molecular adsorption and capillarity, and that these determine the influence of humidity upon the water-vapor transmission. Fick's Law is applicable at humidities less then 75%.

16. Babbitt, Can. J. Research, A 19: 42-55; (1941).

An equation is derived for the amount of vapor diffusing through a slit and the results calculated are compared with experimental values. The diffusion is not proportional to the width of the slit.

17. Baker, *Heating, Piping, and Air Cond.*, 2: 218-219; (1930).

The correct application of low-temperature insulation to piping systems is discussed. The procedures are correct, but the impression is given that protection is against air infiltration, not moisture transmission.

18. Barr, *Gr. Brit., Dept. Sci. Ind. Res.*, Fabrics Coor. Res. Comm., Rpt. 2: App. 3: 113-139: (1930).

Waterproofness is primary subject of report, but water-vapor transmission was measured by sealing 34 sq. cm. of fabric over a shallow tin containing water and exposing it to a "dry" air stream at 98.4 F. Author dismisses process as too tedious when air transmission and waterproofness will suffice.

19. Barre, *Iowa St. Coll. Agri. Mech. Arts, Agri. Exp. Sta.*, Res. Bull. 271; (1940).

The relation of wall construction to moisture accumulation in fill-type insulation is investigated analytically and experimentally. 33 test panels, frame, brick veneer, double tile, concrete L-block, and special constructions being used, were tested with air at 75 F and 50% rel. hum. on one side and air at 12-16 F and 80% rel. hum. on the other side for 25 to 72 days, moisture determinations and accumulations observed.

Materials of construction were checked for water-vapor transmission by four methods, (a) wet-cup, NaCl saturated solution (75% r.h.) inside and 75 F, 50% r.h. air outside, (b) wet-cup, water (100% r.h.) inside and 75 F, 50% r.h. air outside, (c) condensation, 75 F, 50% r. h. air on warm side and ice-water cooled surface on cold side, (d) condensation, 75 F, 100% r. h. air on warm side and ice-water cooled surface (32 F, 100% r. h.) on cold side.

Vapor barriers were improvement, vents on cold side less so.

20. Barrer, "Diffusion In and Through Solids," Cambridge Press; (1941).

Mathematical treatment of diffusion is thorough and extensive. Data presented are based upon measurements made with cell similar to that of Schumacher and Ferguson (115), with water vapor treated as one of several gases and analysis based upon entire group.

21. Barrett and Birnie, *J. Am. Chem. Soc.*, 62: 2839-2844; (1940).

Adsorption of water vapor on silica surfaces is measured by direct weighing on an extremely sensitive microbalance. This spring-type balance is used in several water-vapor transmission measuring units.

22. Barrett, *Trans. Am. Soc. Heat. Vent. Engr.*, 29: 231-240; (1923).

The amount of insulation on a cold surface to prevent sweating is computed and expressed in convenient form, values being checked from experiment. Emphasis is placed on air infiltration, not moisture migration.

23. Berestneff, *Heating and Vent.*, 29: No. 4: 27-32; (1932).

The influence of moisture on the heat conductivity of building materials is analyzed, with differentiation between penetration into a substance and penetration through a substance and further distinction between absorption when exposed to water vapor and when exposed to liquid water. Based upon Matschinsky (91), a theory is developed for the transmission by virtue of partial pressure differential of both water vapor and air. Remedies suggested are moistureproofing both wall surfaces, inserting a moisture barrier in the middle of the wall, and free circulation of air through the wall.

24. Berestneff, *Refrig. Eng.*, 23: 343-346, 352; (1932).

Mechanism of moisture absorption of insulation is divided into two classes, absorption and transmission. Water present in the insulation is classed as free water, sorbed water, and chemically combined water, with attention drawn to the importance of the phase present. The mechanism is correctly analyzed and the conclusion reached that vapor barriers on the warm side and venting the cold side will relieve the problem.

25. Birdseye, Ind. Eng. Chem., 21: 573-576; (1929).
The packaging of quick-frozen foods requires low vapor transmission of the package, and tests are presented for measuring the transmission. The specimen is sealed over a crystallizing dish, one edge loosened and water inserted by pipet, the edge resealed and the dish stored in air at 100 F and dried over calcium chloride or sulfuric acid, and weighings taken regularly. Results reported as relative vaporproofness.

26. Boor and Dixon, Tech. Assn. Papers, 27: 689-697: (1944).
-- Paper Trade J., 119: TS 176-184; (1944).
A thermal conductivity determination of water-vapor transmission, by the Permeameter, is described and data presented for comparison. The specimen is clamped over a liquid and air of known humidity is passed over it and through a thermal conductivity cell where its resistance is compared with that of standard air, relative humidity being determined thus. Comparisons with the Payne cup, General Foods, TAPPI, and Inst. of Paper Chem. methods on TAPPI standard samples of Reynolds A14 laminated, 3-ply glassine, Cellophane MST, Pliofilm 140PID, waxed glassine, ethyl cellulose 610, greaseproof board, and Scutan gave results in the same order of magnitude. Variations of 200% were not serious in view of variations in samples up to 100%. Water in the cup gave condensation on sample, and recommended procedure is testing at both 90% r. h. and 100% r. h. Low permeability papers give results within inaccuracies of instrument.

27. Brabender, Tech. Assn. Papers, 22: 251-255, 95-99; (1939).
-- Paper Trade J., 108: TS31-35; (1939).
A progress report of the TAPPI Water Vapor Permeability Subcommittee suggests a procedure for determining water-vapor transmission. Specimen is sealed over desiccant (magnesium perchlorate recommended) and cup inverted in air at 70 F and 65% r. h., weighing continuing to constant rate of gain. Data are presented from eleven laboratories on seven materials: rubber hydrocarbon-HCl polymer, moistureproof regenerated cellulose, non-moistureproof regenerated cellulose, wet-waxed paper, dry-waxed paper, non-moistureproof cellulose acetate, and glassine, the indication being that temperature and humidity are important as to the unit water-vapor transmission. Special tests on two glassines at different humidity levels show different absolute and relative transmission values, even at the same temperature and partial pressure differential.

28. Brabender, Proc. Food Conf. Inst. Food Tech., 1: 227-235; (1940).
Studies on water-vapor transmission of paper containers for dry foods show increasing rates with increasing temperature and with increasing relative humidity. The sharply increasing rate at high relative humidities for hygroscopic materials is pointed out.

29. Brabender, Tech. Assn. Papers, 23: 358-361; (1940).
-- Paper Trade J., 110: TS241-244; (1940).
-- Paper Ind., 22: 838; (1940).
A progress report of the TAPPI Water Vapor Permeability Subcommittee recommends a standard test procedure for determining water-vapor transmission of paper and paperboard. Procedure is identical with TAPPI Standard T448m-41 (129).

30. Brabender, Tech. Assn. Papers, 27: 473-476; (1944).
-- Paper Trade J., 119: TS160-163; (1944).
Water-vapor transmission through moisture-sensitive materials was investigated by use of a new cell having two specimens sealed on opposite sides of the desiccant and stored in air at 100F and 90% r.h. for several days. 3-ply glassine laminated with microcrystalline wax was tested, showing a constant rate of gain for ten days, a decreasing rate for ten days, and another period of 25 days with a constant rate. Checks indicated that ordinary rosin oxidized and absorbed moisture, forcing the use of dehydrogenated rosin.

31. Brackett, Tech. Assn. Papers, 26: 125-128; (1943).
-- Paper Trade J., 116: TS116-119; (1943)

Among many packaging problems in the quick-frozen food industry is that of water-vapor transmission. A liner material should have a maximum transmission rate of 0.4 grams per 100 square inches per 24 hours per mm. (Hg) partial pressure differential at 100 F and 95% r.h., and 0.02 grams at 0 F.

32. Browne, Ind. Eng. Chem., 25: 835-842; (1933).

The effectiveness of paints in retarding moisture absorption by wood was studied at Forest Products Laboratory by exposing coated and uncoated wood specimens (originally in equilibrium with air at 65% r.h.) to air at 97% r.h. for one week, weighing before and after. Tests were made on primers, primers plus two coats of white-lead, linseed-oil paint, and three coats of many paints such as aluminum paint, colored paints, paints containing varnish vehicles, and paints brushed on or sprayed on. All figures are given as "effectiveness ratings." Only primer effective is finely divided aluminum in varnish vehicle or some granular pigment paints. Brush application better than spray.

33. Canada, Dept. of Finance, Housing Admin., Bull. MS39-6; (1940).

Approved vapor barrier papers are listed, including building papers, asphalt saturated and coated sheathing felts, asphalt saturated rag felts, duplex or laminated papers, waxed papers, insulation plaster boards, rock or mineral wool batts.

34. Canada, Dept. Finance, Housing Admin., Bull. MS39-6a; (1940).

An explanation of condensation and the proper use of vapor barriers is given, based upon Babbitt (14) and Teesdale (137).

35. Canada, Dept. Finance, Housing Admin., "Memorandum Specifications," (1941).

Among other building specifications is that for insulation, requiring the use of a vapor barrier on the warm side, the transmission being a maximum of 0.753 grains per square foot per hour per inch (Hg) partial pressure differential.

36. Carson, U.S. Bur. Standards, Misc. Pub. M127; (1937).

Data on water-vapor transmission of various membranes are presented to show the great variety of test conditions, methods, and units of measurement. Ten variables are discussed which affect the transmission rate, including time, area, leakage, thickness, partial pressure differential, relative humidity, temperature, total pressure, diffusion in still air, and the physical state of the moisture. Suggested mechanisms of transmission are gaseous diffusion, solution diffusion, hygroscopic attraction, and migration of adsorbed molecules.

37. Carson, Food Industries, 10: 14-16, 130-132; (1938).

This article is a presentation and recapitulation of Carson (36).

38. Carson, Paper Trade J., 107: TS213-215; (1938).

Various methods of sealing membranes to a test cell are presented, emphasizing sharp definition of the test area and prevention of edge leakage.

39. Charch and Scroggie, Paper Trade J., 101: TS201-209; (1935).

A test for the determination of the water-vapor transmission of cellulose wrapping materials is described. The specimen is sealed over a small dish of water and the assembly exposed in an oven at 100 F to air circulating over sulfuric acid. An oven is described capable of maintaining a temperature within 0.2 degree and a humidity less than 2% r.h.

40. Clay, Address before Master Painters and Decorators Assn. Cleveland Chapter, October 29, 1943.

The effect of moisture on painted walls is explained, particularly as difficulty arises from condensation resulting from improper use of vapor barriers or lack of vapor barriers.

41. Cope and Kinney, Heating, Piping, and Air Cond., 12: 703-706; (1940).
An interesting technique is described for the use of sprayed latex as a vapor barrier around cold-water piping.

42. Close, Trans. Am. Soc. Heating Vent. Engr., 36: 153-164; (1930).
-- Heating, Piping, and Air Cond., 1: 417-422; (1929).
Proper thicknesses of insulation for the prevention of condensation on interior building surfaces are presented in equations and graphical form. No comments in regard to use of vapor barriers.

43. Comar and Miller, Ind. Eng. Chem. Anal. Ed., 15: 737-740; (1943).
Water-vapor transmission of agricultural spray coatings was measured with a Payne cup, the film being spun on bond paper. Distilled water was used inside the cup and the air was maintained at 25 C and in equilibrium with technical calcium chloride, the test lasting exactly 150 minutes. Moisture impedance increased with large increases in oil content and with slight increases in wax content; the addition of bentonite filler increases the thickness but reduced the unit impedance.

44. Committee on Condensation Control, Chicago meeting, July 28, 1944.
An inter-industry committee was organized to correlate information regarding condensation in buildings. Immediate recommendations on the application and limiting transmission (1.25 grains per square foot per hour per inch (Hg) partial pressure differential) of vapor barriers were referred to a technical subcommittee for study.

45. Cushman and Gardner, "The Corrosion and Preservation of Iron and Steel," First ed., 172-175, McGraw-Hill, (1910).
Gardner, "Paint Technology and Tests," pp. 81-84, McGraw-Hill, (1911).
Water-vapor transmission test is described, the specimen being sealed with Canada balsam over a 2-oz. wide-mouth glass bottle containing sulfuric acid. The assembly is exposed to air saturated with moisture and at a constant temperature for a week. Calcium chloride is used occasionally to replace the sulfuric acid.

46. Dana and Miller, State Coll. of Wash., Eng. Exp. Sta., Eng. Bull. 59, (1939).
A description of top-opening and side-opening farm freezing plants includes advice on the use of a vapor barrier on the warm side. The recommended barrier is 35-lb. asphalt impregnated paper, sealed with liquid asphalt.

47. Deeg and Frosch, Modern Plastics, 22: No. 3: 155-156, 198, 200, 202; (1944).
Cup is described and data presented for the measurement of water-vapor transmission through plastic sheets. Cup is modified Payne type containing water, with specimen clamped between metal rings and sealed with silk gaskets and stop-cock grease. Air is maintained at 25 C over calcium chloride, the length of run varying. Effect of different plasticizers and fillers is shown, decreased transmission with increased wax content is demonstrated, and some materials are shown to have variable transmission with variable relative humidities.

48. Diefenbach, Paper Ind. and Paper World, 26: 992-993; (1944).
The use of ultraviolet light to cause fluorescence of coatings and laminants show unevenness in thickness, which checked against the water-vapor transmission as measured by the Payne cup.

49. Doty, Aiken and Mark, Ind. Eng. Chem. Anal. Ed., 16: 686-690; (1944).
Water-vapor transmission through organic films was measured by an adaptation of the Schumacher-Ferguson cell, using a rubber gasket for a seal and measuring the transmission as an increase in the downstream pressure, measured on a MacLeod gage. Data show the non-proportionality of thickness and transmission for hydrophilic materials, the direct increase in transmission with increasing temperature, and the lack of proportionality between partial pressure differential and transmission for hydrophilic materials.

Theoretical discussion assumes two forms of transmission, capillary diffusion through holes and activated diffusion through the polymer.

50. Dubois and Tressler, Paper Trade J., 109: No. 20: 15-18; (1939).
-- Ice and Refrig., 97: 449-451; (1939).
Water-vapor transmission of 25 wrapping materials for frozen foods was measured by exposure to air at 5 F and 50% r.h. while sealed over ice in a crystallizing dish. The sealing wax is 22% paraffin, 23% beeswax, and 55% petroleum jelly. Data are given for waxed papers and parchments, vegetable parchments, and viscose sheets.

51. Dunlap, Heating and Ventilating, 35: No. 4: 23-25; (1938).
A testing unit is described, being located at the Forest Products Laboratory for measurement of heat and water-vapor transmission. Two rooms are maintained at 72 F and 40% r. h. for one and 0 F for the other, with the invervening wall made up of test panels.

52. Eastman Kodak Co., Ind. Lab. Std. Practice No. 729; (n.d.).
Procedure for determining water-vapor transmission of coating materials is described. The coating material is spread upon insulating board, cheesecloth, or Fiberglas cloth and sealed with 33-67 beeswax-rosin over deep crystallizing dishes containing a desiccant (magnesium perchlorate), the assembly being tested in a cabinet at 125 F and 84% r. h. Transmission rates may be affected by the backing material selected.

53. Edgar, Agri. Eng., 18: 359-361; (1937).
Experiments in the use of insulation in potato storage warehouses are described. Inside air is at about 40 F and high humidities. Rock wool insulation was placed between two layers of waterproof paper, some installations having vents in the outer paper and some having none. The vented insulation gained 3.5% in weight during one season; the unvented gained 10% in weight.

54. Edwards, U.S. Bur. Standards, Tech. Paper 113; (1918).
A discussion of various test procedures for the measurement of the permeability of ballon fabrics to hydrogen is followed by a description of the method of the Bureau. The specimen is subjected to a sweeping stream of dry hydrogen on one side and a sweeping stream of dry air on the other, with the air stream being passed through a gas interferometer for determination of the hydrogen passing through the membrane. The effect of testing conditions on the transmission of hydrogen is discussed.

55. Edwards, Ind. Eng. Chem., 25: 846-847; (1933).
Comparison is made between two methods of measuring water-vapor transmission through paint films, the painted-panel technique of the Forest Products Laboratory and the cup technique under steady-state conditions of the Aluminum Research Laboratories. Checks are obtained, allowing for the decreasing partial pressure differential existing in the FPL method.

56. Edwards and Pickering, U. S. Bur Standards, Sci. Paper 387: 327-362; (1920).
-- Chem. Met. Eng., 23: No. 1: 17-21; (1920).
-- Chem. Met. Eng., 23: No. 2: 71-75; (1920).
Using the same apparatus described by Edwards (54) a careful study was made of the transmission rates for various gases through rubber membranes. Data show that transmission varies with composition, increases with aging and over-vulcanization, decreases with thickness, and increases with increasing partial pressure differential and temperature.

57. Edwards and Wray, Ind. Eng. Chem., 28: 549-553; (1936).
Water-vapor transmission of paint films was measured by a dry-cup method, sealing the membrane over activated alumina. At a constant temperature of 80 F the relative humidity was varied from 10% to 100%; at a constant moisture content

of 12.8 grams per cubic meter the temperature was varied from 60 F to 90 F. Aging varied from 0 to 36 months.

Transmission rates at high humidities are inapplicable to low humidities because of a break in rate curve at about 80% r.h. Transmission decreases slightly with increasing temperatures. Aging causes initial decrease in transmission as paint oxidizes, followed by increase as film fails,

58. Emley, Amer. Management Assn., Marketing Series 42: (1941).
Chem. Industries, 48: 582-584; (1941).

A general discussion of water-vapor transmission through packages includes data from Carson (36), mentions problems of waterproofing, requests standardization of tests.

59. Fabel, Kunstseide, 15: 383-386; (1933).

Water-vapor transmission of Cellophane films is measured by a cup method, using a glass crystallizing dish and Picein as a sealer. Calcium chloride is the desiccant at an operating temperature of 30 C.

60. Fawkes, Amer. Management Assn., Marketing Series 32: 3-14; (1938).

The application of film-coated paper to packages is amplified with regard to special techniques of labeling and coating with lacquers, thus reducing water-vapor transmission, air transmission, and losses of flavor. Papers were tested by a modified method of Abrams and Chilson, using calcium chloride in the cup and air outside at 90 F and 90% r.h. Data show effect of paper type, creasing, printing inks, and method of labeling.

61. Galton, "On Ventilation, Warming, and Lighting for Domestic Use," Int. Health Exhib. Handbooks, Second ed., London, (1884).

A good discussion of information then available which includes a proper viewpoint toward the reasons for condensation on walls.

62. Gardner, "Physical and Chemical Examination of Paints, Varnishes, Lacquers, and Colors," Ninth ed.: 239-241; (1939). Inst. of Paint and Varnish Research, New York.

Measurement of water-vapor transmission is carried out by several methods, with emphasis on the early method of Gardner. The central part of the cap for a 4-ounce screw-cap jar is cut out and the specimen held in place by the tightening of the cap, the bottom edge then being sealed with paraffin wax. The jar may contain calcium chloride and be kept in either a sealed jar containing water or in a cabinet containing air at 32 C and 88% r.h.; or the jar may contain water and be sealed in a desiccator.

Pictures and descriptions are given for the Cornwell cup, with clamping rings and rubber gaskets, the Payne cup, and the Dold cup, with matching glass flanges.

63. Gettens, Tech. Studies Field Fine Arts, 1: 62-68; (1932).

A preliminary report on the measurement of water-vapor transmission of protective coatings for portraits gives in detail the procedure first advocated by Gardner (62). A 30 mm. diameter hole in the center of the screw cap for a 4-ounce jar permits the specimen to be clamped by the cap and rubber gaskets so as to seal water inside the jar. The jar is then exposed to air at 32 C and desiccated with calcium chloride. All data are for liquid coatings spread on Paperglas by dipping, some coatings being copal, gum elemi, shellac, ester gum, cellulose nitrate, vinyl ester, beeswax, Japan wax, spar varnish, and glyptal lacquer.

64. Gettens and Bigelow, Tech. Studies Field Fine Arts. 2: 15-25; (1933).

The procedure previously reported (Gettens, (63)) was slightly modified by eliminating the screw cap, replacing it with an aluminum disk cemented to the jar. The specimen, films dipped onto Paperglas, was clamped between the aluminum disk and a brass flange, no gaskets being used. The jar contains water and the outside air is maintained at 32 C and 2-3% r.h. by silica gel. 71 films are reported; waxes showing the lowest transmission rate, natural resins tenfold that of waxes, and plastics 50-100 fold that of waxes.

65. Gregory, J. Tex. Inst., 21: T66-84; (1930).

Water-vapor transmission of textile fabrics is measured by a wet-cup method. The textile is sealed over a shallow dish containing water at 37.5 C, and the surrounding air is maintained at 20.5 C and 65% r.h. A maximum time of four hours is used.

66. Griffiths, Gt. Brit., Dept. Sci. Ind. Res., Food Invest. Bd. Spec. Report 35: 73-82; (1929).

Moisture absorption of insulating materials is investigated. Controlled-humidity air is forced through the material until it reaches constant weight. Timber and cork gave highest values for absorption, and slag wool the lowest. Low temperature investigation showed an accumulation of ice in the slag wool, leading to the suggestion that the warm surface should be protected against the entrance of moist air.

67. Halladay, Tech. Assn. Papers, 26: 415-424, 390-391; (1943).
-- Paper Trade J., 115: TS153-162; (1943).

The interpretation of the results of determinations of water-vapor transmission by ordinary cup methods is handled statistically, based upon the theory of least squares. The effect of many variables is thus smoothed out and consistent values for the rates obtained by less-skilled laboratory help.

68. Harvey, Tech. Assn. Papers, 7: 84-86; (1924).
-- Paper Trade J., 78: TS256-258; (1924).

The measurement of water-vapor transmission through boxboard is described, the apparatus being a triangular frame with metal bottom and top, the samples being sealed on the three sides. The air inside the frame is saturated by being exposed to felt soaked with water, and the outside air is at 77 F above calcium chloride. Results are expressed as per cent moisture-proofness.

69. Hawley, U. S. Dept. Agri., Tech. Bull. 248; (1931).

The relations between water and wood are discussed in detail, including the static effects on physical properties and the dynamic effects of the movement of liquids.

70. Hechler, McLaughlin, and Queer, Trans. Am. Soc. Heat. Vent. Engr., 48;505-516; (1942).
-- Heating, Piping, and Air Cond., 14:574-579; (1942).

Simultaneous heat transmission and water-vapor transmission measurements are made in a special guarded hot box arrangement. Data are presented to show a slight increase in water-vapor transmission with increasing partial pressure differential, the material being fibreboard.

71. Heinig, Teesdale, and Curran, Tech. Assn. Papers, 22: 359-369; 1939).

Equipment for the measurement of water-vapor transmission through building papers is described, and data are presented for about 140 samples of commercial papers. Specimens 10 inches square are sealed over a shallow metallic dish containing water and sphagnum moss, using roofing cement, and the dish stored in an atmosphere of 80 F and 30% r.h. Weighings are continued at weekly intervals until steady-state is established. The papers tested fall into classes, which in order of decreasing transmission rates are: saturated papers, infused or dipped papers, reinforced duplex papers, duplex papers, and saturated and coated papers. Apparently the presence of an unbroken surface of the water-resistant material is the principal factor in resistance to water-vapor transmission.

72. Herfeld, Collegium, 851:65-73; (1941).

Leather is tested for water-vapor transmission by sealing the sample to the cover for a beaker about 36 mm. in diameter (free area), the beaker containing water and being placed in an atmosphere passing over sulfuric acid. Regular weighing establishes the permeability index of the leather.

73. Herrmann, Bell Lab. Record, 13: No. 2: 45-48; (1934).
-- Rubber Age, 36: No. 2: 73-74; (1934).

Equipment is illustrated and described for the measurement of water-vapor transmission through various substances, whether rigid, subject to cold flow, or highly resistant to transmission. Basically the device is a wet-cup method, operating at various conditions and with modifications to permit the study of different types of materials. Representative data are presented for hydrocarbon wax, thiokol, asphalt, gutta-percha, polystyrene, phenol fiber, soft vulcanized rubber, benzylcellulose, and cellulose acetate. Fick's Law seems to apply.

74. Hobbs, J. Am. Leather Chem. Assn., 36: 346-350: (1941).

Water-vapor transmission through leather is measured in a cell made up of a tannin dish covered with the sample sealed between two brass rings, the entire assembly sealed at the edges and exposed in an atmosphere of 72 F and 65% r.h., with magnesium perchlorate in the dish. Comparative tests showed this test to be more reliable than those using calcium chloride and water. Edge losses were measured to be about 25% on thick specimens.

75. Hosey, Heating and Vent., 39: No. 9: 49-53; (1942).
-- Heating and Vent., 40: No. 5: Ref. Data 245-246; (1943).

The mechanism of condensation in insulation and its prevention are accurately presented. The use of sufficient insulation to raise the temperature of the warm side of the insulation to above the dew point is recommended, plus the use of a water-vapor proofing material to prevent transmission into the insulation. Tables of minimum insulation thicknesses for prevention of sweating on cold piping are given. The reference data charts have no mention of the necessity of vaporproofing.

76. Hukill, Agri. Eng., 20: 67-70; (1939).

Wall construction for air-conditioned houses and refrigerated storages is described, with detailed discussion of the temperature and dew-point gradients which may be established in a house and the probable occurrence of condensation. No data are presented; problem discussion is general.

77. Hyden, Ind. Eng. Chem., 21: 405-410; (1929).

Manufacture and properties of regenerated cellulose films (Cellophane) are related, with description of test for water-vapor transmission included. Specimens are sealed over a glass dish containing water and exposed to air at 100 F and circulating over sulfuric acid. Values are given for moisture-proof Cellophane, waxed brown paper, waxed glassine paper, and a series of tests on waxed brown papers.

78. Hyland, Canada, Dept. of Finance, Housing Admin., Insulation Manual, (1942).

In a discussion of the use of insulation the proper requirements and application of a vapor barrier are given, being taken from the Memorandum Specifications (35).

79. Institute of Paper Chemistry, Report 30 (Am. Paper and Pulp Assn); (1941-1944).
-- Paper Trade J., 116: No. 14: 11-15; (1943).
-- Paper Trade J., 116: No. 23: 10-13; (1943).
-- Paper Trade J., 116: No. 24: 16-19; (1943).
-- Paper Trade J., 117: No. 1: 12-15; (1943).
-- Tech. Assn. Papers, 27: 681-638; (1944).
-- Paper Trade J., 118: TS11-19; (1944).

Extremely thorough report on the measurement of water-vapor transmission through papers. Divided into six parts, only three have been published in journals as shown above.

Part I: A general discussion of the status of measurement of water-vapor transmission, with emphasis upon the errors involved in the cup methods. A comparison method is proposed, using a standard reference diffusion scale.

Part II: An electric sword hygrometer is described. This instrument is based upon the variation in electrical conductivity of a film of polyvinyl acetate with relative humidity. Details of construction, calibration, and use of the instrument are related.

Part III: A variation upon the wet-cup method is given, using a saturated solution of ammonium dihydrogen phosphate in the cup, giving 92% r.h. at the temperature of 100 F, and air outside at 23% r.h. A standard creasing procedure is given, using a force of 6 pounds per inch.

Part IV: A bibliographic study with about 60 references, all on the transmission of water vapor through materials.

Part V: Electric methods rapid in operation are described for the measurement of water-vapor transmission. In one, the specimen sealed over a cup containing water is exposed to a partially sealed space on the other side. The resistance to diffusion may be varied by varying the openings, and the measurement is made when the electric hygrometer in the semi-sealed space indicates constant humidity, the rate being determined by the previously calibrated openings. In the other method the space is completely sealed, and the rate of increase in humidity in the space is measured by the electric hygrometer, from which increase the transmission may be determined.

Part VI: A controlled relative humidity cabinet is described, being so designed that the cups containing solution and specimen may be weighed without removing them from the cabinet. Different devices for the measurement of relative humidity are described.

80. Kittelberger, Ind. Eng. Chem., 30: 328-333; (1938).
The water-vapor transmission of paint films is measured by coating one side of thin panels which are then sealed over 4-ounce sample bottles containing water. Warping is prevented by metal clamps, and the bottles are held at 120 F and 17-20% r. h. until weighings show a constant rate of gain. Blanks of unpainted wood panels correct for the resistance of the wood itself.

81. Kline, U. S. Bur. Standards J. Research, 18: 235-249; (1937).
Water-vapor transmission through aircraft finishes is measured by the use of a cup method, operated both as a wet method and a dry method. The film of finish is made by spinning on an amalgamated tin disk, and is sealed to an aluminum ring which is sealed to a glass dish containing either water or phosphorus pentoxide, after which the assembly is exposed to the air in a constant-temperature cabinet at temperatures and humidities desired. Results are given for various organic finishes, most of which are sufficiently absorptive so that the transmission when in contact with water and with water vapor is the same. The transmission is increasing with increasing temperature, and is not proportional to the partial pressure differential.

82. Levy, Plastic Products, 11: No. 2: 52-53; (1934).
Water-vapor transmission through cellulosic membranes is measured by a wet-cup method, using water in the cup and an atmosphere of 70 F and 50% r.h. on the other side. Also organic liquids were used and the transmission was found to be proportional to partial pressure differential except where the liquid was a solvent for the membrane. Data are given for tissue papers, glassine papers, vegetable parchment, regenerated cellulose, and films of cellulose esters and ethers.

83. Lishmund and Siddle, J. Oil and Colour Chem. Assn., 24: 122-137; (1941).
Detached varnish films are tested for water-vapor transmission in a special cell made up of two cups clamped together facing one another, with the specimen between, the clamping arrangement being such that no twisting occurs upon tightening. Moist air is circulated through one side and dry air through the other side, with pressure control. Results show no linear relation between thickness and transmission, but a linear relation is evident with partial pressure differential provided relative humidities are kept low.

84. Livingston, Amer. Management Assn., Packaging Series 3: 31-36; (1942).
Water-vapor transmission tests are made on substitute wrappers for foil papers, with calcium chloride on one side and air at 90 F and 80% r.h. on the other. Package tests are described and results given as an "index."

85. McBain and Bakr, J. Am. Chem. Soc., 48: 690; (1926).
A sensitive quartz balance is used for the weight of moisture absorbed on silica and other materials.

86. McDermott, Refrig. Engr., 42: 103-111; (1941).
Good survey of theories and mechanisms of water-vapor transmission is given, with interrelation in functioning structures, methods of control, methods of evaluation, and unexplained phenomena.

87. McKean, Amer. Management Assn., Packaging Series 6: 11-16; (1943).
In relating the evils of corrosion of war materials sent overseas an excellent description of two principal methods of packaging is given. "Slushing" involves coating of the material directly with preventive, such as heavy lubricant or wax. "Dehydration" involves packaging with a vapor barrier and maintenance of low relative humidities inside by absorption in silica gel. Acceptable materials are Pliofilm, Saran, laminated foil-kraft, and laminated creped paper.

88. McPherson, Refrig. Engr., 24: 209-213, 248; (1932).
-- Refrig. Engr., 24: 277-282; (1932).
Migration of moisture in refrigerator insulation is demonstrated. Hermetically sealed icebox with absorbed moisture present shows movement of water to bottom innermost insulation, with inside temperature at 42 F and outside temperature at 86 F. Leaks sharply increased the rate of saturation of the insulation, but internal vents permitted air to flow to cooling coils and relieved problem somewhat.

89. Madgwick, Phil. Mag., 13: 632-641; (1932).
Theory is developed for the flow by absorption and transmission of fluids through porous solids. No data are included.

90. Martley, Gr. Brit., Dept. Sci. Ind. Res., Forest Prod. Res., Tech. Paper 2: (1926).
Water-vapor transmission through timber plugs up to five inches in thickness is measured by use of a modified cup method. The plug is sealed over a glass dish containing water and the assembly sealed into a jar containing sulfuric acid. Data are presented for different woods and thicknesses.

91. Matschinsky, Gesundsheit-Ingenieur, 54: 169-172; (1931)
The migration of moisture through building walls and floors is described and theory developed to permit investigation and control of condensation. Suggested procedures are use of vapor barrier on both sides of insulation with air circulation inside, full venting of outer wall surface, or installation of vapor barrier at midpoint of wall.

92. Mattiello, "Protective and Decorative Coatings," Vol. 4: 194-222; (1944).
John Wiley and Sons, New York.
A thorough survey of the adsorption, permeability, water resistance, and structure of organic surface coatings includes good reviews and descriptions of the various methods of measurement of water-vapor transmission.

93. Miller, Heating and Ventilating, 35: No. 11: 56-58; (1938).
Calculation of water-vapor transmission and heat transmission through walls is summarized with emphasis upon the method of analysis, the quantity of vapor passing through, and proposed corrective methods. No data are given, although tests are described using a Gardner jar method with temperatures from 70 to 80 F and partial pressure differentials of 0.35 to 0.75 psi.

94. Muckenfuss, Ind. Eng. Chem., 5: 535-549; (1913).
In the study of aging of paints the water-vapor transmission of the films is investigated. A complex apparatus using eight separate parts and a double mercury seal allows the measurement of the rate of transmission from water on one side to a desiccant on the other. Data are given for implement paints, varnishes, exterior varnishes, rosins, barn paints, exterior enamels, outside whites, red leads, interior varnishes, and cement coatings. Gaseous diffusion and solution are considered to be the mechanism of transmission.

95. Muckenfuss, Proc. Am. Soc. Testing Mat., 14: Part 2: 359-425; (1914).
-- Engineering, 98: 159-160; (1914).
Further information is given in regard to the apparatus and its use for measuring water-vapor transmission (see (94)). Paint films decrease steadily in transmission until deterioration sets in, and films as tested on screens show different transmissions in different directions. Again solution is stressed as an important factor in transmission.

96. National Mineral Wool Assn., Mimeograph, unnumbered, undated.
This mimeograph is for instruction to builders and recommends strongly the use of vapor barriers on the warm side of walls in all new construction. Also recommended is the maintenance of relative humidities below 30-40%.

97. New York Paint and Varnish Prod. Club, Circ. 546: (1937).
Standard method for testing water-vapor transmission is described in detail. Films are placed on Patapar by dipping, and specimens from this material are clamped on a Payne cup containing water, the entire unit being kept in an atmosphere of 100 F over phosphorus pentoxide. Weighings are made until steady-state conditions are reached.

98. Parlett, Tech. Assn. Papers, 25: 411-422; (1942).
-- Paper Trade J., 114: TS265-276: (1943).
A discussion of the economic approach to the use of insulation in a paper mill includes charts regarding the use of insulation to prevent sweating of cold piping. Information is taken from Stone (126), and emphasis is upon preventing infiltration of air along with providing sufficient insulation to raise the surface temperature above the dew point.

99. Payne, Ind. Eng. Chem. Anal Ed., 11: 453-458; (1939).
Data are presented to show the advantages of Fiberglas over Patapar for the base material in testing the water-vapor transmission of paint films. Tests were run by the New York Paint and Varnish Prod. Club standard method (97).

100. Payne and Gardner, Ind. Eng. Chem., 29: 893-898; (1937).
Data for transmission of water vapor, ethyl acetate, methanol, acetone, and benzene through varnish films are presented. Specimen films were dipped onto pure cellulose paper and the sheet clamped between metal flanges over a metal cup containing the liquid being tested. The air is at 25 C outside and is dried over calcium chloride. No gaskets are used. Films tend to absorb, suddenly release, then reabsorb vapors. Solubility is controlling variable, with non-proportional relation between water-vapor transmission and partial pressure differential.

101. Queer, Heating and Ventilating, 35: No. 3: 63-65; (1938).
Condensation on walls and windows is discussed, with vapor barriers and venting recommended for walls.

102. Rabak, Tech. Assn. Papers, 24: 534-536; (1941).
-- Paper Trade J., 111: TS110-112; (1940).
-- Proc. Food Conf. Inst. Food Tech., 1: 193-198; (1940).
Data are given for materials used in packaging frozen foods. Specimens were clamped between rubber gaskets over a test cell 13.4 cm. in diameter containing calcium chloride. Outside air was circulated at 21.1C and 50% r.h., and -17.8 C and unknown r.h. Coated boards, impregnated boards, waxed papers, and viscose films were tested.

103. Rogers, Am. Arch. and Architecture, 149: 83-84; (Nov. 1936).
Accompanying data sheets on insulation, this article discusses the migration of moisture but admits of no cure.

104. Rogers, Architectural Record. 83: No. 3: 109-115, 118-119; (1938).
Work of Teesdale (137) and Rowley (108) is presented to the architectural group, with a crea

with a careful and accurate discussion of the proper use of a vapor barrier, accompanied by graphic illustrations. Good vapor barriers are said to include asphalt impregnated, surface-coated, and glazed building papers, laminated sheathing papers, double faced reflective insulations, and aluminum paints.

105. Rossman and Schultze, Korrosion und Metallschutz, 19: 13-19; (1943).
Data on water-vapor transmission through lacquer films are given in relation to film structure, temperature, pressure, relative humidity, air motion, chemical composition, and thickness. Transmission is directly proportional to the diffusion constant, and is greater for liquid water than for water vapor in most cases.

106. Rowley, Sigma Xi Quarterly, 27: 147-168; (1939)
The influence of climate on housing is particularly confined to the need for insulation. Discussion of insulation leads to the problem of water-vapor transmission through the walls, which is explained theoretically and for which controls are demonstrated. Data and illustrations are given for tests on the use of paints and paper vapor barriers in test houses.

107. Rowley, Trans. Am. Soc. Heating and Vent. Engr., 45: 545-560; (1939).
-- Heating, Piping, and Air Cond., 11: 452-456; (1939).
A theory covering the transfer of vapor through materials is detailed in regard to walls of buildings. Principal driving forces are partial pressure differential and equilibrium moisture content of the material referred to the relative humidity of the surrounding atmosphere. Proper use of vapor barriers, on the warm side, and improper use, on the cold side, are explained.

108. Rowley, Algren, and Lund, Trans Am. Soc. Heating and Vent. Engr., 44:95-130; (1938).
-- Heating, Piping, and Air Cond., 10: 49-60; (1938).
Condensation within walls is studied by subjecting model houses to conditions similar to those actually found. Data and illustrations are presented to show the effect of different types of wall construction and the use of different vapor barriers. Interior conditions were maintained at about 70 F and 40-45% r.h. while outer conditions were at - 20, - 15, - 10 F. The need for vapor barriers is amply demonstrated.

109. Rowley, Algren, and Lund, Trans. Am. Soc. Heating and Vent. Engr., 45:231-252; (1939)
-- Heating, Piping, and Air Cond., 11: 41-49; (1939).
Investigation of condensation problems and their relation to building construction is extended further than in the previous paper (108), by further study in some detail of many different vapor barriers in many different applications.

110. Rowley, Algren, and Lund, Univ. of Minnesota, Engr. Exp. Sta., Bull. 17: (1940).
This bulletin is an expanded and slightly supplemented version of previous work by the same authors (107 and 109).

111. Rowley, Algren, and Lund, Univ. of Minnesota, Engr. Exp. Sta., Bull. 18: (1941).
The effect of condensation in buildings is studied by actual investigation of a frame bungalow constructed within a controlled cold room. Air inside the house was normally maintained at 70 F and 40% r.h. Air outside the house was at temperatures varying from 15 F to -15 F. Different panels of the walls could be removed, permitting the employment of many different types and methods of application of vapor barriers and regular inspection of them. Among the variables studied were the effect of window and door frames, electric outlets in outer walls, wall venting, and attic ventilation.

112. Rowley, Jordan, and Lund, Univ. of Minnesota, Engr. Exp. Sta., Bull. 20: (1943).
Supplementary to a discussion of fuel conservation is an abridged version of previous work by these authors (110 and 111) covering the reasons for the use of vapor barriers and their proper application. The recommendations are attic ventilation, vapor barrier applied under plaster or on inner surface, and maintenance of low relative humidities inside the house.

113. Ruddick, Canada, Dept. Agri., Dairy and Cold Storage Series, Bull. 36: (1914).
Ruddick and Burgess, Canada, Dept. Agri., D. and C. S. Series, Bull. 44: (1916).
Ruddick and Burgess, Canada, Dept. Agri., D. and C. S. Series, Bull. 49: (1917).

In describing the construction of cold storages it is stated that the insulation must be kept dry, and a vapor barrier is recommended on the "inside." Recommended vapor barriers are damp-proof sheathing paper and pitch.

114. Sanborn and Hucker, Tech. Assn. Papers, 26: 329-335; (1943)
-- Paper Trade J., 116: TS185-191; (1943).

A report on packaging materials for dehydrated vegetables includes tests of water-vapor transmission by the standard TAPPI method (129). Data are given for glassine sheets, parchments and waxed paper sheets, special laminated sheets, and paperboards, with extra attention given to Cellophanes. Package tests are described, the differential being from air at 105 F and 85% r.h. to calcium chloride inside the units. Submersion tests and low-temperature drop tests are given for the same materials.

115. Schumacher and Ferguson, J. Am. Chem. Soc., 49: 427-428; (1927).

Apparatus for measuring diffusion of gases through membranes is described. The specimen is clamped between two cells by a pipe union type of fitting, including ball bearings to reduce torsion, sealed against leakage with mercury, and the entire unit evacuated. Liquid may be introduced by capsule into one side and broken at any desired instant. The diffusion may be measured by two methods, determining the increase in pressure on the dry side, or absorbing the diffused material on substances retained in a calibrated quartz spring balance of the McBain-Bakr type (85).

116. Schumacher and Ferguson, Ind. Eng. Chem., 21: 158-162; (1929).

Water-vapor transmission through rubber of various compositions is studied by means of the cell developed previously (115). Water is introduced and both the increase in pressure and the absorption on phosphorus pentoxide suspended on a McBain-Bakr balance are determined. The procedures check at the temperature of 25 C. Transmission through rubber is inversely proportional to the square of the thickness, decreases with increasing hardness, increases with increasing water content of the rubber, and is unaffected by minor variations of composition.

117. Schuetz and Schroeter, Chem.-Ztg., 65: No. 97/98: 475: (1941).

Water-vapor transmission of packaging materials is determined by sealing the specimen over a glass dish containing silica gel and exposing the assembly to air at 20 C in a constant-humidity cabinet.

118. Sears, Schlagenhauf, Givens, and Yett, Tech. Assn. Papers, 27: 580-581; (1944).
-- Paper Trade J., 118: TS27-28; (1944).

Data are presented as part of a program to compare various methods of measuring water-vapor transmission. Standard samples of Renoflex (a laminated Cellophane-foil-kraft), Cellophane, greaseproof board, 3-ply glassine, Pliofilm, ethyl cellulose, Scutan, and Pyroxcote (lacquered label stock) were tested by the standard GFMVT method, a constant-rate-of-gain GFMVT method, a GFMVT method using ammonium dihydrogen phosphate instead of water to give 92% r.h., and the Institute of Paper Chemistry method. The various GFMVT methods check, while the IPC method gives lower values. See also Weber (157).

119. Shuman, Ind. Eng. Chem. Anal. Ed., 16: 58-60; (1944).

Apparatus for measurement of gas transmission through films is described. The specimen is sealed over a flat surface covered with porous filter paper, after which that side is evacuated. The opposite side is exposed to pure gas at one atmosphere pressure, and the diffusion is measured by a manometer on the evacuated space. Rubber gasketing acts as the edge seal.

120. Soc. Auto. Engr., Aero. Mat. Spec. AMS 3610: (1942).

Specifications are given for moisture-resistant transparent plastic film. Maximum diffusion rate is to be 7.5 x 10^{-7} pounds per square foot per hour per millimeter partial pressure differential, measured at 77 F with 15-20% r.h. air on one side and 80-90% r.h. air on the other, this limit still holding after creasing twice at right angles with a 3-psi load. The specimen is sealed over a dish containing a saturated salt solution to give the low-humidity atmosphere and exposed in a cabinet to the high-humidity atmosphere, with weighings continued to a steady-state condition.

121. Soc. Auto. Engr., Aero. Mat. Spec. AMS 3810; (1944).
Specifications are given for adhesive tape, including moisture diffusion, which is limited to 0.075 grams per square inch, measured by sealing the tape over a circular opening in a bottle cap, the bottle containing a weighed crucible of calcium chloride and being stored in an atmosphere in equilibrium with potassium sulfate saturated solution at 104 F.

122. Southwick, Amer. Management Assn., Packaging Series 7: 21-28; (1943).
Water vapor and its peculiarities and habits are discussed in this general article. The effect of equilibrium humidity is stressed, along with exposure time and quantity packed.

123. Staedel, Papier-Fabr., 31: No. 41: 535-540; (1933).
-- Paper Making, 54: No. 9: 231-233; (1935).
Water-vapor transmission through papers is measured by stretching the paper over a shallow metal dish containing water and exposing the assembly to a constant-humidity air stream, usually 20 C and 65% r.h. Data are given for parchment, greaseproof, Cellophane, waxed paper, and moistureproof Cellophane. Partial pressure differential is considered as the most important factor, and the transmission is considered as a function of the hygroscopicity of the fiber.

124. Stillwell, Gt. Brit., Dept. Sci. Ind. Res., Forest Prod. Res., Tech. Paper 1: (1926).
Water-vapor transmission through woods is measured by a modified cup method, the timber plugs being sealed into a deep glass dish or tube containing water and the assembly sealed into a glass jar containing air over sulfuric acid. Data are presented for different woods in different thicknesses, with some correlation in regard to absorption, thickness, and transmission.

125. Stone, Refrig. Engr., 41: 326-327; (1941).
Insulation requirements and vapor barrier needs for cold storage units and cold ducts are discussed. Curves are presented for estimating thickness of insulation when conditions are known. Some data presented on water-vapor transmission through corkboards and finish materials used on cold storage units.

126. Stone, Refrig. Engr., 46: 31-37; (1943).
Required thickness of insulation to prevent condensation on low-temperature piping is computed from formula and graphs based upon thermal resistances of materials and temperatures involved. Information given for flat surfaces and for large cylinders.

127. Symington and Burroughs, Fibre Containers, 28: No. 4: 107-109; (1943).
A committee report of the Development Committee, Folding Box Assn. of America, describes in detail the mechanism, procedure, and typical results of the General Foods Moisture Vapor Transmission cabinet and test method.

128. Taylor, Herrmann, and Kemp, Ind. Eng. Chem., 28: 1255-1263; (1936).
Water-vapor transmission through organic materials is treated with considerable care and precision. Tests are made with different units, one being a modified wet-cup method for rigid and semi-rigid materials of normal transmission rates and also for cold-flow type materials when a supporting disk is used. A modified version of the Schumacher and Ferguson apparatus (115) is used for materials having extremely low rates of transmission. Equations are developed for calculating the diffusion constant. Data show dependence of transmission rate upon time of testing when material is absorbent, the increasing rate with increasing partial pressures

for absorbent materials, the variation in rate with thickness for absorbent materials, the increase in rate with temperature, and the delaying action of the presence of water-soluble constituents. The mechanism of transmission is considered as diffusion through non-sorbent materials, with polarization of sorbed molecules influencing strongly for sorbent materials.

129. Tech. Assn. Pulp and Paper Ind., Standard T448m; (1944).
-- Paper Trade J., 111: TS61-63; (1940)
-- Paper Trade J., 118: TS37-39; (1944).

This standard test for water-vapor transmission through paper and paperboard was accepted in 1940 and revised in 1944. Originally, the specimen was sealed over a glass dish or metal dish, flat and shallow, containing either a desiccant or water. The assembly, sealed with 50-50 beeswax-rosin, was exposed to a circulating atmosphere of air at 73 F and 65% r.h., weighing being made at intervals until a constant rate of change in weight was assured.

First revision was to conform with new testing room humidities, changing the 65% r.h. to 50% r.h.

1944 revision was to eliminate the use of water in the cup because any fluctuation in the temperature produced condensation on the under surface of the specimen, thus altering the rate of transmission. Also the standard units were modified to permit the use of English units.

130. Tech. Assn. Pulp and Paper Ind., Standard T 464m; (1944).
-- Paper Trade J., 119: TS35-38; (1944).

This standard test for water-vapor transmission through sheet materials at high temperatures and high humidities was developed to fill a need for tests comparable to service conditions. It is based on the GFMVT method with slight modifications. The specimen is sealed over the flat, shallow dish containing calcium chloride or magnesium perchlorate with 60-40 amorphous wax-paraffin wax, and the assembly stored in the cabinet maintained at 100 F and 90% r.h. Air is circulated, and light aluminum covers are to be used when removing for weighing. Weighings are made daily until a constant rate-of-gain is detected. A tare assembly is not advised because of the long period needed to reach equilibrium. Controlled temperature around the cabinet is advised because of the effect of outer temperatures upon the dew point inside the cabinet.

131. Tech. Assn. Pulp and Paper Ind., Standard T465m; (1944).
-- Paper Trade J., TS81; (1944).

This standard creasing test is to be used before testing for water-vapor transmission. Samples are creased so that ratio of crease length to test area is 1.0 for metric units, or 2.54 for English units. Accordion creases are made by folding and resting a platen on the folds for 10 to 15 seconds. The platen weighs 6 pounds per inch of crease.

132. Tech. Assn. Pulp and Paper Ind., Tech. Assn. Papers, 20: 90-102: (1937).

This symposium on water-vapor transmission includes data from Carson (36), descriptions of tests from Abrams and Brabender (2), Taylor, Herrmann, and Kemp (128), and Charch and Scroggie (39), and additional descriptions of tests from Eastman Kodak and some paper companies, all using cup methods. The effect of surface conditions, rate of moisture absorption, temperature, and mechanism of transmission are discussed.

133. Tech. Assn. Pulp and Paper Ind., Tech. Assn. Papers, 26: 62-66; (1943).

This symposium on water-vapor transmission includes a discussion of package tests on film packages, and a description of an economically constructed cabinet for constant-humidity work when using the dry-cup method.

134. Tech. Assn. Pulp and Paper Ind., Tech. Assn. Papers, 27: 135-139; (1944).

This discussion of water-vapor transmission follows the presentation of several papers and is primarily in regard to these papers, but many minor points are rather thoroughly considered. Data are presented on the slight increase in transmission through laminated glassine resulting from creasing, with comparisons made between the standard test and the actual creasing performed in a bag machine. Details of cabinet construction are discussed.

135. Tech. Assn. Pulp and Paper Ind., Tech. Assn. Papers, 27: 575-579; (1944).
This symposium of papers includes discussion of many details involved in the papers presented. Included is a discussion of practical aspects of testing, and a discussion of the details of the high-humidity standard test for water-vapor transmission.

136. Teesdale, U. S. For. Service, For. Prod. Lab., Mimeograph; (1936).
This is a reply to questions regarding the accumulation of water in homes, and it discusses the reasons for condensation and the proper control. Little data are presented. Recommended barriers in old construction are two coats of aluminum paint on inner wall surface or a vaporproof backing paper underneath the wallpaper.

137. Teesdale, U. S. For. Service, For. Prod. Lab., Mimeograph R1157; (1937).
-- Domestic Engr., 150: No. 6: 64-67; (1937).
-- Amer. Bldr. and Bldg. Age; (Dec. 1937).
-- Heating and Ventilating, 35: No. 5: 55-56; (1938).
Condensation in walls and attics is explained and remedies proposed. The effect of higher humidities inside buildings is brought out, and the effect of insulation is explained as not that of "drawing" water, but of increasing temperatures throughout the wall to cause condensation to occur inside the wall rather than on the surface. Recommended vapor barriers are asphalt impregnated and surface coated sheathing papers, laminated sheathing papers, and double-faced reflective insulation. Venting is advocated, but with the reservation that heating costs may be slightly increased.

138. Teesdale, U. S. For. Service, For. Prod. Lab., Mimeograph R1186; (1938).
-- Agri. Engr., 20: 353-356; (1939).
-- Concrete, 48: No. 8: 16; (1940).
Condensation problems in farm buildings are discussed, with a complete explanation of reasons and possible preventions. The use of insulation and vapor barriers is recommended but is admittedly expensive for such installations. The uselessness of vapor barriers alone against surface condensation is brought out.

139. Teesdale, U. S. For. Service, For. Prod. Lab., Mimeograph R1196; (1939).
-- Univ. Illinois, Engr. Exp. Sta., Circ. 37: 104-117; (1939).
-- Heating, Piping, and Air Cond., 11: No. 4: 213; (1939).
-- Auto. Heat and Air Cond., 10: No. 4: 20-21; (1939).
Domestic Engr., 153: 38-39; (Apr. 1939).
Condensation problems in modern buildings are discussed, with an explanation of the mechanism of transmission and condensation. Data are presented for comparison of different materials used in walls, and vapor barriers are recommended. It is suggested that all new construction north of the Ohio River should have vapor barriers installed in the walls, and old construction should be protected by the use of two coats of aluminum paint or a metal-foil insulation beneath the wallpaper.

140. Teesdale, Nat. Mineral Wool Assn. Proc.; (1940).
-- Heating and Ventilating, 37: No. 11: 46-47; (1940).
Current problems in moisture condensation are studied from the complete standpoint of constructing and testing model houses. Some house units are kept under controlled conditions on both sides, while others have the exterior conditions left to the chance of weather. Panels are removed from the walls to check moisture content, accumulation within the wall, and temperature gradients. Those panels without vapor barriers showed moisture pickup reaching to 60% moisture content, while those with effective barriers reached only to 11-15%. Ventilation to the outside was tried, but was found ineffective during extremely cold snaps.

141. Teesdale, Heating, Piping, and Air Cond., 14: 736-742; (1942).
Comparative resistance to water-vapor transmission of various building materials is discussed, this work being primarily an expanded version of the work of Heinig, Teesdale, and Curran (71). All data are converted into English units, and information is added in regard to building materials other than papers.

142. Thies, Tech. Assn. Papers, 22: 199-204: (1939).
-- Paper Trade J., 108: TS 79-84; (1939).
The chemical nature, manufacture, application, and properties of Pliolite are discussed. Pliolite is a coating material for paper. Water-vapor transmission is measured by sealing the specimen over a container holding water and exposing it to 40 C and 0% r.h., and data are given as a function of thickness of coating.

143. Thomas and Reboulet, Ind. Eng. Chem. Anal. Ed., 2: 390-391; (1930).
Water-vapor transmission of waxed papers is tested by an accelerated method. Samples are clamped between two brass flanges and sealed with petrolatum, then one side is connected with tubing to a U-tube filled with calcium chloride, the other being connected to a large bottle containing water. A pressure of 0.2 inch is maintained on the wet side for two hours at 30 C. The transmission is measured by the total increase in weight after two hours.

144. Trillat and Matricon, J. Chimie Physique, 32: 101-115; (1935).
Transmission of dry and moist air through Cellophane is measured, using a MacLeod gage for the flow rate meter and an ionization gage for the water-vapor rate. The ionization gage does not, however, serve as a flow meter for the air since absorption takes place on the walls of the container and the specimen itself.

145. Tressler and Evers, Paper Trade J., 101: TS113-115; (1935).
Water-vapor transmission rates for papers are measured by a wet-cup method. The specimens are sealed over a glass crystallizing dish with water inside and the assembly kept in an oven at 21.1 C and 50% r.h., weighings being made until steady-state is reached. Some tests were made at - 14.5 C, with ice in the dish. Each material had a different relation between transmissions at the different temperatures.

146. U.S. Army, Ordnance Dept., Tent. Spec. AXS-1322; (1944).
Specifications for moisture-vaporproof barriers include testing procedures and limiting values for transmission rates. Standard test is the GFMVT method. Creased samples must have a limiting rate of 0.05 grams per 100 square inches per 24 hours for Type I, 0.15 for Type II, and 0.25 for Type III.

147. U.S. Army-Navy, Aero. Spec. AN-C-67a; (1943).
Specifications for moisture-impervious containers are established, among the requirements being a maximum water-vapor transmission of 0.25 grams per 100 square inches per 24 hours after creasing four times, as measured by the GFMVT method.

148. U.S. Army-Navy, Aero. Bull. 162b; (1944).
Supplementary to Army-Navy Aero. Spec. AN-C-67 (147) is a list of acceptable products and their manufacturers.

149. U.S. Bur. Standards, Circ. 376: (1929).
Thermal insulation of buildings is discussed and moisture migration is mentioned, particularly in regard to condensation on the interior surface. Low-temperature insulation is studied in regard to condensation, but the recommendation is for air-proofing, based on ideas of infiltration.

150. U.S. Bur. Standards, Comm. Std. CS105: (1943).
Specifications for properties and applications of mineral wool insulation in low-temperature installations are established. Included is a required vapor barrier on the warm side, having a maximum transmission of one gram per square foot per day under a partial pressure differential of 17.1 millimeters of mercury.

The barrier shall be continuous, and recommended types are two hot-mopped layers of asphalt bonded with open-mesh fabric, one hot-mopped layer with duplex creped paper pressed in, or two hot-mopped layers of asphalt properly heat bonded.

151. U.S. Fed. Pub. Housing Auth., Natl. Housing Agency, Defense Housing Spec., Div. D-8; (1942).

Specifications are established for insulation to be used in defense housing construction, including the use of a vapor barrier north of the normal January 35-degree isotherm. The barrier is to have a maximum transmission of 2.5 grains per hour per square foot per pound per square inch partial pressure differential, when tested by "methods established by the Forest Products Laboratory."

152. U.S. Fed. Pub. Housing Auth., Natl. Housing Agency, Temporary Housing Spec., Div. T-6; (1943).

Specifications are established for the insulation to be used in temporary housing construction, including the use of a vapor barrier. The barrier is to have a maximum transmission of 2.5 grains per hour per square foot per pound per square inch partial pressure differential, when tested by TAPPI Std. T448m.

153. U.S. War Production Board, Gen. Conservation Order M-380: (1944).

Moisture-vapor barrier is defined and its use restricted. It is defined as any laminated or coated material, coated with a heat-sealing medium, composed of paper laminated to metal foil, and having a maximum transmission of 0.25 grams per 100 square inches per 24 hours when tested at 42 millimeters of mercury partial pressure differential at 100 F.

154. Van Alst Machine Works, "GFMVT Cabinet Instructions," (n.d.).

The cabinet consists of two concentric cylindrical shells with insulation between and a rack inside. Water is kept in the bottom and air is circulated continuously through the unit. Specimens are sealed with 60-40 amorphous wax-paraffin wax to the shallow dishes containing calcium chloride, which are then placed in the rack, the air inside being at 100 F and 90-95% r.h. An initial conditioning period of four hours is followed by a test period of 68 hours, the increase in weight being a measure of the water-vapor transmission.

155. von Sternberg, Nat. Painters Mag.; (1939)

Moisture troubles with paints are discussed, with 26 points which cause trouble if not corrected in a house. The problem of moisture migration is one of these, and can be corrected by installation of a vapor barrier on the warm side of the wall, correcting the excessive humidity conditions, and venting the exterior wall.

156. Walker and Hickson, Bur. Standards, J. Res., 1: 1-17; (1928).
-- Ind. Eng. Chem., 20: 591-596; (1928).

Accelerated tests for organic coatings included the measurement of water-vapor transmission at intervals throughout aging tests. Three coats of the material were applied to No. 100 wires sieves and the resulting sheet fastened with rubber bands to a glass petri dish containing calcium chloride the unit then being subjected to air at 30 C and saturated, with alternations to an atmosphere of 30 C and 32% r.h. Weighings were kept regularly. Later larger rectangular samples were tried, using a calcium chloride drying tube, but this was abandoned because of leakage.

157. Weber, Tech. Assn. Papers, 27: 582-584; (1944).
-- Paper Trade J., 118: TS24-26; (1944).

Data are presented as part of a program to compare various methods of measuring water-vapor transmission. Standard samples of Renoflex (a laminated Cellophane-foil-kraft), Cellophane, greaseproof board, 3-ply glassine, Pliofilm, ethyl cellulose, Scutan, and Pyroxcote (lacquered label stock) were tested by standard GFMVT procedure, constant-rate-of-gain GFMVT method, constant-rate-of-gain GFMVT method without desiccation, and standard TAPPI procedure T448m. Results showed the possible omission of desiccation during conditioning. All methods showed the same relative transmission through the samples, but the lower differential TAPPI method failed to differentiate between high resistance materials, while the GFMVT method did so. See Sears, et. al. (118).

158. Weber and Reichel, *U.S. Bur. Standards*, Bldg., Mat. and Struct. Rep. *BMS93*; (1942).

Accumulation of moisture in walls of frame construction was measured by erection of seven test panels on a house exposed to average Washington, D.C., winter weather and with interior conditions controlled to 75 F and 70% r.h. The panels were made with no stud space insulation, but some were with insulation board sheathing while others were wood sheathing. Some of each type had vapor barriers inside and some outside, some had building paper outside and some did not. In all cases during a 14-day period when the outside air temperature averaged 28 F the walls without vapor barriers suffered condensation in the stud space, while the walls with barriers did not. The use of building paper outside increased moisture in the stud space, even with no condensation and a vapor barrier. Insulation board differed from wood sheathing only in a slightly higher temperature level through the wall.

159. Weedon, *U.S. Navy, Bur. Aero.*, Report *AML(M)-599*; (8 August 1942).

Water-vapor transmission tests on various packaging materials were conducted according to the standard GFMVT method, and data are presented. Transmission rates for more than 100 materials, ranging from plastic sprays and films to papers, plain and laminated, are given. (Contents of this report were made available for publication through courtesy of the U.S. Navy.)

160. Weedon, *U.S. Navy, Bur. Aero.*, Report *AML(M)-600*; (1 August 1942).

Seventeen sets of standard samples were sent to laboratories for measurement of water-vapor transmission by different methods. Results are presented for Pliofilm, parchment, glassine, and cellophane by GFMVT method, dry-cup (except GFMVT), water wet-cup, solution wet-cup methods. GFMVT was most consistent, water wet-cup least. (Contents of this report were made available for publication through courtesy of the U.S. Navy.)

161. Weedon, *Tech. Assn. Papers*, 27: 642-645; (1944).
-- *Paper Trade J.*, *117*: TS 213-216; (1943).

Standard specifications for packaging materials for aeronautical supply are discussed. Proper application of materials is emphasized. Proposed modifications in specifications, such as creasing tests for water-vapor transmission measurements, are mentioned.

162. Weissberg, Jessup, and Weber, *U.S. Bur. Standards*, Bldg., Mat. and Struct. Report *BMS35*; (1939).

Stability of sheathing papers as determined by accelerated aging is discussed with data on many different properties, including water-vapor transmission. Transmission rates were measured by the dry-cup TAPPI method, calcium chloride to air at 21 C and 65% r.h. Weather cycle aging caused little increase in transmission throug laminated papers and asphalt impregnated papers, none through metal-foil laminated papers, but considerable through reinforced laminated papers. Laminated papers, however, lost most of their resistance to water transmission after aging. Metal-foil laminated papers were unaffected.

163. Wilson and Lines, *Ind. Eng. Chem.*, *17*: 570-573; (1925).

Water-vapor transmission through leather was measured by placing the leather sample between atmospheres over water and over sulfuric acid. Specimens were all tested by use of a jar arrangement.

164. Woolley, U.S. Bur. Standards, Bldg. Mat. and Struct. Report BMS63; (1940).
The theory of moisture migration and condensation in structures is elaborated.

165. Wray and Van Vorst, Ind. Eng. Chem., 25: 842-846; (1933).
Water-vapor transmission through paint films was measured by two methods, one for the film alone sealed over activated alumina and exposed to an atmosphere at 27 C and 95% r.h., the other for the film on both sides of wood panels sealed over activated alumina and exposed to an atmosphere at 27 C and 95% r.h. Data indicate that not only the vehicle but the pigment has a strong influence on transmission. Higher powder contents and finer grades of powder decrease the transmission.

166. Wray and Van Vorst, Ind. Eng. Chem., 28: 1268-1269; (1936).
Water-vapor transmission data for lacquer films is reported in the same units, as measured by the same equipment as earlier reported (165). Transmission decreased with aging, and transmission from contact with liquid water was less than from water vapor for single-coat films, although this is reversed for three-coat films. Forced drying was not beneficial.